CNWRA 91-013

PROBABILISTIC FAULT DISPLACEMENT AND SEISMIC HAZARD ANALYSIS LITERATURE ASSESSMENT

Prepared for

Nuclear Regulatory Commission
Contract NRC-02-88-005

Prepared by

Renner B. Hofmann

Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas

November 1991
(Rev. February 1993)

0/1

426.1
WM-11
NH15

delete all distribution except: CF, PDR + NUDOCS full-text

ABSTRACT

A significant sample of U.S. literature concerning probabilistic fault displacement and seismic hazard analysis (PFD&SHA) is reviewed. Probabilistic seismic hazard analysis (PSHA) methodologies of the Electric Power Research Institute (EPRI) EQHAZARD code, and the Lawrence Livermore National Laboratory (LLNL) SEISM 1 code, are reviewed. A draft procedure for seismic hazard analysis at high-level nuclear waste (HLW) repositories, being developed by the American Society of Civil Engineers, is also reviewed. This procedure, in its draft form, primarily addresses the use of the "stochastic method" for determining seismic strong motion accelerations and spectra. As requested by U.S. Nuclear Regulatory Commission (NRC) staff, literature concerning details of inputs to these probabilistic analyses are reviewed and their relevance to the licensing process (analyses) is provided. This review regarding application of probabilistic fault and seismic analyses to a long term high-level nuclear repository concludes that the:

- Probabilistic seismic analysis methods reviewed appear suitable for calculating mean hazards for use with performance assessments if uniform guidance regarding acceptable inputs and expert opinion elicitation is provided;
- Stochastic method is not sufficiently benchmarked against observations to resolve questions raised in the literature;
- Empirical ground motion attenuation curves, developed for the western U.S., are conservative for the Basin and Range tectonic province but none are specifically developed for use in this region;
- Near field of seismic shaking is not adequately specified in attenuation functions and that guidance may be required to ensure a complete and accurate description of strong motion;
- Use of expert opinions without complete supporting rationales may broaden probability distributions well beyond historical or geological observations thereby providing erroneous results for all but mean or median hazard calculations;
- Probabilistic fault displacement analyses referenced in the literature are not formally developed as a mathematical discipline or as computer codes and that effort will be required to formalize them for computer use;
- Recently developed concepts for nuclear power plant seismic analysis, e.g., characteristic fault slip and earthquakes, appear unsuitable for a high-level waste repository which has a much longer period of performance concern;
- Theory of chaos and methods for its utilization may be developed sufficiently by the time the Yucca Mountain repository site is submitted for licensing review that it may affect probabilistic assessments of seismic or faulting hazard;
- Cycles of seismic activity reported from investigations of paleo-fault offsets in the Basin and Range tectonic province may have a major influence on seismic and fault displacement hazard analysis at Yucca Mountain;
- Effects of seismic shaking and fault displacement on high level waste repository performance are not well defined and may result in a high level of hazard uncertainty.

As indicated by the framers of 10 CFR Part 60, seismic and fault displacement concerns are important elements in HLW repository hazard and performance evaluations. Research to resolve these issues has raised new questions and probably will continue to do so.

CONTENTS

CONTENTS (Cont'd)

FIGURES

TABLES

PREFACE

This report is in fulfillment of Geologic Setting (GS) Element Subtask 3.4.2.4. It is the Probabilistic Fault Displacement and Seismic Hazard Analysis (PFD&SHA) work item 107-002 for Phase 2, Activity 2.1, Subtask 2.1.1 in the CNWRA FY91 Work Plan (Change 6). Topics to be addressed were mutually agreed upon by CNWRA and NRC/NMSS staff to satisfy the deliverable: "Literature Review, Analysis and Uncertainty in Methodologies Letter Report".

This report was prepared to document work performed by the CNWRA for the NRC under Contract NRC-02-8[illegible]05. Activities reported here were performed for the NRC Office of Nuclear Material Safety and Safeguards (NMSS), DHLW Management. This report is an independent product of the CNWRA and does not necessarily reflect the views or regulatory position of the NRC.

Opinions expressed are intended to apply only to the application of PFD&SHA to a high-level nuclear waste (HLW) repository.

ACKNOWLEDGMENTS

The author wishes to acknowledge Dr. Amvrossios Bagtzoglou who prepared Appendix B of this report, and Drs. Wesley C. Patrick, John L. Russell, Gerry L. Stirewalt, and Kenneth D. Mahrer for their reviews and comments. Also acknowledged are the comments and guidance from Drs. Philip Justus and Abou-Bakr Ibrahim of NRC/NMSS during their reviews of draft versions of the report. Comments from Mr. Norman Eisenberg and Mr. James Park of NRC/NMSS, and a thorough review of the original report by Dr. Phyllis Sobel of NRC/NRR, which led to this revision, are gratefully acknowledged. Additional pertinent literature now available in the document room at NRC offices in Rockville, MD is acknowledged in this revision but their review remains a potential future effort.

1 INTRODUCTION

This report documents the results of a literature search and assessment which was conducted to aid in determining the viability of potential Probabilistic Fault Displacement and Seismic Hazard Analysis (PFD&SHA) compliance determination methods. This effort is related to application of PFD&SHA for a high-level nuclear waste (HLW) repository, and does not address other types of facilities.

PFD&SHA methods have not been applied to an HLW repository at the time of preparation of this report. Such a facility has a period of performance concern about 200 times that of a nuclear power plant. Significant differences in performance period and functions between these types of facilities is a motivation for preparation of this report. Of particular concern are the lower annual hazard probabilities associated with the 10,000 year period of concern regarding facility performance. Hazard estimates greater than the mean or median may be unacceptably large. There is also concern about extension of Probabilistic Seismic Hazards Analysis (PSHA) methods developed for the eastern U.S. to a site in the western U.S. and the extension of PSHA methods to probabilistic fault displacement (PFD) analysis.

This literature review and analysis includes technical elements and input variables that are a part of PFD&SHA methodologies. It is limited, by time and scope, to a significant sample of U.S. literature. The impetus for this task results from analytical requirements which depend upon expert opinion. PFD&SHA methodologies quantify these opinions by elicitation from teams of experts or panels of individual experts rather than from one expert performing a deterministic or probabilistic analysis. The likelihood of the opinion being correct is also elicited and included in the process. Probability distributions about empirical curves derived from data are also propagated in the analyses. Hazard curves are the output from PFD&SHA. They may be used as input to a performance assessment (PA) analysis. Hazard curves are a form of consensus quantification. Identification of expert-opinion uncertainty provides an additional tool for decision making and support for those decisions. Recommendations are offered in the development of a U.S. Nuclear Regulatory Commission (NRC) staff technical position (STP) on the subject of fault displacement and seismic hazard analyses.

This report reviews categories of design earthquake determinations. They are defined as types of seismic hazard analysis (SHA) in the National Research Council (1988) report. The simplest types of SHA contain limited statistical information. More advanced analyses use probabilistic methods to treat both data and expert opinions. Much less information concerning PFD analyses was found in the literature. PFD analyses may be approached by converting paleo-fault offset measurements and dating to equivalent earthquakes by using the moment equation and processing with PSHA methodologies. PFD may also be directly calculated but few papers address such procedures.

Three examples of design earthquake analysis are reviewed. Two incorporate expert opinions and an estimate of the probability that these opinions are correct. The third methodology, based on seismic source theory, represents an alternative to traditional empirical attenuation functions. This report also addresses characteristics and uncertainties in the input data required by the example methods.

Acronyms used in this report are summarized in Appendix A.

2 PROBABILISTIC METHODOLOGIES

Deterministic methods for fault displacements and seismic hazards may not be sufficient to find inadequacies in pertinent databases or to address all relevant high level nuclear waste (HLW) repository design issues. Probabilistic assessment of fault displacements and seismic risk may be necessary to identify uncertainties in hazard assessments used to prescribe design and operation inputs. As a result, recent studies of fault displacement and seismic hazards has emphasized using probabilistic risk assessment to obtain a quantitative measure of risk. Thus far, applications of these methodologies have been to nuclear reactors with nominal life spans of 30 to 50 years. The applicability of current probabilistic methodologies to a mined HLW repository has not been well established. This review provides support for the development of an STP concerning PFD&SHA. In this section, available probabilistic methodologies are reviewed.

2.1 SEISMIC HAZARD ANALYSIS

SHA methodologies have evolved from:

- Simple maximum expected vibratory ground motions based on an evaluation by one expert to
- Probabilistic analyses using ranges of data and standard deviations to
- Consideration of the statistical distribution of expert opinions.

A particular type or level of methodology may be preferred for a particular site/facility combination. All the methodologies employ a means of attenuating strong motion from an earthquake of a given magnitude at various distances. Current practices for obtaining attenuation function, either empirically or theoretically, are reviewed in this report. Other elements of the design earthquake determination process are estimating recurrence times of various magnitudes and determination of whether the recurrences are time related or not. Another component of SHA is definition of the source, or source area when the source is not well known. These elements are briefly discussed in this section as a part of the description of the various methodology types and in the examples of methodologies. They are addressed individually in later sections of the report.

2.1.1 Methodology Types

A categorization of SHA is well summarized in the 1988 National Research Council publication "Probabilistic Seismic Hazard Analysis". Five categories of seismic hazard analysis, I to V, are defined:

Type I	Deterministic Seismic Hazard Analysis
Type II	Semiprobabilistic Seismic Hazard Analysis
Type III	Single Model PSHA
Type IV	Multiple Model PSHA
Type V	Hybrid Procedure

Results from a PSHA may be input to a PA of a particular facility in which probabilistic analyses for many risks are aggregated. Ultimately, a final probability of failure or a given exposure of the populace to radioactivity is determined.

Type I, deterministic SHA, has the following characteristics:

- One or more earthquakes are defined by the analysis for use in design, without consideration of probability of occurrence.

- A design earthquake is described by a particular magnitude and minimum distance from the facility or by a Modified Mercalli Intensity (MMI) of damage at the site. An alternative identified as a "characteristic earthquake" on a fault segment may be also given. A characteristic earthquake is of a magnitude that is less than that which would result from displacement along the total fault length. This concept was published, e.g., by Schwartz and Coppersmith (1984), after most, if not all, license applications were submitted for existing nuclear power plants in the U.S. The concept may have arisen during reviews of material submitted after construction began.

- Products of the analysis are peak accelerations (from attenuation relations), strong motion seismograms (time functions which may be synthetic or selected or scaled from recordings of actual earthquakes), or spectra. Accelerations, time functions, or spectra (for example see Joyner, 1984) derived in Type I analyses are often described with the adjective 'deterministic.'

- Probabilities enter only as standard deviations of data about a mean. Probability determinations for a design acceleration, however, are made after a 'deterministic' value is calculated without regard to probabilities. Such probabilities were prepared, primarily at the request of the Advisory Committee on Reactor Safeguards (ACRS), when new geologic information was discovered which caused a review of design criteria. These estimates were made after NRC acceptance of a license application and sometimes after construction was completed. The calculations were made by one or two staff members. Inputs such as source zones and attenuation functions were decided upon by the staff members involved. These are essentially single-expert probabilistic analyses for the highest design vibratory ground motion that had been calculated from a prior deterministic analysis.

Not stated in the National Academy of Sciences (NAS) report is the past frequent dependance on the NRC Regulatory Guide 1.60 design spectra (Newmark, et al. 1973 and Newmark and Hall, 1982), sometimes modified by deconvolution programs (e.g., SHAKE, FLUSH, and later codes on this evolutionary ladder).

Type II, semiprobabilistic SHA

- Type II has the same characteristics as Type I except that the earthquake is defined in probabilistic terms (e.g., the one in 100 year earthquake). This type of analysis has been the basis of building-code zone maps in the U.S. and Canada (see for example Milne and Davenport, 1969). However, it has had little application to the U.S. nuclear industry except indirectly for nonsafety-related structures governed by building codes. The probabilistic analysis procedure to derive peak acceleration, however, may have comparatively high levels of sophistication. Examples are EQRISK, McGuire (1976) and FRISK, McGuire (1978) computer programs which are based on Cornell's (1968) probabilistic analysis.

Type III, single-model PSHA, has the following characteristics:

- Input to the model is comprised of a single acceleration attenuation function, a single areal distribution of earthquakes, and a single earthquake recurrence function for each earthquake source zone or fault. Algermissen et al. (1982) is cited as an example by the National Research Council (1988).

- Its output is a graph of annual probability that a specific peak acceleration will be exceeded at a site. Contours of acceleration corresponding to a specified annual probability of occurrence may be mapped over a site area.

Type III analyses, and permutations of it, have been used for off-shore drilling and natural gas facilities. Permutations include contouring accelerations of a given return period over broad geographical areas. The procedure is derived essentially from multiple calculations using a Type II analysis. It is used extensively in Canada, e.g., Hofmann et al., (1982), for large bridges, liquified natural gas facilities, or other large civil structures whose failure could pose a secondary hazard to the populace. It is also considered in the siting of Canadian nuclear facilities.

Type IV, Multiple Model PSHA, characteristics differ from Type III as follows.

- Multiple earthquakes are input as in Type III. Multiple definitions of seismotectonic provinces and ground-motion attenuation functions are used because scientists and engineers do not have a consensus regarding which might be most correct.

- Uncertainty in expert opinion is defined by groups of experts and assuming that truth lies within the bounds they espouse. Quantification is attempted by a statistical analysis of the opinions and expert self appraisals of the uncertainty in their respective opinions. Examples given in the National Research Council (1988) report are the Seismic Owners Group/Electric Power Research Institute (SOG/EPRI) study (EPRI, 1988) and the Lawrence Livermore National Laboratory (LLNL) study (Bernreuter et al. 1984). Additional such analyses are reported in Bernreuter et al. (1989a and 1989b).

- A degree of belief or uncertainty in the model espoused (uncertainty) is estimated by each expert or team of experts.

Although the Type IV methodology may be used to quantify numerical estimates of uncertainty associated with different tectonic interpretations, there are potential problems. The use of multiple and extreme hypotheses (regarding faulting, tectonics, ground-motion attenuation, maximum magnitude, etc.) permits the inclusion of disparate views into a final analysis. Examples might include an applicant's views encompassing only experiences in recorded history and the sometimes highly conservative projections of intervenors. A mean plus some standard deviation is usually required for design criteria. Consequently, the attendant scatter should increase conservatism of the result beyond that which a best and unbiased estimate would provide (if such could be found). The use of this process may encourage the promulgation of extreme views by litigants who hope that the result may be biased in their favor. Theoretically, this can be overcome by using large panels of reasonably unbiased experts. Assumptions that the scatter in differences of opinion represents a real measure of uncertainty may be either overly conservative or overly optimistic because:

- Large uncertainties resulting from the inclusion of radical and technically unsupportable hypotheses may not be realistic.

- A seemingly radical hypothesis eventually may become universally accepted, eg. continental drift.

- The mean developed by a large group may provide confidence in a theory that may ultimately be proven wrong.

As an example, one might consider that at a time before Columbus' explorations, a consensus might have been that the earth was flat; only the distance of Spain from the edge of the earth was uncertain. Type IV analyses are potentially a socially acceptable solution to a technical problem. It may be the best solution available, but credence in the probabilities derived cannot be high. Perkins et al. (1988) summarize the matter in the U.S. Geological Survey (USGS) review of the SOG/EPRI methodology. They quote Brillinger (1985):

> The EPRI/SOG study makes essential use of personalistic probabilities. I suggest that these probabilities are without significance if they cannot be meaningfully related to the real world. Some empirical validity is needed. That the Earth Science Teams were willing to guess values, is surely not all that is needed to justify the use of those values.

The same may be said of the similar LLNL approach (Bernreuter et al., 1984). Brillinger's commentary can be moderated by a staff position which requires a rationale for each expert opinion on technical matters for which adequate data are not available. Expert opinions without rationales were used in the eastern U.S. nuclear power plant analysis. However, because of the long period of performance concern for a HLW repository, rationales may be necessary to narrow probability distributions to useful limits. Earthquake design inputs (accelerations, velocities, or spectra), based on a standard deviation or other criteria than the mean or medium value, may become unreasonably large. Therefore staff should be prepared to assess such rationale and exercise the authority to accept or reject it. Leaving in all expert opinions, whether well justified or not, has the effect of including all views to produce a "democratically" derived result. This may have social/political advantages but may also render results inaccurate or unusable.

Development of PSHA methodologies was initiated by NRC's Office of Nuclear Reactor Regulation (NRR) at LLNL and by electric utilities at EPRI. They were initiated to accommodate the USGS requirement that the 1886 Charleston earthquake must be considered possible anywhere in the eastern U.S. because no obvious associated faulting was found e.g., Rankin (1977). This means that a first-P-wave-motion body wave magnitude (m_b) of 6+ must be assumed to occur with some finite probability in areas where no earthquakes have been known to occur and where there are no known active tectonic structures. The USGS suggested that probabilistic measures be used to establish the hazard posed by their new dogma.

Whenever possible, definitions of input variables should be quantitative rather than relying on opinions. An example is the definition of seismotectonic boundaries. These can be defined in terms of Quaternary tectonics or historical seismicity, although they are often defined on geomorphological or gross geological grounds subject to qualitative interpretation. Wherever quantitative definitions are possible, they should be specified in STPs or other NRC guidance to limit the substitution of opinions for data. All PSHA methodologies are under development and revision. Their review in this report is limited to published papers, which may not represent the current status of such methods.

Type V, hybrid procedure is a Type III or IV PSHA combined with deterministic procedures to derive detailed characteristics of the seismic hazard, e.g., strong motion time functions.

Whether this procedure merits a separate category is questionable. The deterministic characterization of the details of strong motion is common in most, if not all, recent PSHA in any of the categories above. Further, many of these analyses for detailed characteristics are also probabilistic, in the sense that variations about a mean are established. This subject is discussed in following report sections.

The word 'probabilistic', as a descriptor of fault displacement or seismic analysis, has come to mean that the methodology employs expert opinions in the absence of data and that those opinions are treated probabilistically. Such methods are used when adequate data are unavailable or when theory cannot distinguish between which of several interpretations of data is correct. This meaning is different from past definitions in which statistical variations in data are analyzed to yield probabilistic hazard curves but expert opinions are not treated, e.g., Yegian (1979).

Deterministic methods essentially use the opinions of one investigator. PFD or PSHA attempts to establish the uncertainty in that opinion by polling other experts. Through regulatory precedent, the uncertainty in PFD&SHA may be effectively limited. Because regulation of a mined HLW repository has a limited technical precedent base, these limitations are not as clear as they might be for nuclear power plants. However, the broader experience in nuclear power plant regulation should be considered when applying PFD or PSHA to repository analysis. Probabilities are also applied to data, not just opinions; and the word probabilistic also applies to this process. In the balance of this report, the adjective is applied as the context requires. Neither 'probability' nor 'uncertainty' is used exclusively to represent treatment of opinions.

In PSHA, a distinction is made between randomness and uncertainty. In both the LLNL and SOG/EPRI methods (discussed in the following sections), the concepts of randomness and uncertainty are separately defined. Randomness is stated by EPRI (1988) to be a property of a phenomenon expressing its variability. It is defined from a statistically significant sample, and no further data are expected to change it. Uncertainty represents variability in opinions. Reiter (1985) divides uncertainty into two components, randomness and systematic uncertainty.

> "Random uncertainty can be thought of as that uncertainty associated with the apparently inherent and irreducible randomness in the earthquake source and wave propagation. Systematic uncertainty is that associated with our imperfect knowledge of the appropriate models and associated parameters that describe the generation and propagation of earthquake motion."

New data might cause a closer agreement and therefore could reduce systematic uncertainty. Randomness is treated as a variable which can be integrated, or summed, if it is determined from a series of discrete events.

2.1.2 LLNL Methodology

The LLNL Type IV methodology was commissioned by the NRC to reassess design bases for nuclear power plants in the eastern U.S. It was initiated after the USGS declared that the Charleston earthquake could occur anywhere in the eastern U.S. with some probability. This statement is the result of many years of study to find the cause of the Charleston earthquake in terms of a fault or tectonic structure. Results were not conclusive, e.g., Rankin (1986).

The calculations of Bernreuter et al. (1984) were made using LLNL's seismic hazard codes (SHC), later named SEISM. A code version with additional ground motion attenuation functions, SEISM 1, was used in the calculations reported in Bernreuter et al. (1985 and 1989a). Some of its inputs are similar to those of a deterministic procedure as described in 10 CFR Part 100, the regulation for nuclear power plant siting. Examples are maximum and minimum earthquake magnitudes. Probabilities of occurrence and of possible source-to-site distances are also carried in the calculation. The calculations are repeated many times by using inputs from individuals on a panel of experts. Unlike prior deterministic studies, probabilities are used where known and are estimated by the panel members where not known. An aggregation of these analyses results in a tentative or test redefinition of the earthquake design basis for ten eastern U.S. nuclear power plant (Bernreuter et al., 1984). Variability in results were large because different experts on the panels defined different seismotectonic zone boundaries, maximum earthquake magnitude, strong motion attenuation function, and estimates of uncertainty in these parameters.

Bernreuter et al., (1984) states that in the LLNL study 33 different acceleration attenuation functions were employed and a mean hazard curve was established. None of the attenuation functions had the benefit of close-in strong motion records of larger earthquakes. This most critical part of any attenuation function remains a point of conjecture and extrapolation. Most attenuation functions are extrapolated to the near-field based on little or no data. However, with no consensus, a procedure like LLNL's may be the only workable way to approach the problem.

Later developments in eastern U.S. seismicity studies are reported by Bernreuter et al. (1989a). This analysis was modified somewhat based on findings regarding differences between the EPRI and LLNL results as reported in Bernreuter et al. (1987). Further, additional acceleration attenuation functions were incorporated in the SEISM 1 code to reflect some expert's preference for seismic source theory methods, e.g., as described by Hanks and McGuire (1981). The LLNL PSHA methodology is well described by Bernreuter et al. (1984), which provides the basis for this review of the LLNL procedure. Although variations on this theme have resulted from further comparisons of the LLNL and EPRI methods, e.g., Bernreuter et al. (1989b) as applied to the eastern U.S., they are not analyzed in this report. These permutations may be important to considerations of hazard for relatively short lived facilities. Their impact on the fundamental methodology as applied to an HLW repository is less important than the basic precepts of the method. Ongoing changes in methodology detail are topics for future reports.

NRR urged affected nuclear power plant owners to develop their own methodology. Most of them did so through the SOG and EPRI (EPRI, 1988). The LLNL and SOG/EPRI methodologies are similar. Initial differences included attenuation functions, minimum and maximum earthquakes, catalogues of earthquakes, whether soil or site corrections were used, instructions given to experts, and whether teams or panels were used. Resulting hazard curves for eastern U.S. nuclear power plant sites differed. Subsequent work, e.g., as reported in Bernreuter et al. (1989a and 1989b) state that some differences were eliminated in later analyses by LLNL and EPRI.

Figure 2-1 shows a flow chart of the LLNL method from Bernreuter et al. (1984). The result, or hazard, is presented as a constant percentile hazard curve (CPHC) in terms of an "Annual Probability of Exceedance" versus "Acceleration," e.g., see Ang and Tang (1984). This approach is different from one in which a final design acceleration is used with the combined normalized Regulatory Guide 1.60 suite of design spectra. Current practice usually requires site-specific design spectra. This occurs where a thorough study of site-specific design spectra is presented or if the design earthquake is much higher in magnitude than those used in developing the Regulatory Guide 1.60 spectra.

Hazard curves, resulting from the LLNL or SOG/EPRI methods, allow combining the hazard probability with an engineering analysis of consequent failure. The probability of radiation release from the failure may also be estimated. The amount of the release may be compared with the criteria for radiation exposure in applicable regulations. This permits setting design ground motion on other than strict adherence to 10 CFR Part 100, Appendix A. The basis for this regulation is a limiting radiation exposure to an individual or the population, which may be used directly as criteria for engineering performance of the repository.

Low estimated confidences in expert opinions and the large variation in opinions would be amplified by the extended time during which an HLW repository is to remain functional. The approach may result in very conservative design values for the least seismically active parts of the country. Technical opinions may better converge in more seismically active areas where recorded data are available. At this time there are no published studies comparing convergence between eastern and western U.S. seismic hazards. Mean design values may be higher at some western U.S. sites but variance may be lower. Therefore, it is possible that a one-standard deviation risk might be lower for a 10,000-year design ground-motion in a moderately seismic region than in an almost aseismic region for which uncertainty is higher because of limited data.

To use the LLNL or SOG/EPRI methods at Yucca Mountain, the desire for a high level of assurance over a 10,000-year period should be an important consideration. This period of interest requires information regarding the nature of intraplate earthquakes, their causes, and near-field strong motions. More data to improve confidence are always desired, although the state of knowledge is better now than in the past. However, acquiring paleo-fault displacements and ages of offsets over a substantial area that includes Yucca Mountain is important. It would provide a catalogue of large paleo-events and displacement rates for faults with significant offsets in the Quaternary period. A better understanding of Basin and Range regional fault displacement phenomena would add to the confidence that could be placed in PFD&SHA for Yucca Mountain. SEISM 1 does not contain a specific algorithm for fault sources, although they can be approximated by multiple narrow source zones with hypocentral restrictions on each zone. NRC/NRR anticipate including a fault-specific algorithm in a SEISM 3 version of the code. A completion date for SEISM 3 is not known at this time.

The LLNL procedure began empaneling of experts on seismicity (originally 14 members) and ground-motion modeling (originally 6 members). Not all experts participated through the entire analysis of the eastern U.S. Individuals from these panels gave their opinions independently regarding various choices of:

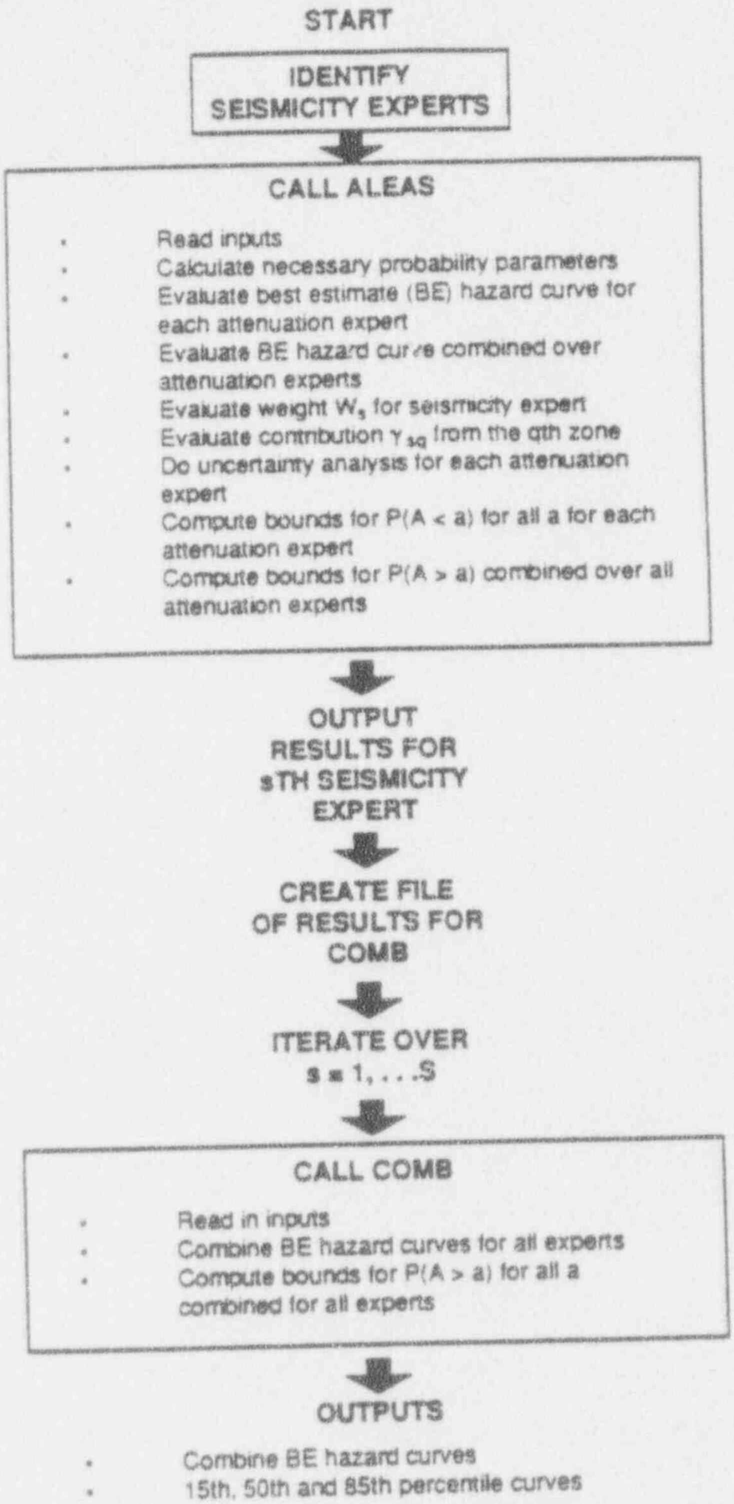


Figure 2-1. Flow diagram of the LLNL PSHA process (from Bernreuter et al., 1984)

- Seismic source zones and their confidence in their choices.

- Attenuation functions (termed ground-motion models which include a factor for site soil conditions) and their confidence in those choices.

- Upper magnitudes for each source zone.

- Magnitude recurrence relationships (form and parameters) for each source zone are derived from several lists of earthquake data.

- Self weights on the confidence of the expert to provide advice for various geographic regions.

Earthquakes are assumed to occur randomly throughout a seismic source zone. Permutations of the best estimates (BE) of each expert concerning the above variables are combined to obtain an estimate of acceleration at a site. Sites of ten eastern U.S. nuclear power plants were chosen as test cases. Statistics concerning all the BEs, combined with the confidences expressed in them, are processed to obtain a hazard curve for the site. The curve is acceleration versus the annual probability that the acceleration will be exceeded (exceedance). Other than BEs may also be employed although their associated confidences are lower. A minimum magnitude is agreed upon. Because MMI was used in the initial LLNL study, a relationship between MMI and the Lg wave magnitude (Mb_{lg}) was developed by Bernreuter et al. (1984). This magnitude is closely equivalent to M_L or m_b, the Richter local magnitude, and the first-P-motion body wave magnitude, respectively. Peak ground acceleration is assumed to occur with a log-normal distribution. The occurrence of earthquakes are assumed to be point sources with a Poisson distribution. Later LLNL studies, e.g., Bernreuter et al. (1989a), considered moment magnitudes as well.

Hazard statistics are made by calculating acceleration using various combinations of source zones from one expert with the attenuation function from another panel expert. As many as seven classes of attenuation/recurrence models may be used with one source zone pick. In each calculation, the expert's confidence in his opinion of his zonation map, or attenuation/recurrence function, is used to estimate total uncertainty in the resulting acceleration hazard. Where data are used, e.g., to establish an attenuation function, the variability in the data is used to determine uncertainty for that parameter.

2.1.3 SOG/EPRI Methodology

The SOG/EPRI methodology is a Type IV, which relies upon teams of experts to provide suites of alternative input variables. Members of each team work together to provide an analysis. Each team develops a separate analysis, the results of which are treated together in a statistical analysis. The procedure is discussed in some detail in EPRI's NP-4726: "Seismic Hazard Methodology for the central and eastern U.S.," Vol. 1, Part 1, Theory, and Vol. 1, Part 2, Methodology (Revision 1), 1988. Vol. 1 is preceded by an 83-page NRC/USGS review forwarded by James E. Richardson, Asst. Director for Engineering in the Office of NRR and by a responding letter from T.A. Ruble, Chairman of the SOG Licensing Steering Panel. Also participating was the SOG, comprised of 39 of 48 electric utilities, who are concerned with the seismic issues that may apply to their nuclear power plants.

EPRI created a PSHA computer code EQHAZARD which is available to SOG members. It automates probability calculations. EPRI (1988) states that a major part of the package is to provide a standard for input variables, such as tectonic region boundaries, and a "paper trail" for documenting expert opinions.

Unlike the LLNL procedure, which uses expert opinions as offered, the SOG/EPRI method often provides a selection of choices. Examples are, maximum magnitude and methods of smoothing 'a' and 'b' coefficients in the standard recurrence relationship of Gutenberg and Richter (1956). SOG/EPRI's method uses a fault tree analysis to decide whether a given tectonic structure is active or a given group of earthquakes is associated with a tectonic structure, etc. These parameters, their estimated probabilities of being correct, and one or more peak ground-motion attenuation functions are used with a procedure like McGuire's (1976) EQRISK to develop hazard curves. Ranges of estimates by various teams are included as though they were scatter in data. Hazard curves have the form of probability of exceeding a peak ground-motion value for a given time period versus a peak ground-motion variable (acceleration, velocity, or displacement).

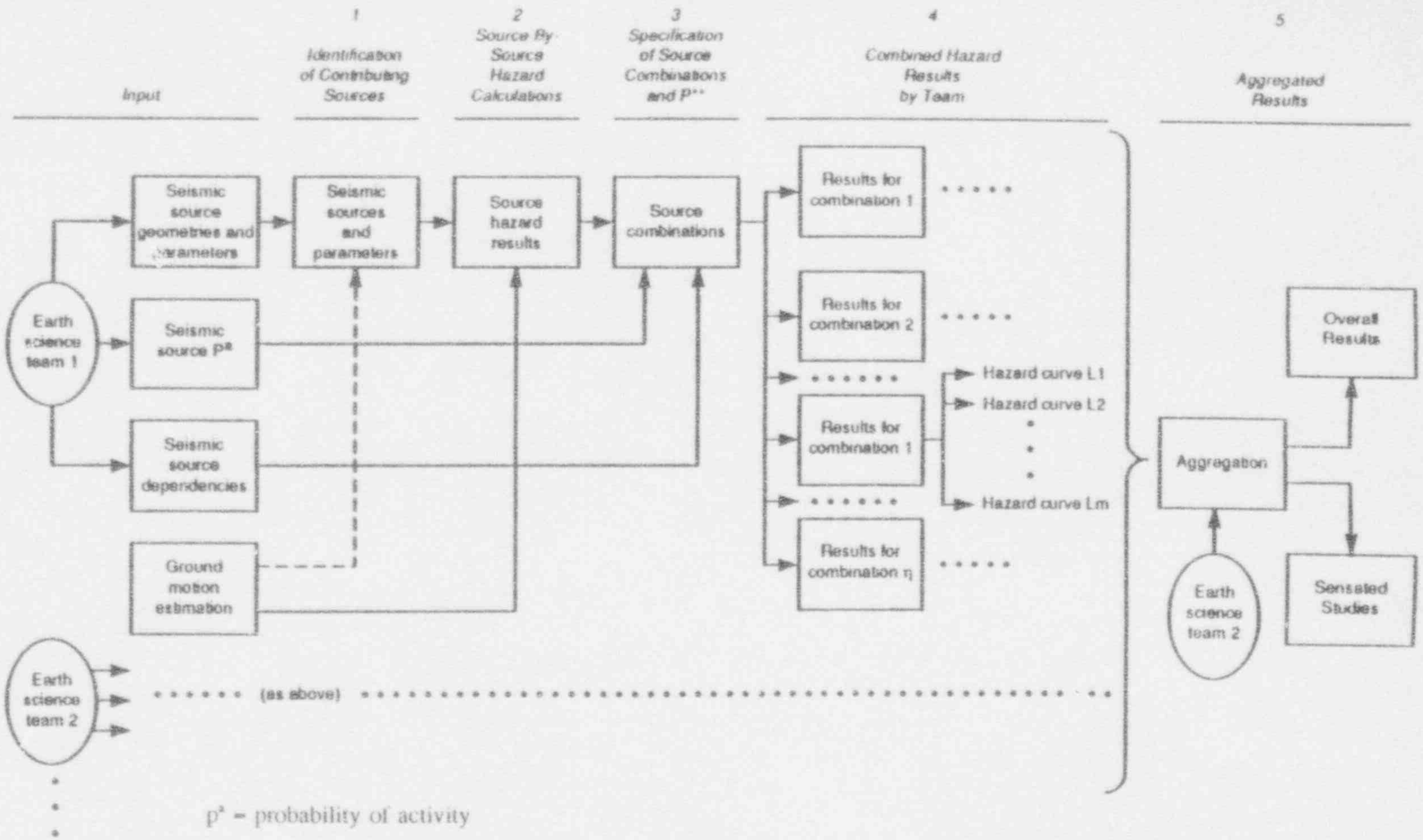
Figure 2-2 is a flow diagram of the SOG/EPRI process taken from their report (EPRI NP-4726-A, Revision 1, 1988). Although not stated in Volumes 1 and 2, the EPRI teams appear to have used only a stochastic methodology rather than empirically derived acceleration attenuation curves.

Following the protocol of the SOG/EPRI method, earth-science teams are asked to estimate the degree of uncertainty in their BE and in alternative estimates of a parameter (e.g., peak magnitude or tectonic feature boundary). Estimates from the teams are compared and a mean risk developed. Outlying estimates are then eliminated and the mean recomputed. However, at the recommendation of the USGS and NRC, outliers are allowed to remain in the methodology. A motivation for this may be that some teams were comprised of industry contractors. This may suggest a potential conflict of interest that might be perceived to cause sharper convergence of results. The omitted process might be beneficial, however, if the teams were drawn from a more diverse, possibly international, population.

This methodology does tend to incorporate randomness in uncertainty modules. It encourages the division of randomness into categories that are too small to contain a statistically significant sample. It then treats these in a fault- or logic-tree as used in performance assessment, e.g., McGuire (1990). An example is allowing slope and intercept values of a recurrence relation to vary over very small areas. The integration may be over a statistically insignificant sample. Each small area would be treated as if it were an isolated source region or tectonic province. That this additional degree of freedom improves the result is not clear. Because no new information is added, however, it could introduce errors. The purpose of this scheme is to reduce large hazard differences consequent to small changes in zone boundaries.

Mean values resulting from the teams' efforts were determined as mean log values. The USGS/NRC reviewers believed that this biased results so the arithmetic mean was required. The SOG/EPRI report states that both the probability distributions from individual teams and the variation between teams were used to establish the "consensus" risk (Figure 2-3a).

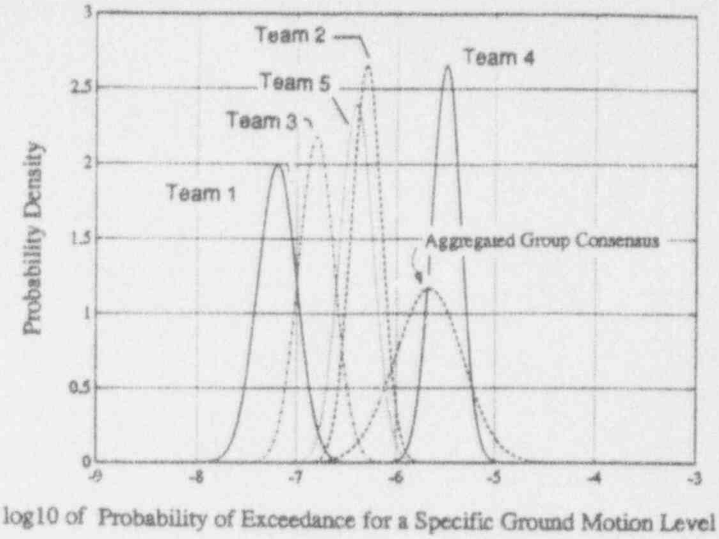
An aggregation of team opinions calculated at CNWRA, when all team weights are unity and a log normal distribution function of exceedance is assumed, is also on Figure 2-3a. Other assumed probability distributions would change the aggregation. A larger set of teams would be required to adequately define a probability distribution. Probability density represents the group or team confidence



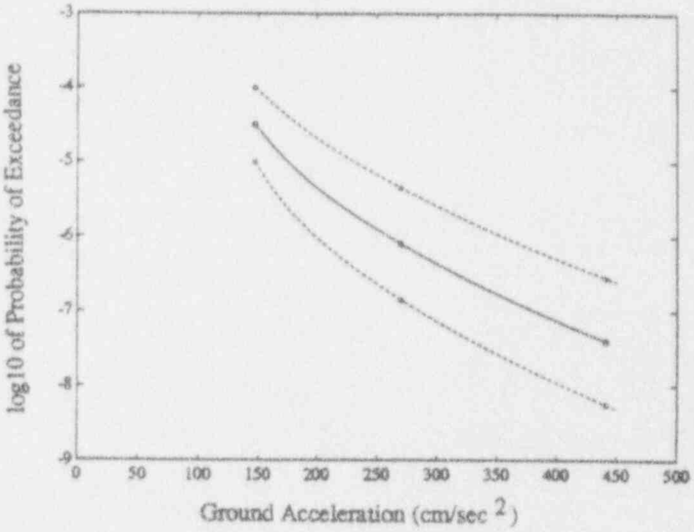
p* = probability of activity

Figure 2-2. Flow diagram of the SOG/EPRI PSHA method (EPRI, 1988)

2a Aggregation of Uncertainty (After EPRI, 1988)



2b Example of Seismic Hazard and Standard Deviations



2c Global Error (or Convergence) Measure

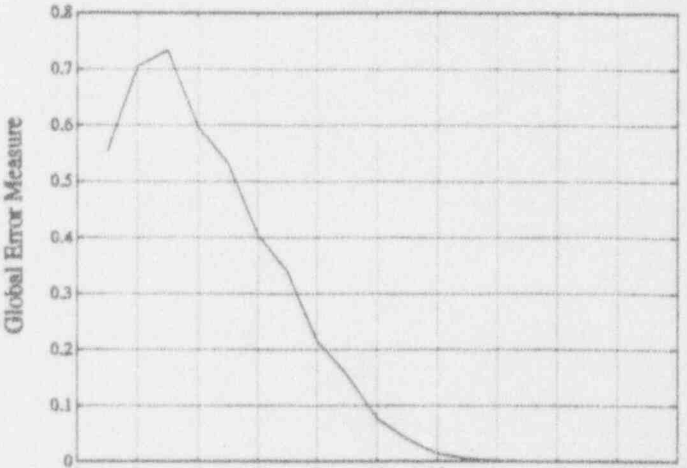


Figure 2-3. Interpretation of the SOG/EPRI aggregation procedure for obtaining a mean probability of exceedance from results of several teams of experts

in the probability of exceedance value they have chosen for a particular value, e.g. of acceleration, at a particular site.

Consistency of the team in their probability density judgements appears to be a joint convergence factor. That is, if the team has a wide spread in probability densities for various sites, its weight will be reduced compared to a team which generates probability densities that are more consistent among sites. Hazard curves for a site may be comprised of a range of accelerations at various probabilities of exeedance; for example, see Figure 2-3b. There may be a standard deviation about the hazard curve which is derived from the aggregated team values, e.g. in Figure 2-3a. The aggregated value in Figure 2-3a is determined from formulae in EPRI (1988) and an equation solve routine in MATLAB. This exercise is discussed in Appendix B of this report. These calculations were made to be sure we understood the EPRI aggregation procedure and to illustrate how the aggregation was accomplished. Because team estimates of confidence in their probabilities of exceedance differ, as do their exceedance values, the aggregated probability density is lower than for each individual team. The aggregated probability density for an individual ground motion value for a particular site, as depicted in Figure 2-3a, provides a measure of the standard deviation about that point as indicated in Figure 2-3b.

This brings up another point about EPRI's proposed weighting analysis. USGS and NRC reviews of EPRI (1988) conclude that weighting of team opinions is not warranted. However, a less conservative mean value (e.g. of acceleration at a site) might result from some probability distributions, when all weights are assigned a value of unity. In the EPRI aggregation process, alternative team weights are adjusted and tested repeatedly, according to the formula in Appendix B, until the maximum value of probability density for the aggregated team opinions is reached. Deviations from this maximum aggregated probability density are called a "global-error measure" by EPRI. It may be more accurate, in PSHA, to use a term such as "convergence measure." Figure 2-3c depicts the global-error or convergence measure versus the number of iterations in which various weights are assigned to the teams. The global error measure will rise until a combination of weights is found which cause the error to decrease. Individual weights in this order of weights is then adjusted until no change in the individual rates will cause a further decrease in the error measure. This is an iterative process. Some experimentation with the code in Appendix B would be needed to decide whether this effect is of concern for reasonable probability distributions applicable to typical PSHA problems. Figure 2-4 identifies subroutines and the order of data flow. Preprocessing routines test earthquake catalogues for aftershocks and delete them from the determination of recurrence. A flow diagram of EQHAZARD, from the SOG/EPRI report, is in Figure 2-4.

2.1.4 NRC-Funded Evaluation of SOG/EPRI and LLNL Methodologies

NRC contracted LLNL to perform a study to determine why the results of their study differed from the results of the SOG/EPRI study for eastern U.S. nuclear power plants. LLNL reported their results in NUREG/CR-4885 by Bernreuter et al. (1987). Their conclusion was that the two methodologies are essentially the same and that results differed primarily because SOG/EPRI used:

- A higher minimum magnitude than LLNL (It was made the same in later studies but differences in results were not markedly reduced).

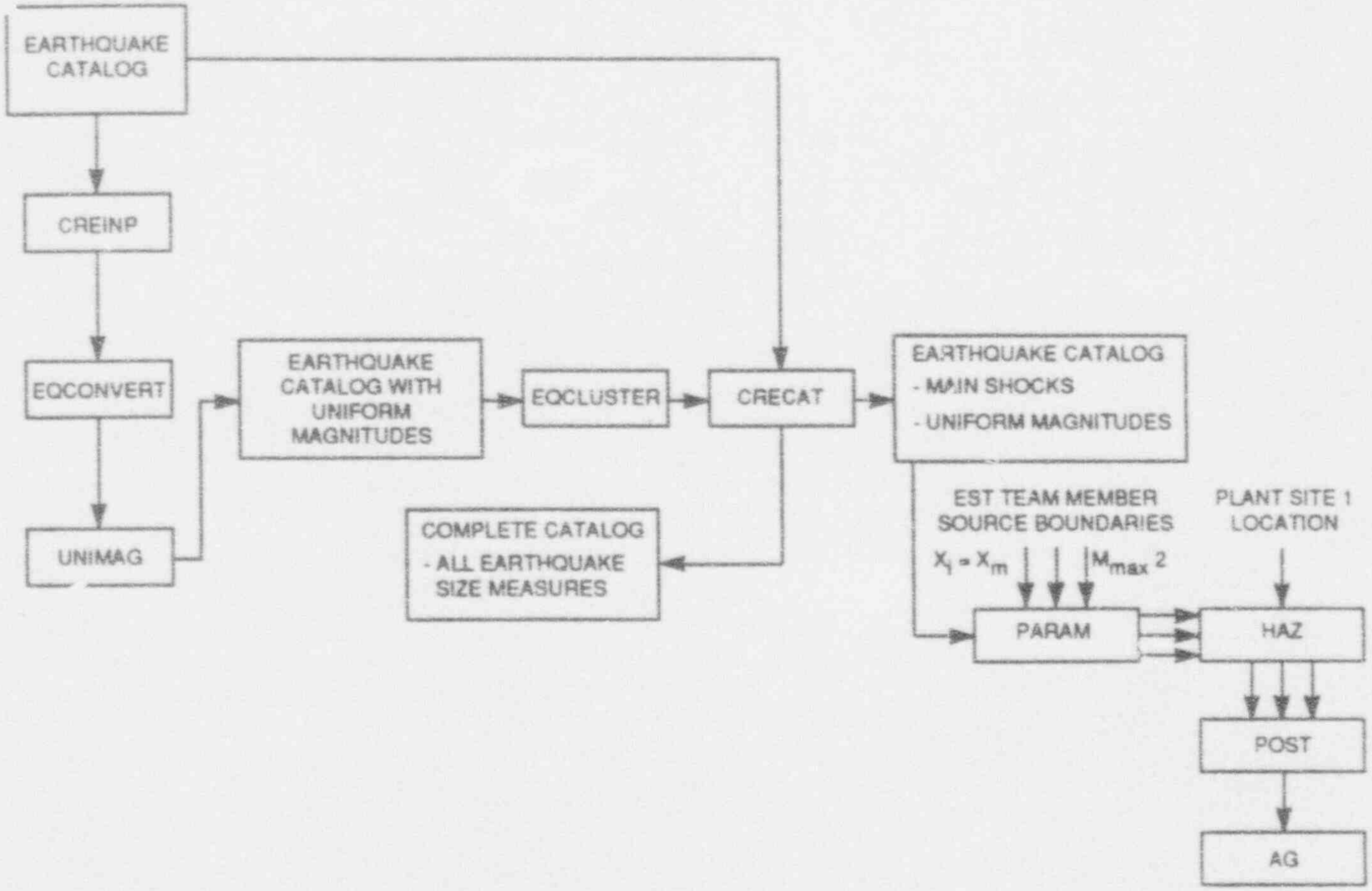


Figure 2-4. Flow diagram of the EQHAZARD computer program

- Fewer attenuation functions used by EPRI, perhaps only one, resulted in 1.5 to 3 times higher accelerations by LLNL than SOG/EPRI. Although EPRI (1988) does not discuss attenuation curves, it states that each team had a ground-motion expert. This suggests that alternative attenuation functions were used. However, it appears that only the Hanks and McGuire (1981) approach was used by all teams (A.B.K. Ibrahim - personal communication August 1992) and that the NRC staff urged the use of alternative attenuation functions. Ruble (1988) stated that SOG/EPRI would use only the conservative Nuttli and Herrmann (1984) function, in response to the USGS/NRC analysis.

- Less uncertainty in earthquake recurrence functions (through instructions to teams).

- Different treatment of the background zone (the area not defined as a seismotectonic zone).

- No site correction factor (influential in a few cases).

Factors that were expected to affect results of the two studies, but did not do so, are:

- Different number of experts on panels or teams,

- Different catalogues of earthquakes, and

- Different methods of eliciting, manipulating, and compiling seismic parameters from the panels or teams of experts. However, the aspect of self-assessment elicitation of likelihood of correctness of expert estimates does appear to have had an effect.

The conclusion of Bernreuter et al. (1987), that with similar input criteria the two methods produce similar results, adds credibility to the general approach and narrows the areas requiring priority research. Whether these results are applicable to a repository, whose performance must be evaluated over a 10,000-year period, remains to be determined. These pioneering explorations of a concept, however, could provide a starting basis for their application to repository evaluation (with the caution previously noted). A new application would be required if it were to be tested for Yucca Mountain in the western U.S. Results from expert opinions may be more convergent for the Yucca Mountain site, when on-site geological data are available. Unlike the eastern U.S. seismicity study, historic seismicity is sufficiently high to provide improved verification of geologic information. The increased time of performance concern, however, could result in sufficiently higher standard deviations of hazard, and variation between mean and median values, to more than offset advantages from added seismic data.

Analysis of this and the preceding section with respect to a mined repository suggests that a much higher dependence on paleo-faulting data will be required for system performance assessment over 10,000 years. More extensive paleo-faulting data would have improved confidence in the results for the central and eastern U.S. studies reviewed, as well. Further, it is likely that an attenuation function for predominantly dip slip earthquakes in the Basin and Range province would provide better results than functions based on combined-source-type California data. Eastern U.S. attenuation functions used in the studies reviewed here are not likely to be optimum for Yucca Mountain. The function of a mined repository is different from a nuclear power plant to which these studies applied. Fault displacement, as opposed to vibratory ground motion, becomes a large component of hazard. Substantial effort will be required to apply these methods to a deep underground repository rather than a power plant because of the extensive differences between the two types of facilities. A mined HLW repository has a 10,000-

year performance evaluation period rather than the nominal 50-year life span of a nuclear power plant. Yucca Mountain is in the western U.S., where surface faulting is observable and seismicity is at a higher level. In the eastern U.S., earthquakes are poorly associated with a particular fault or other geological structure. The principles developed to date appear applicable to a repository hazard analysis. Details of the process and the relative amounts of expert opinion versus data will be different for Yucca Mountain. Because of a generally higher Quaternary activity rate in the Basin and Range province than in the central and eastern U.S., more data are obtainable and less reliance on expert opinion may be required.

Guidance could be provided concerning those elements of opinion elicitation and treatment that contribute to differences between the LLNL and SOG/EPRI analyses. Because the application of PFD&SHA to Yucca Mountain will differ significantly from the eastern U.S., these differences should be considered. Because this is a new application, a warning that revisions are likely should be included in the guidance.

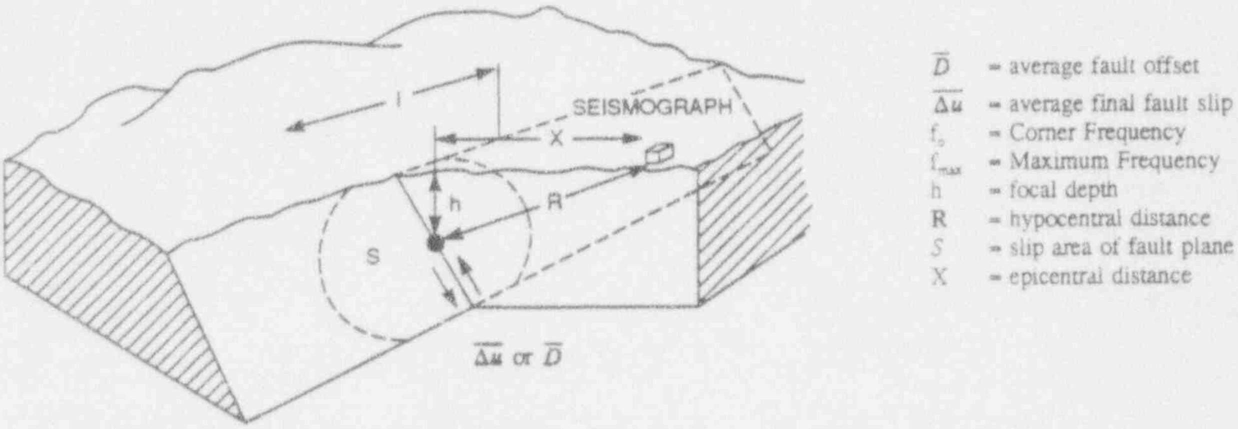
Beavers et al. (1990) describe the application of the LLNL and SOG/EPRI methods to other than reactor DOE facilities; that is, the Paducah, Kentucky, and Portsmouth, Ohio, Gas Diffusion facilities. Results from the two methods were combined with equal weights to each method. This reference is an abstract of work performed primarily by Martin Marietta Energy Systems, Inc., at Oak Ridge, Tennessee. The EPRI method teams used three ground-motion attenuation models. The LLNL method used five experts to define attenuation models. If reports are available from these or similar studies, further insight into the development of these methods may be obtained.

2.1.5 ASCE Methodology

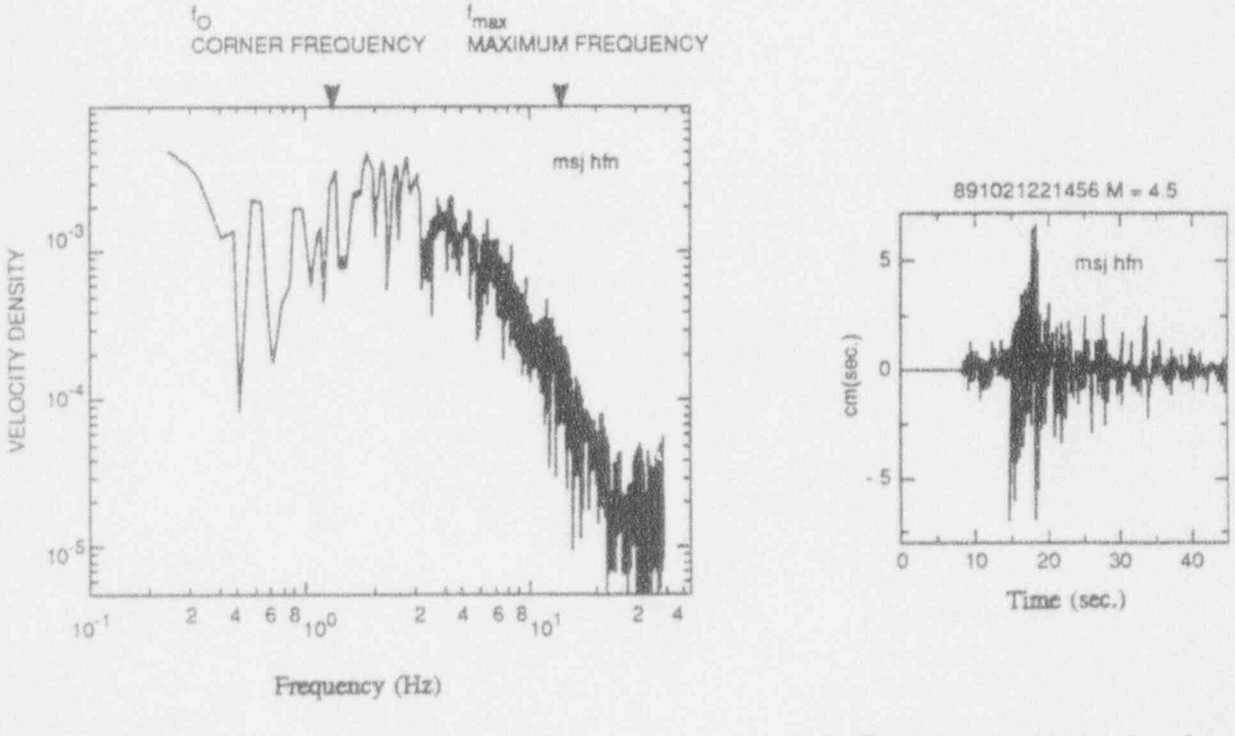
This methodology is being supported by the American Society of Civil Engineers (ASCE) Dynamics Committee under the tentative title of ASCE Design Guideline Definition on Design Loads (currently unpublished). Its principal author is W.J. Silva, supported by EPRI and the Edison Electric Institute (EEI). It is currently a Type I or II methodology with a potential for extension to Types III to V. The draft ASCE document provides a broad and comprehensive review of many methods. ASCE's recommended method is based upon a simplification of seismic source theory rather than on empirical attenuation versus magnitude and distance (see Brune, 1991 for a recent summary of source theory research). Presentations by Swan (1991) and by Silva (1991) also provided insight into this developing methodology. An example study which incorporates this method is in Toro et al. (1992).

2.1.5.1 Background of the ASCE Methodology

The proposed method employs McGuire's (1976) EQRISK program and introduces the use of a procedure built upon Hanks and McGuire (1981). This procedure estimates peak acceleration from earthquake-spectra corner frequencies, spectral amplitudes, and estimates of seismic moment. Figure 2-5 identifies the corner and maximum frequencies of an earthquake spectrum. Seismic moment, M_o, is a measure of earthquake energy that shows less saturation at higher values than do magnitude scales. Usually expressed in terms of 10^x dyne centimeters, seismic moment may be estimated from fault-slip area dimensions and stress drop. Stress drop, $\Delta\sigma$, is assumed to be 100 bars in this method. See Brune (1970) or Boatwright (1984b) for definitions of stress drop. This process is called the "stochastic" or "band-limited-white-noise" (BLWN) procedure. White noise is a term used to represent acoustic vibrations containing all frequencies in the region of interest, just as white light contains all frequencies



a. Sketch of fault and distance to seismograph (after Hofmann, 1974)



c. Earthquake spectrum (from Jarpe et al., 1989)

b. Earthquake time function (from Jarpe et al., 1989)

Figure 2-5. Corner frequency definition

in the visible light spectrum. White noise is recognized by its power spectrum, a straight line parallel to the frequency axis within the bandwidth. (See e.g., Sherriff, 1991).

Although unpublished at this time, the ASCE methodology is expected to be released as an ASCE recommendation. Comments from the DOE and the Edison Electric Institute (EEI) regarding NRC's draft STP on investigations to identify fault displacement and seismic hazards at a geologic repository suggest an imminent release. Consequently this analysis is tentative until a final document is published. This methodology marks a departure from those in nuclear power plant (NPP) licensing and is supported by DOE and EEI. Because its application to mined-repository siting and design seems likely, it is of interest to this review.

ASCE's draft document recommends that the Hanks and McGuire (1981) method always be used. The procedure proposed is also briefly described by Silva and Green (1989). They credit a computer code, RASCAL (prepared for the U.S. Army Corps of Engineers - see Silva and Lee, 1987), in generating strong motion estimates and synthetic time histories. This code may be complementary to or a component of the final ASCE methodology. ASCE's draft document uses as principal references cited: Hanks and McGuire (1981), Boore (1983b) and (1986), Atkinson (1984), Boore and Atkinson (1987), and Toro and McGuire (1987). Much of this work has its beginning in the work of Brune (1970). Brune (1991) reviews several aspects of this type of development that have been published between 1987 and 1990.

Earthquake magnitudes represent a measure of source energy. Source energy is a function of the displacement area, amount of displacement, and the stress drop associated with the fault displacement. Methods used to define magnitudes and consequent ground motions in nuclear facility licensing all use ground-motion amplitude at a known distance. Curves of attenuation compensate for different distances in estimating magnitudes from amplitude measurements or in predicting ground-motion amplitudes from an anticipated magnitude. The method uses a measure of source parameters other than trace amplitude. The larger an earthquake source, the longer is the wavelength of waves it produces. A large fault slip area generates more long period waves than a source area of small physical size. The point where low frequency earthquake spectral amplitudes begin to decrease, therefore, is a measure of source size. This is known as the corner frequency and can be regarded as a chief variable in this method. Depending on assumptions made, the S-wave spectral amplitude rather than the corner frequency and maximum frequency becomes the chief variable. In this method, amplitudes attenuate with distance but this distance dependency is not in the same mathematical form as the attenuation functions of empirical methods.

In the proposed ASCE procedure, the generalized Hanks and McGuire (1981) seismic-moment relationship is used to compute peak acceleration in contrast to the empirical relationships more commonly used. ASCE procedure also permits estimation of velocity power spectra. All computation is performed by formulae except for the generation of time functions to be used in dynamic finite element design. These are computed by summing Green's functions which may be represented by strong motion or sensitive recordings of small earthquakes. Green's functions are described in advanced mathematics texts, e.g. Jeffries and Jeffries (1956). The usual source citation is "*The Mathematical Papers of the Late George Green*, London, 1876 page 245", although the idea may have been first published by Green (1839). The synthesized strong-motion record represents motion from a source whose energy output is similar to that desired. In effect, Silva and EPRI have decided that differing opinions concerning acceleration attenuation have been resolved by the Hanks and McGuire seismic moment method. The method assumes that many parameters regarding earthquake sources are constants, not variables.

The seismic moments used in this method are also directly computable from paleo-faulting information and an assumption regarding stress drop. This permits what has been learned about earthquakes and their recurrence to be applied to probabilistic fault displacement because moments are analogous to magnitudes. This calculation could be employed in PSHA to augment historical seismicity with paleo-earthquake information. It could be used to estimate fault dimensions and slip from earthquake seismograms to provide input to probabilistic fault-displacement analyses.

Hanks and McGuire's (1981) approach is an extension of the Hanks and Kanamori's (1979) moment-magnitude concept to the prediction of strong ground motion. Note that EPRI appears to discount earthquakes at Yucca Mountain as a potential hazard and recommends that only fault displacement be considered, (Coppersmith and Youngs, 1990b).

The ASCE approach has at its core the simulation of strong-motion spectra with white noise filtered to accommodate a corner frequency. The method also estimates peak acceleration from seismic moment and an assumed stress drop of 100 bars. A corner frequency is a single number represented by a point on an earthquake record spectrum where low frequencies taper off. Intervening spectral frequencies, between the corner frequency and a maximum frequency where tapering again begins, are stated to be a straight line in the usual velocity spectral representation. The maximum frequency, f_{max}, is assumed to be a constant.

The straight line corresponds to white noise. For strong motion, this intervening portion of the spectrum seldom looks like a straight line. However, the proponents of this method imply that it may not be important whether it is a straight line or some other shape. They imply that it is sufficiently straighter than the tapering end segments that it adequately represents white-noise.

This approach uses only that part of the seismogram which encompasses the S-wave arrival. All characteristics developed refer to the spectra of this portion of the seismogram, not the entire seismogram. The S-wave window begins at a time represented by the source to station distance divided by the intervening medium's shear velocity. It ends at a time equal to the inverse of the corner frequency, which is believed equivalent to rupture duration with the assumption that the rupture velocity is similar to the shear wave velocity.

Hanks and McGuire (see Figure 2-5) state that the S-wave portion of a strong motion seismogram contains the peak accelerations which their method is designed to reproduce. Essentially the balance of the seismogram is ignored. In this way the variability of the entire strong motion spectrum can also be ignored. Their view is that the S-wave portion can be adequately represented by white noise.

Hanks and McGuire (1981) develop equations for root-mean-square accelerations (a_{rms}) and maximum accelerations (a_{max}) that are a function of:

- the corner frequency, f_0,
- spectral envelope level,
- f_{max} (assumed a constant),
- R, epicentral distance,
- stress drop,
- shear velocity and
- specific attenuation, Q^{-1}.

The theoretical equation substitutes for empirically derived attenuation functions but assumes the earthquake is a point source. It is not likely to be accurate at source-to-site distances that are less than fault rupture dimensions. However, Hanks and McGuire argue that a fault could be divided into many small sections and vibratory ground motion from the rupture of each small section (an equivalent small earthquake) summed. The theory is extended to develop strong motion spectra, e.g., Boatwright (1982), Aki (1982), or Papageorgiou and Aki (1983). Boore and Atkinson (1987), using a different procedure, developed a stochastic method for determining velocity power spectra.

Others, e.g., Earthquake Engineering Research Institute (EERI) (1989), propose developing time functions from spectra produced by the Hanks and McGuire (1981) method. Green's functions are developed from the time function of small earthquakes recorded in the area of interest. Several of these small time functions are added such that their energies total an energy similar to that of the earthquake magnitude desired, as proposed by Kanamori and Stewart (1978).

The combination of the following procedures, as proposed by ASCE, has the potential for providing a statistically based first estimate of strong motion at any site without dependence on site- and source-specific earthquake strong-motion records:

- Hanks and McGuire's (1981) synthetic strong-motion representation
- McGuire's (1976) and (1978) earthquake risk analysis procedures
- Use of Green's functions to generate earthquake time functions (e.g., Kanamori and Stewart, 1978, and Kanamori, 1979)
- Finite-element analyses to account for sedimentary layering, depth of burial, and topography (e.g., Bouchon and Aki, 1980).

This procedure would interface well with PA methodologies to incorporate seismic risk with other risk-generating phenomena.

The Hanks and McGuire (1981) method does not have a significant published record of use at this time. It should not be used without thorough benchmarking against many near-field strong-motion records. An analysis of differences in results generated compared to observed data should be included in the benchmark process.

2.1.5.2 Literature Review of Seismic Source Theory Concerning the Hanks and McGuire (1981) Procedure

Because the Hanks and McGuire (1981) article is central to the recommended ASCE procedure, literature concerning assumptions made by them are reviewed. Some discussions are by this author; others are identified with the references from which they were obtained. The discussions are not to criticize the very elegant developments and investigations of these and many other authors. The discussions center on whether the method has sufficient conservatism to be generally applicable to nuclear waste facilities. Concern with the secondary hazard, posed by possible releases from nuclear facilities, requires that such conservatisms ultimately be identified and, if possible, quantified.

Hanks and McGuire's (1981) procedure is one of several techniques proposed by specialists in this field to model strong ground motion. Aki (1985) lists several of these models and their input parameters.

Model	Parameters
Dynamic Source	Initial and yield stresses, sliding friction, and a constitutive law that varies with position on the fault plane
Dislocation	Slip rate, rupture time, and rise time as a function of position on the fault plane
RMS Acceleration	Dynamic stress drop, f_{max}; seismic moment; corner frequency; and a band-limited signal envelope
Specific Barrier	Fault length and width, maximum slip, barrier interval (or local stress drop), and rupture velocity
Asperity	Fault length and width, rupture velocity, geometry of patches, and dynamic stress over the patch
Empirical Green's Function	Fault length and width, rupture velocity, moment, rise time of sub-event and of modeled event, and distribution of slip

The Hanks and McGuire (1981) procedure, as summarized above, is the RMS acceleration method. In addition to Aki's parameters, Hanks and McGuire (1981) assume that the signal is limited to that of the S-wave, that the spectrum of the S-wave between band limits is random noise, and that all earthquakes have the same stress drop. There are several other assumptions in the method. Other authors have discussed them. Examples of overviews of this subject are in Boore (1983) and Anderson (1991). Summaries of these discussions and comments by this author are organized by topic.

Assumption that Only S-Waves Need Be Considered in Strong-Motion Analysis

- Extending the corner frequency concept for S-waves from teleseismic determinations of moment to strong-motion records may be a problem. As the source (a fault of finite size) is approached, body waves and the Rayleigh wave are components of a single pulse. This is known from the work of Lamb (1904) and is fundamental to our knowledge of seismic effects. Lambs theoretical work defining the response of a point on a halfspace to an impulse elsewhere on the halfspace, has been extended by others to dislocations at depth. An example is Kuhn (1985), who proved that arrivals other than the direct S component of the pulse cause the highest accelerations under certain ranges of source and receiver depths and distances. As pointed out, e.g., by Aki (1984), Kanamori and Anderson (1975) and Brune (1968), crack propagation can be viewed as a moving generator of such pulses. Therefore, the location of an S-wave arrival in a strong-motion seismogram can be tenuous. The S pulse may be broadened because of dislocation propagation and may be inseparable from other phases. Under these circumstances (close to the fault), the S-wave, as defined, may not be the sole contributor to peak acceleration.

- Houston and Kanamori (1990) attempted to determine strong motion from teleseismic records for three large earthquakes. Comparison of the modeled peak strong motions, based on the assumption that each was due only to S-waves, resulted in severe underestimation of the actual strong motion recorded. They believe that the differences are caused by contributions to peak motions from other phases and from site effects. If contributions from other phases are important, the premise of the Hanks and McGuire (1981) procedure is compromised.

- Ou and Herrmann (1990) state that "The simplified approach of estimating peak motion through random process theory cannot explain everything.... However random process theory provides a baseline ground-motion estimate for focusing on these important site effects" (geometrical focusing, frequency-dependent amplification, liquefaction effects, etc.).

- Sommerville et al. (1991) briefly discuss methods for simulating high-frequency ground motion near a fault. Concerning the method of Hanks and McGuire (1981), they point out its high efficiency but note that "...they do not include wave propagation effects rigorously." Consequently, Sommerville et al. chose to employ "...hybrid methods...in which known aspects of the wave propagation are modeled deterministically while unknown aspects are modeled stochastically."

- Di Bona and Rovelli (1988) find that using a narrow window of S data from a long time-function causes miscalculation of stress drop because the definition of stress drop implies integrations from plus to minus infinity in the frequency domain. The S-wave has a limited frequency bandwidth, and the low frequency cutoff is a function of window length. Di Bona and Rovelli state that the effect of a limited time-function window is to underestimate stress drop for lower values of seismic moment (M_o) and overestimate stress drop for larger values of M_o. According to their calculations, the errors can be between one and two orders of magnitude, depending of the formula used to determine the Brune (1970) stress drop. This effect may partly explain the unexpected observation that stress drops computed from S-waves are relatively constant compared to the large ranges of stress drop computed from total seismograms. Stress drops higher than 1000 bars have been observed on hard rock for very small earthquakes, e.g., Chouet et al. (1978) and Trifunac (1972). Sommerville et al. (1980) list stress drops from 0.0 to 4.7 bars for a sequence in the western Basin and Range tectonic province.

Assumption that a Constant Stress Drop Is Appropriate

- A constant stress drop, for all magnitudes, fault types, or regional stress fields, is required for the Hanks and McGuire approach. They state that stress drop is always near 100 bars when it is determined from the root-mean square acceleration of earthquake shear waves, (a_{rms}). They also point out that other means of determining stress drops for earthquakes produce orders of magnitude of variation. In the literature examined, there is no thoroughly convincing explanation for this phenomenon. Until this observation is resolved, some concern will exist about the completeness of the theory and about the fact that it may not adequately encompass all the variables inherent in strong-motion generation. Papageorgiou (1988) makes other estimates of stress drop for large earthquakes. Boatwright (1984a) discusses several measures of stress drop (apparent stress, dynamic, a_{rms}, Brune, and static) and calculates them for eight aftershocks of the 1975 Oroville earthquake. See also section 3.2.2.4 of this report.

- McGarr (1984a), like Brune (1970), presents evidence that peak acceleration near an earthquake source is independent of magnitude but is dependent on stress state. He states that at larger distances, the Hanks and McGuire analysis may be more appropriate. McGarr develops expressions for peak acceleration in extensional and compressional environments, but states that for strike slip faults the problem is indeterminate. However the solution lies between the expressions for the other environments. This result differs from Hanks and McGuire, who do not differentiate between near- and far-field effects or between thrust (compressional) and normal (extensional) faulting. Most strong-motion concerns are in the near field of faulting, because this is the region of strongest shaking. McGarr states that "All other factors being equal, earthquakes in thrust or reverse faulting regimes produce substantially greater acceleration than normal faulting events." McGarr's equation would provide a better estimate of peak ground-motion parameters where the stress state is known. Stress orientation is relatively well known in the Nevada Test Site area, e.g. Zoback (1989), McGarr and Gay (1978), Zoback and Zoback (1980 and 1989), Richardson and Solomon (1979), Patton and Zandt (1991), and Gomberg (1991a and 1991b). McGarr (1984b) also has determined a mean stress state versus depth function. It permits estimating peak acceleration from nearby earthquakes at locations in mines. This function would be of value in estimating peak accelerations for earthquakes near the repository and at depth.

Assumption that S-Wave Spectra Are White Noise

- The process of cutting out only the S-wave portion of a seismogram and determining spectra from it may tend to create the appearance of white noise. The cause is incomplete mitigation of the window function's spectral contribution through Hanning or other time function tapering, e.g., Blackman and Tukey (1958). The problem of additional spectral contributions from the window occurs primarily when time function amplitudes are high at the window boundaries. This often occurs at the time of the S-wave arrival.

Assumption that Nonstationarity May Be Ignored

- The approach does not consider phase or nonstationarity. Others have attempted to modify the Hanks and McGuire stochastic approach through time and frequency filtering to achieve the nonstationarity of spectral content observed in real strong-motion time functions, e.g., Vanmarcke and Rosenblueth (1989). In so doing, however, the relative simplicity of the Hanks and McGuire method is diminished. Coupling this complication into a Cornell/McGuire risk-assessment may be difficult. Other approaches which do not require that white noise be assumed or that only S-waves contribute to peak accelerations may prove to be more efficient. Nonstationarity is important, as was discovered in dynamic analysis of the new Olive View San Fernando hospital which failed during the 1971 earthquake. Details of analyses were published by Ruthenberg et al. (1979 and 1980) and Mahin (1976). The analyses used the Pacoima dam strong-motion record which had produced the highest peak acceleration recorded to that date, 0.64 g. Peak response of the hospital frame was not induced by peak acceleration but by a lower amplitude longer period portion of the strong motion (which was identified as a shear phase). The failure was not caused by peak acceleration, which Hanks and McGuire attribute to the S-wave. Further, the use of their method could not produce a strong-motion record with the nonstationarity observed.

- Many large earthquakes are multiple events. At some distance from the source, there are many S-wave arrivals that are separated in time. The first of these S-wave arrivals would be the only one chosen for analysis. Repetition of these peak acceleration S pulses, which are eliminated from the analysis, drives structures to their peak response and, at times, to their failure. Some aspects of this problem are discussed by Papageorgiou (1988). Whether an asperity model or a barrier model of faulting is the most appropriate, controls whether the assumption of constancy of presumed variables made by Hanks and McGuire is adequate. Evidence is presented for a barrier model (Aki, 1984), which does not support the assumption of constant stress drop or a constant exponent for the spectral frequency, ω. Hanks and McGuire (1981) assume an asperity model.

Assumption That Spectral Attenuation May Be Represented by a Constant, γ

- Singh, et al. (1989a and 1989b) state that observations of 1985 Mexico City strong-motion accelerograms were more energetic than predicted by the ω^{-2} model (or $1/\omega^2$ and sometimes referenced as the ω^2 model) and that, therefore, the model is inadequate. This model is required by Hanks and McGuire. One can argue that the Mexico City earthquake was a special case involving poor soils and a basin. However, the apparently fickle nature of almost every damaging earthquake may also be said to be special. Papageorgiou (1988), states "...observational evidence...support the contention that an ω^2 model with a constant stress drop cannot cover the whole range of seismic spectra." It appears that a risk assessment must include attention to a myriad of details.

- Hartzell and Heaton (1988) point out that self similarity between various magnitude earthquakes fails for very large earthquakes. Spectral decay, for example, is more like $\omega^{-1.5}$ than ω^{-2}. Consequently, the use of smaller earthquakes as Green's functions to derive time functions for shocks of great (M_o) would be inappropriate. Because these results are specifically derived for P, not S, waves the applicability to the Hanks and McGuire method is not certain; and for Yucca Mountain, Nevada, earthquakes of high magnitude are not currently expected to be major contributors to seismic risk. The lack of self similarity of very small earthquakes also has been a topic of interest (e.g., See Scholz, 1991). This implies that magnitude 3 earthquakes and smaller cannot be used as Green's functions to develop synthetic time functions from the output of the Hanks and McGuire method. Therefore, time functions from larger analog earthquakes that have occurred elsewhere may have to be used (because only very small natural earthquakes have occurred at Yucca Mountain). These exceptions create complicating problems which might be better solved with other approaches than that of Hanks and McGuire, e.g., the deterministic approach with a later determination of probability.

- Taking the other point of view, Silva and Green (1989, pg. 591) state that the ω^{-2} model of Hanks and McGuire is appropriately consistent with observations. They base this conclusion primarily on California data.

Assumption That the Moment Magnitudes Do Not Saturate

- Zhang and Lay (1989) point out that, for earthquakes with moment magnitudes larger than about 8, moment cannot be accurately determined without using surface wave information in addition to that in the shear wave window. This suggests that peak acceleration and strong-motion spectra would have contributions from this longer period energy. However, most if not all ordinary engineered structures have natural periods shorter than these frequencies. Large liquid storage tanks, whose sloshing frequencies may be quite low, e.g., 1/8 hertz or less, are a possible exception. Other-than-primary modes of very tall buildings may also be of low frequencies. These frequencies should be accurately determined for strong-motion spectra if an adequate analysis is to be made. Structures which are a part of an HLW underground repository (preclosure or postclosure) are not "ordinary." A complete spectrum may be required to determine their response. The S-wave window may not suffice to fully describe strong motion spectra.

Assumption that f_{max} Is a Constant

- The maximum frequency, f_{max}, bounds the high frequency side of the shear wave spectrum. The flat portion of the spectrum between the corner and maximum frequencies is assumed to represent white noise. This assumption may be the result of several factors [e.g., see Hanks (1982), Aki (1987), Gariel and Campillo (1989), or Papageorgiou (1988)]. f_{max} is required by the moment equation as is the corner frequency. Both are central to the Hanks and McGuire methodology. f_{max} has several potential causes, such as:

  ○ Instrument response,

  ○ Anelastic attenuation,

  ○ Distance over which a fault rupture decelerates (a tectonically conditioned variable),

  ○ Site surface conditions, and so forth.

- Boatwright (1984a) states "...the dynamic stress drops are 56 ±8 percent larger than the rms stress drops. This discrepancy is the result of Hanks and McGuire's (1981) assumption of f_{max}=25 Hz; Hanks [1982, Table 1] estimates f_{max} directly as 17 ±6 Hz. If Hanks and McGuire's (1981) estimates are corrected for this difference, the dynamic stress drops are only 25 percent larger than the a_{rms} stress drops." This suggests a high sensitivity of stress drop to an accurate estimate of f_{max}.

- Aki (1985) summarizes the state of knowledge of f_{max}. It "...represents the frequency point beyond which the acceleration spectrum decays rapidly." He believes that there are two possible contributing effects. The first is a surficial layer with a very low frequency-independent attenuation (Q). The second cause may be a source effect from a finite or plastic zone at the end of the rupturing segment. He concludes "At present, there is no consensus about the origin of f_{max}."

Assumption That Material Response Is Elastic

- The use of Green's functions represented by very low magnitude earthquakes summed to represent the energy of the desired earthquakes tacitly assumes that material behavior is elastic. Large earthquakes are likely to drive material behavior into nonlinear response which would not be predicted by this procedure. This topic is of some controversy, largely in seismological and geotechnical engineering literature not reviewed here. An obvious end member of observed nonlinear response is soil liquefaction.

Comments Regarding Source Complexity

- Boatwright (1984b) is concerned about source size determinations and the consequences of errors in stress drop and variables controlled by stress drop. An ample sampling of the focal sphere (multiple recordings at a range of azimuths) is needed to determine source complexity. A complex source is defined as having more than one asperity. Rupture velocity slows for a complex source compared to a simple source where rupture velocity is close to the shear velocity. Boatwright (1984b) states:

  > The relative uncertainties of the estimates of source size range from 25 to 40 percent for the Oroville aftershocks, where the data quality and sampling of the focal sphere are excellent. For less well-recorded earthquakes, the estimates returned from inversions of the duration measurements become extremely weak.... Ignoring this essential aspect of earthquake faulting in order to simplify estimating the spatial extent of a seismic source can lead to systematic errors in the estimates of source size and static stress drop.

  Oroville earthquake aftershocks were recorded by many well distributed stations. Estimates of uncertainty in moment, stress drop and acceleration from poorly recorded earthquakes may greatly exceed 25- to 40-percent because there is a lack of knowledge concerning earthquake complexity. Larger earthquakes are more complex on the average than small earthquakes. Therefore, this variable could be compensated, in part, by the incorporation of a complexity versus magnitude relationship. This, however, is not a part of the current stochastic methodology but should be inherent in empirical attenuation relationships which use data from large earthquakes.

Comments Regarding Accuracy

- The Hanks and McGuire paper sets limits on their method. They show that their synthetically-derived peak accelerations are within 50 percent of observed values 85 percent of the time. If the real acceleration were 1.0 g, presumably 0.5 g or 1.5 g might be reported by their method. However, if the calculation was one of the remaining 15 percent, 0.2 or 2g could possibly result. Or, perhaps, their method always produces a mean from which the real earthquake may vary by 50 percent. A fundamental question is: Is this level of confidence or uncertainty adequate? From another point of view, can another method do as well or better?

- Hanks and McGuire's representation was developed from spectra of recordings of distant earthquakes, from which seismic moments or moment magnitudes may be determined. Determining an earthquake moment or magnitude (an order-of-magnitude estimate of energy release) permits generalization. To solve for a linear quantity (e.g., acceleration) from an order-of-magnitude estimate, however, requires high accuracy in the order-of-magnitude estimate. Therefore, peak accelerations derived from a generalized magnitude or moment, compared to an empirical correlation, may have a larger variance than desired. The relative mathematical analysis, they conclude: "We also demonstrate that the total moment of the double couples located on a horizontally dipping finite plane just above the interface are indistinguishable from the deformations produced by a similar distribution of double couples located just below the interface but with a total moment that is different by the ratio of the rigidities. This demonstrates that the moment of a dislocation that occurs between two materials is ambiguously defined."

- The process of estimating the best moment for an earthquake involves fitting a mean straight line through oscillating spectral contributions between the corner frequency and the maximum frequency of S-wave spectra. The spectral oscillations may be inherent in data or may be caused by windowing of accelerograms and inadequate digitization. The amplitude level of this straight line is the ultimate source of information used by the Hanks and McGuire method for determining earthquake strong motion. Therefore, peak acceleration and spectra generated by the method are not a result of the conservatisms usually required, i.e. a standard deviation from the mean or median. To use the moment determination process in reverse to determine an acceleration will require that the straight line (horizontal or tilted) nearly bound the variations in the source spectra. This would result in a higher effective moment from which to derive adequately bounded peak accelerations or spectra. This effect can probably be accommodated by multiplying peak acceleration by a constant.

- McGuire, et al., (1984) attempt to verify the Hanks and McGuire method of determining spectral amplitudes in the far field. They plot observed spectral components versus estimated spectral components. Their plot is in velocity, not acceleration. These plots, for 5 percent damped pseudo-velocity spectral components of real earthquakes, e.g., the 1975 Oroville sequence, range over 2 to 3 orders of magnitude. They argue that if predictive methods with more variables are used, those variables must be determined and input to the problem. They also argue that data dispersion, caused by assuming these variables to be constant, can just be propagated through an analysis. Three orders of magnitude, however, seems to be an excessive penalty for use of the proposed simplifications in theory. Further, pseudo-accelerations are usually observed to be even more highly dispersed than are the reported pseudo-velocities.

As with methods used in the past, there are various technical opinions regarding much of the input to this method. When the method is applied in PSHA or PFD, expert opinions could be polled on these different variables, e.g., f_o, f_{max}, stress drop, and the spectral attenuation variable γ. Without a comparable significant history of use, it is difficult to provide guidance in the use of this method. In its present state of development, only a worldwide attenuation function is proposed. In contrast to the work of McGarr (1984a), who provides evidence for large differences in stress drop between types of earthquake faulting, only one constant stress drop is proposed. Although this is a relatively new methodology, licensing of Yucca Mountain is over a decade away. It is likely that this method will evolve to more general acceptance and higher complexity during the intervening years. Considered together, those elements of this method which constitute an attenuation function can be addressed together in an STP. Such guidance would be similar to that concerning empirical attenuation functions.

The applicability of the Hanks and McGuire (1981) method, in its currently proposed implementation, is questionable for a broad range of tectonic and rupture conditions. Whether the Hanks and McGuire approach is a justifiable starting point for strong motion assessment, applied to nuclear facilities, may not yet be determinable. It is not sufficient to provide nuclear design criteria without conducting a parallel deterministic analysis and comparing results. Although some efforts at comparing results of the method to observed spectra or peak accelerations have been made, data variability is often high. A thorough study, comparing results to observations of larger earthquakes at distances shorter than fault dimensions where possible, is needed to verify effectiveness.

Recommendations at this time are that Hanks and McGuire (1981) based risk assessment procedures be considered, but not as the only approach to the problem. If results are not consistent with observations or if no verifying observations exist, additional studies should be required. These may be deterministic if no probabilistic method can produce the required level of detail. Probabilities could be assigned, based on the variability seen elsewhere in other source to site conditions, if no better result is obtainable.

If the method is to be used, guidance should require that the method be benchmarked against an analog earthquake or earthquakes that have instrumental recordings and well observed and documented phenomena. Such earthquakes would have to be similar to those that might be expected to influence the Yucca Mountain site. The magnitude of earthquakes expected to influence the site and their potential distance from the site are not yet fully developed. Analogs for ground motion or fault displacement at Yucca Mountain might be derived from the 1983 Borah Peak, Idaho (e.g., Doser and Smith, 1985), or 1984 Umbria, Italy (Rovelli et al., 1988), earthquakes. These occurred in apparently extensional tectonic environments similar to that at Yucca Mountain. The sources of these earthquakes are dip-slip faults similar to those in the Yucca Mountain area. Because these are recent earthquakes, there may be a larger instrumental database than for earthquakes which have occurred in decades past.

2.1.6 Extension of Deterministic Analyses

Probabilities of deterministically derived peak accelerations (sometimes called worst-case analyses) are prepared for existing nuclear power plants. Examples are in NRC records for some plants. They were prepared by NRC staff and by applicants in response to inquiries by the ACRS. An example is cited by Okrent in a letter attachment to an ACRS memorandum by Bender (1977). Cornell and Newmark (1978) discuss an application of this type of procedure. Specific studies of this type are not reviewed in this report because they are not in the open literature. However, the concept may have advantages in probability assessments for an HLW repository with a 10,000-year period of performance concern. The topic therefore is discussed briefly.

Multiple expert opinions enter into deterministic analyses, as well as into PSHA, but not in a probabilistic manner. The more contentious facilities are likely to employ greater numbers of experts. An example is the Diablo Canyon Nuclear Power Plant Atomic Safety and Licensing Board ASLB hearings. Several NRC technical staff experts analyzed docketed material provided by Pacific Gas and Electric experts and consultants. USGS experts offered conflicting opinions. Intervenor's experts developed independent analyses. Much of the conflict was resolved by NRC's expert consultant, Dr. Nathan Newmark, and the hearing process in which all views were presented and analyzed.

A deterministic analysis has elements that are similar to some elements used in the LLNL and EPRI procedures. Examples are source zones, an attenuation function, and a maximum magnitude. Source to site distances are determined but the process is not as complex. A principle characteristic is that the design acceleration, also called a "g" value, resulting from a deterministic analysis does not have an attached probability. If the NRC Regulatory Guide 1.60 spectrum or a site specific spectrum from several strong-motion seismograms is used with the g value, spectral amplitude exceedances can be established. The process provides a best estimate of acceleration without carrying a probability distribution along for each stage of the calculation. Such distributions often imply a very large acceleration with a small, but finite, probability. Nontruncated probability distributions, propagated throughout design acceleration development, can introduce significantly higher than justifiable values. This becomes a more serious problem if a high level of confidence is desired. This problem does not occur in deterministic analyses followed by a probability assessment. The problem of extreme design accelerations, derived from the extremes of a probability distribution, could become severe for a HLW repository having a performance period of concern of 10,000 years. This problem is less likely, but also possible, for shorter-lived facilities.

A probabilistic extension of a deterministic analysis may be implemented with a recurrence relation. The recurrence is developed for a broad area about the site, for a seismotectonic zone or for a tectonic structure on which the design earthquake was specified. Design accelerations are derived from all the anticipated magnitudes and source to site distances. From these, the probability of the deterministic acceleration may be derived. The deterministic value is usually assigned to a certain magnitude earthquake that is determined to be likely at a certain distance. Based on the recurrence relation and numbers of smaller earthquakes which have been observed, the return period of the design earthquake is determined. Values most commonly derived for existing nuclear power plants are in the 10^{-3} to 10^{-4} per year range. Because systems important to safety are designed to accommodate this level of shaking and no higher levels are anticipated, further probabilistic analyses are not made.

If future strong-motion recordings suggest that a higher upper limit design acceleration is appropriate, the probability of the new value may also be determined and propagated through a failure analysis of systems important to safety. A potential result is that certain components may be found vulnerable. If so, engineering revisions may be required.

A deterministic design acceleration, or spectrum, with an added assessment of probability of occurrence, could be input to performance assessment computational models. The principal difference from PSHA is that a variation in technical opinion or an estimate of its uncertainty is not included.

If no criteria are available to assess technical opinion correctness or likelihood of correctness, there is little recourse to propagating opinion-spread consequences through design acceleration calculations. Implementing this procedure as a PSHA methodology requires that several deterministic design criteria would have to be developed by individual experts. As in the LLNL and EPRI methodologies, a probability distribution could be established for the resulting mean probability of occurrence.

A deterministic procedure with a post-calculation probability estimate does not have the sophistication of PSHA. It has the advantage of not employing self estimates of uncertainty in expert opinions which indeterminately broaden probability distributions. The method is not advanced as an alternative to PSHA or criticized here. It is simply presented as a method, with a record of use, which may be extended to determine statistics of seismic design criteria.

2.1.7 Adequacy Evaluation Recommendations

The following recommendations regarding evaluation of the adequacy of potential strong motion seismic determinations result from the literature assessment:

- Any prediction methodology proposed should be tested against known near-field earthquake strong-motion recordings from faulting and soil or rock conditions similar to those at the facility site.
- To evaluate the adequacy of probabilistic procedures, they should be tested against long-term data from paleo-faulting investigations or against earthquake occurrences in seismically active regions where there are sufficient data to assess the reasonableness of results.
- Expert opinions should be avoided where quantifiable variables can be used.
- Details of any proposed methodology should be checked against literature to assess the opinions, often founded in data, of other investigators. Serious differences should be resolved.
- Particular elements of PSHA that could be addressed in staff technical positions are as follows.
    - ○ Probabilistic hazard analyses which depend upon expert opinion should have statements regarding the employment background of the experts. Criteria should be established regarding the number of experts on panels or teams. The breadth of required backgrounds should be specified, e.g., from universities, consulting firms, and foreign versus local organizations. The disciplines required should also be specified.
    - ○ The rationale for adjustments to attenuation curves (used directly or as embedded in the analysis process) to account for strong motion in the near-field (a distance less than the largest fault dimension) should be required for all PSHA analyses. Near-field ground motion, usually the ground motion of highest concern in the response of structures, is the region from which the fewest records are available. Near-field attenuation curves, with a theoretical and observational basis, should be more highly weighted than those based solely on judgement.
    - ○ All PSHA methodologies should be benchmarked (the entire process - not just certain elements) against several known earthquakes with an adequate database. Applicants should be required to show that the PSHA benchmark analyses are not unduly influenced by *a priori* knowledge.
    - ○ If data are available and reasonably obtainable, expert opinion should not be accepted in lieu of obtaining the data.
    - ○ Expert opinions should not be accepted without an accompanying substantive rationale. Clearly faulty rationales and accompanying opinions should be rejected. It is a responsibility of the technical staff to set guidelines in standard review plans or staff

technical positions. Should this fail to discourage clearly unsupported or unsupportable rationales from being presented, the staff may present their arguments to the ASLB. This recommended requirement may be foregone, in the interest of having a democratic input to the process, for short-lived facilities. However, such a luxury is not likely to be affordable for an HLW repository.

Rationales for these recommendations are in three categories:

- Expert opinions, if not correct, may have an effect on outcome that is unexpected. Therefore, expert opinions should be tested to the extent possible, either singly or jointly as used with data or other opinions. Tests may have to be devised which do not have the same goal as PFD&SHA. The sensitivity to variables which can be defined only with opinion should be determined because slight variations may produce large effects for hazard estimates made over long periods of time, e.g., 10,000 years.

- Expert opinions tend to increase the variation of hazard results in analyses that treat them in the same way that data is treated. If a hazard with higher than a mean probability of occurrence is desired, this increased variation will translate to a higher design value. Therefore, the variation in opinions should be as well justified for PFD&SHA as it would be for a deterministic analysis. Technically unjustified opinions could unnecessarily increase conservatism manyfold.

- Near-field strong-motion effects have not been sufficiently studied to produce a broad consensus among investigators. Seismic modeling, using several approaches as briefly summarized in Section 2.1.5.1, provides a means to obtain an estimate. See also Hofmann (1974). Results of adjustments to extrapolated empirically-derived ground motion attenuation functions should be tested to the extent possible with available data. The near-field of strong motion is where the highest ground motions are expected if site conditions remain the same with distance. Although it is often the most critical part of an analysis it is frequently not addressed.

2.2 FAULT HAZARD ANALYSIS

The process of faulting without concern for the attendant shaking (earthquakes) also poses a hazard to a geologic repository. Faulting may displace permeable layers disrupting or diverting hydrologic flow. This could cause a local rise in the water table or create a higher perched water table. Creation of fault gouge without complete offset of a permeable layer may also occur. Faulting is known, at times, to provide a permeable path for fluids. Areas of mineralization caused by hydrothermal deposition and alteration caused by moving groundwater or hydrothermal solution are frequently found along faults or at the intersection of faults. There is the concern that new or renewed faulting may intersect a canister causing its disruption and early release of radioactive waste. Stress changes caused by fault slip and/or accompanying earthquake vibrations are known to cause temporary local decreases in the depth to the water table, e.g., Wood et al., 1985.

There are two methods of PFD for a deep repository:

- By trenching and/or drilling through faults and dating the time of several offsets using radioisotope ratios or by other means, (for example, see section 3.1.4). The amounts of offset and their times of occurrence can directly provide a recurrence rate with standard deviation for faulting without converting the data to equivalent magnitudes. If a magnitude conversion is made, recurrence coefficients can be compared to historical seismicity to support the directly determined recurrence. If the recurrence does not fall within the range of earthquake recurrences observed globally, the trenching and age dating process may not have been adequate.

- By indirect inference from the historical earthquake record. The amount of offset and size of the offset or rupture area can be estimated from an earthquake magnitude, the moment equation, and knowledge of the earthquake source mechanism.

Literature was searched for examples of these two approaches to PFD. Trenching/drilling and age dating techniques should provide a better estimate of long term faulting statistics. This methodology is not described in the literature to the same level of detail as the indirect method, which relies on PSHA as a first step.

2.2.1 Direct Computation

Cornell and Toro in Hunter and Mann (1990) mention two approaches to site faulting prediction. They refer to them as "magnitude-occurrence" and "faulting-occurrence" models. There is not as much material published on PFD hazard analysis as there is concerning PSHA development. Youngs and Coppersmith (1985), Coppersmith and Youngs (1990a and b), and Wells et al. (1989) mention the subject. Cranwell et al. (1990) in their Appendix D discuss means for estimating the probability of faulting and whether it will intersect a repository site. The problem is not to determine the level of shaking accompanying a fault offset but to determine the probability of a fault offset. This concern is restricted to facilities that are located across faults or which are otherwise affected by fault offsets. An example is a potential deep HLW repository at Yucca Mountain, Nevada.

An alternative to empirical curves or theoretical methods for predicting consequences of fault slip is to find one or more analogs to the expected event. One such consequence is a rise in groundwater level. Unfortunately, water table depths for available analogs are not similar to those at Yucca Mountain. River and spring flow data from other earthquakes, where groundwater depths are similar to Yucca Mountain, might be more appropriate if there is adequate descriptive literature. Events that could be investigated are the 1954 Stillwater earthquake of $M_S = 6.8$ and the 1954 Dixie Valley earthquake of $M_s = 6.9$ (See Ryall and VanWormer, 1980). If groundwater is deep at the site of other earthquakes, there is probably little information available concerning water table fluctuations because very deep water wells are uncommon. However, water level fluctuations of 35 meters, lasting from 6 to 10 months, were observed in carbonate rocks following the Borah Peak event (Wood et al. 1985). The cause of these fluctuations is not well understood. If such fluctuations were repeated enough times in 10,000 years they could affect radioisotope migration. Therefore, some effort should be applied to finding a suitable analog earthquake for this effect.

Fault offset may interrupt hydrologic flow by increasing gouge thickness and creating an impermeable barrier (e.g., see Nybakken, 1991, and Kana et al., 1991). Fault movement may also open fractures or fracture intersections providing a highly permeable pathway for solutions or gases. Changes in hydrologic flow can alter the performance of the repository in retaining radioactive material. Ideally, a PFD analysis should include the probabilities of impermeable gouge formation or the creation of new pathways. For the most part, the literature reviewed combines earthquake and faulting analyses.

The principle interest in statistics concerning fault displacement has been to improve the determination of earthquake recurrence rates with paleo-faulting data. These data include information concerning larger magnitude earthquakes than may have been observed during recorded history. Concern over the direct effects of faulting on a mined repository has increased interest in fault hazard analysis by itself. For example, Cranwell et al. (1982 and 1990) Bingham and Barr (1979), and Hunter (1983) have discussed PFD in the preparation of performance assessment scenarios. A methodology for fault hazard analysis is not well developed. Typically a sequence of events is established in an event tree as a first step, as shown in Figure 2-6 from Hunter (1983). If paleo-faulting and/or earthquake faulting data are available for a site, probabilities could be developed and assigned to each event of the tree. Without data, the use of expert judgement or a uniform distribution of probabilities would be used in such a scheme.

Recent faulting or earthquake event analyses have defined a weak temporal relationship between the time to the next event and the size of the last event on a given fault system e.g., Brown et al. (1991). The larger the last earthquake or fault displacement, the longer it will be to the next large earthquake or fault displacement. If the last large event was very large, the next large event may not be as large. (See also Anagnos and Kiremidjian, 1984, and Shimazaki and Nakata, 1980). Where seismicity or fault displacement recurrence is high, the methods outlined below by Callender (1989) may be used to establish the recurrence:

> Recurrence methods examine the presence and amounts of offset of one or more dated units exposed naturally or artificially by a given fault trace. Most stratigraphic units either postdate or predate a given rupture event. Examples of such units are alluvial fan deposits, sag pond or lacustrine deposits, or river terrace deposits. The ages of the deposits that are and are not faulted by a given rupture bracket its age (Sieh, 1978, and Weldon and Sieh, 1985). Some deposits are inferred to have occurred during the rupture event itself [e.g., colluvial wedges along the buried trace of a fault (Swan, et al., 1980)]. Some faulted stratigraphic units may be correlated with offset landforms like stream channels or terraces or with topographic fault scarps Sieh (1984), Sieh and Jahns (1984), Weldon and Sieh (1985), Swan, et al., (1980).

The preceding articles by Sieh are concerned only with the San Andreas fault system, which is the most active system in the conterminous U.S. In other parts of the U.S., where seismic and fault displacement recurrence are lower, the precision of interoccurence times is also lower. Radioactive age dating methods are complex for any age material and, as rock layers become older, the accuracy of age determination is reduced. The Basin and Range Province is sufficiently active that such trenching and radioisotope age dating methods are applicable but accuracy will not be as high as for the San Andreas fault. As Callender (1989) points out, good age control on deposits is frequently lacking. If each major fault slip interoccurence time cannot be accurately determined, an average over several or many fault slips is sometimes possible. An average slip rate can be determined from the time period and total or average displacement. If the maximum offset can be determined for the time period of interest, an upper limit slip rate for that fault also can be determined.

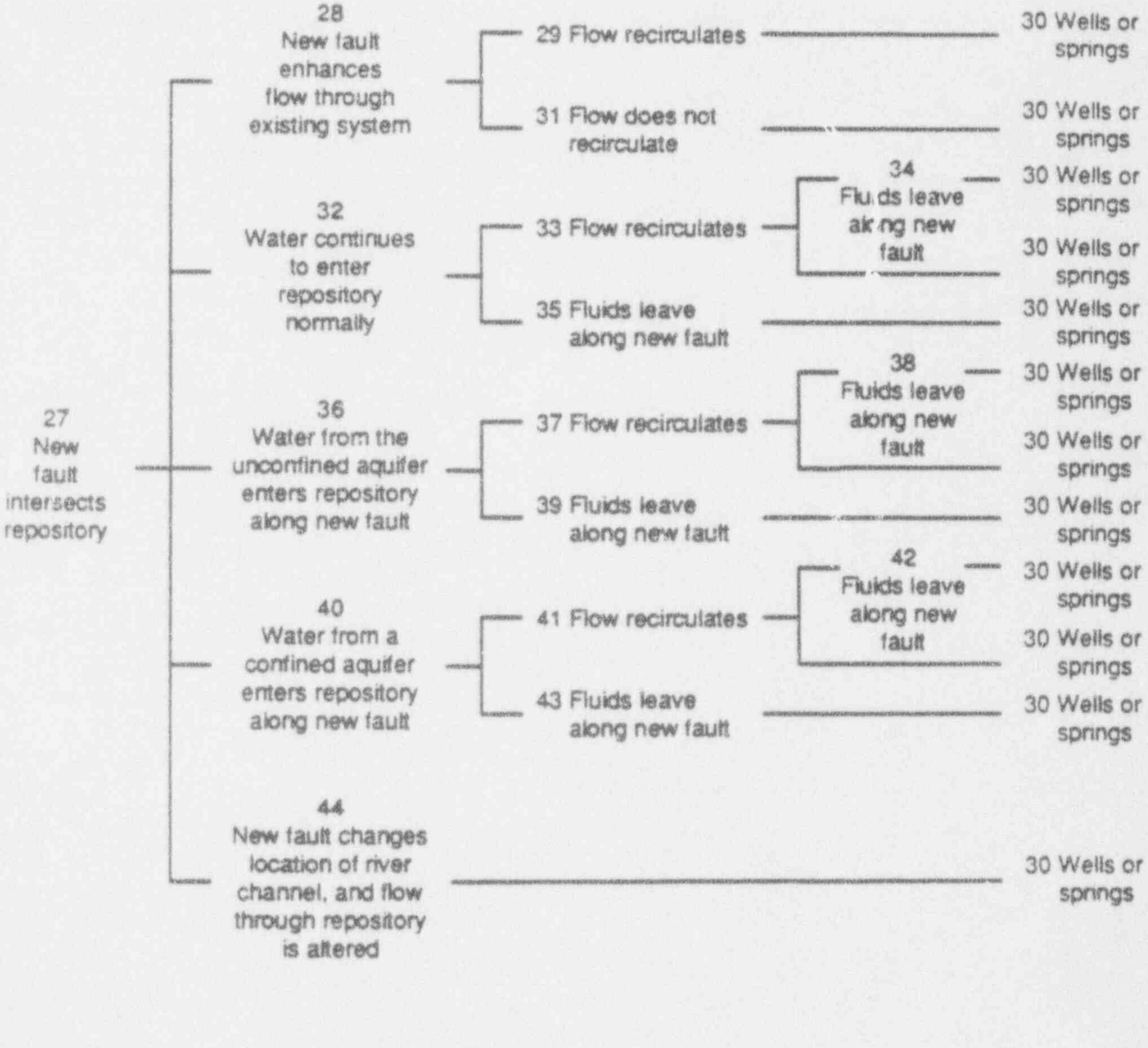


Figure 2-6. Example of an event tree containing several scenarios (from Hunter, 1983)

The number and offset of various slip events can be used to establish a recurrence relationship. If this is not possible because of geology or costs, an exponential relationship may be formulated using a slip rate equation e.g., Youngs and Coppersmith (1985). Such a relationship includes terms for seismic moment and maximum magnitude. The use of these concepts is unavoidable. Moment, however, is related to the slip area on the fault and to stress drop. Therefore, maximum magnitude can be derived from maximum slip. Consequently, the use of formulae derived from a global knowledge of earthquakes does not imply that historic local earthquake patterns are being employed to extend a limited historic data base to 10,000 years. Youngs and Coppersmith (1985) compare an exponential magnitude distribution based on slip rate and one based upon historical seismicity from a study of California Transverse Range seismicity. Although their comparisons show differences, results are more similar than might be expected.

Suzuki and Kiremidjian (1991) explore the possibility that slip rates vary randomly over time. They point out that even when characteristic events can be identified, the interoccurence time is never exactly the same. A statistical treatment of slip rate is a logical advancement to enable inclusion of this known variability in Type IV hazard analyses and ultimately in performance assessment.

The state of development of probabilistic fault displacement methodologies is not as advanced or as well defined as for earthquakes. The faulting process is largely hidden from investigators on the earth's surface. Even where surface rupture occurs in modern earthquakes, the slip area is more likely to be defined by the region of aftershocks occurring over an area on a fault plane. New surface normal dip-slip faulting is often distributed on a wide zone of parallel fracture which makes it difficult to estimate total offset. Fault offset at depth may be on a single plane. There are no master lists of fault slips world-wide or even continent-wide, as there are for earthquakes. Future estimates of fault slip likelihood over a 10,000-year period may be made with a purely fault slip hazard methodology. The methodology would be based entirely on paleo-faulting and might be viewed as more reliable than an extrapolation of seismicity available for a limited span of about the past 100 years. It is the kind of effort that will be undertaken on a case by case basis for localized regions.

VanWormer and Ryall (1980) discuss faulting in the Basin and Range and suggest that a tectonic province-wide investigation may be necessary to gain sufficient understanding. Their thesis regarding paleo-faulting in the Basin and Range, based on published dates of paleo-offsets, is that a large offset occurs on a fault or fault segment followed by a period of quiescence. Although fault creep unaccompanied by earthquakes sometimes occurs, this phenomenon is not considered significant for most analyses. It is presumed that a large earthquake usually accompanies a large fault offset. Another fault then begins a period of activity, builds to a large shock and is again followed by a period of quiescence. These periods of quiescence are on the order of 1000 years. They conclude that more concern with large earthquakes should be placed on Basin and Range faults that have not had a recent large earthquake than those that have had them in historic time. Wallace (1985) and (1987) made similar observations of the distribution of large paleo-faulting displacements throughout the Basin and Range.

The random distribution of large paleo-earthquakes in the Basin and Range suggests that future seismicity or fault rupture probability should be assessed with geodetic estimates of annual basin extension. Ward, (1990), and Smith et al. (1990) discuss geodetic and other measure of extension in the Basin and Range tectonic province. Lyzenga et al. (1986) discuss tectonic motion in parts of California. Richardson and Redding (1991) discuss plate movements over North America. The Basin-wide extension would be distributed over known normal faults for the 10,000 years of repository performance. A random response of faults in the region to the geodetically measured slip could be assumed. Amounts of slip could follow a recurrence relation derived from earthquake data. Earthquake statistics could be derived from studies like those of VanWormer and Ryall (1980). An effort addressing some elements of such a proposed study is being developed by the CNWRA for its "Tectonics" analyses.

Theoretically, a PFD methodology should be no more complex than that for earthquakes. The principal hazard to a mined waste repository is enhancing gaseous or fluid migration by the opening or extension of existing faults. Migration may be diverted by impermeable gouge or increased by faulting through a canister. These aspects of the hazard do not seem well investigated. Data were not found regarding the relative statistics or conditions of generation for potential permeability changes resulting from fault slip. Development of this important data should be encouraged through research and continued monitoring.

Kiremidjian (1984) addresses risk-consistent design of pipelines subject to fault slip. Nuclear waste canisters in boreholes are sufficiently similar to a length of pipe that this analysis could be applied with some modification. Canisters are assumed not to be placed in a borehole intersecting a fault. Therefore a new fault, or the extension of an existing fault, would be required to offset a canister. Kiremidjian found a closed form solution to a probability equation on the assumption that rupture length was much smaller than fault length. When a new fault is first formed, these two lengths are equal and the closed form solution would not apply. A means of estimating potential error, if the closed form solution is used or if a different solution is approximated, would have to be devised. A formula for rupture length as a function of slip is determined from strike slip faults. For Yucca Mountain, a similar formula based on dip slip or oblique faulting would have to be determined. The same applies to the formula which relates displacement to magnitude. Uncertainty in the dip-slip data set would have to be determined as it was for the strike-slip data set. Kiremidjian's structural analysis method requires the medium in which the pipe is buried to lack cohesion. Because Yucca Mountain tuff rock is cohesive, the analysis method would be different. The approach, however, appears applicable to a waste canister intersected by a fault.

A review of PFD literature produced little information concerning how such a procedure is or would be implemented. Because of the long period for which a geologic repository must remain functional, however, an effective PFD has greater potential for contributing to its safety assessment than a PSHA. In some ways, a PFD is simpler than a PSHA. The product of a PFD is the probability of a given fault displacement on a particular existing fault or possibly on a new fault. Ground motion attenuation functions are not normally a concern. Tectonic zone boundaries are usually not of concern. Recurrence of a slip event is a concern. Minimum and maximum displacements are likely to be matters of expert opinion because an observed paleo-offset may have occurred in one event or may have accumulated over hundreds of years or more. Age dates of fault offsets and expert opinions concerning the accuracy and precision of age dating techniques are matters for probabilistic analysis. Uncertainties in opinion can be large and are likely to be site specific. Opinions regarding the distribution of strain over a particular fault or system of faults are potential inputs to a probabilistic analysis. Further, if PFD is to be used to augment PSHA based on earthquake data, all the usual PSHA parameters plus the conversions between fault displacement data and earthquakes become matters for uncertainty analyses. Both the direct use of PFD, or PFD derived from long term seismic activity, should be a part of a mined HLW repository analysis. The direct use of PFD would define fault displacement. This could be used to define the probability of hydrologic barrier creation caused by gouge formation or permeable pathway creation from fault roughness or fault intersections in a given stress field.

A PFD should have the following elements as a minimum:

- An estimate of the accuracy and precision of age dating methods used to determine paleo-displacement episodes. This may be a matter of expert opinions with attendant estimates of uncertainty.

- An estimate of the resolution of the method. An estimate should resolve whether the method can separate fault slip events (which were likely to be accompanied by earthquakes) 10s or 100s of years apart. It should resolve if a single offset could be a cluster of smaller offsets occurring a short time apart. A range of reasonable interpretations should be established.

- A recurrence relationship should be established, based on the above and knowledge of the relationship between earthquake magnitudes and fault offset. Relationships should be demonstrated to be reasonable compared to current seismicity in the tectonic province of concern. Rationales for development of such relationships and their form may be matters of expert opinion and will be likely to be treated as they are in a typical PSHA. A recurrence relation for fault offset can be approximated in this way, assuming that aseismic slip is not common.

- If only major offsets can be identified, an interpretation that permits smaller offsets to occur on subsidiary faults should be developed. Using knowledge of subsidiary fault formation associated with large fault offset, e.g., as presented by Bonilla et al. (1984) or by Slemmons (1977).

- An annual exceedance probability hazard curve for a given offset should be developed for particular faults that may affect repository performance.

Donath and Cranwell (1981) offer a probabilistic approach to the generation of new faults and the probability of recurring displacements on existing faults. Their approach should be applicable to any faulting situation but their examples appear to apply only to faults in a compressional stress regime. The Yucca Mountain site is in an extensional regime where fault movement is primarily normal dip-slip. The approach assumes that the stress regime at depth is well known. Orientation of a fault to the stress regime is important. Probabilities are largely based on differences in fault orientation and uncertainty in stress orientation. Log normal and normal distribution functions are proposed. Random properties are also assigned to the coefficient of friction. Because most of the variables and their probabilities are unknown, this scheme appears amenable only to expert opinions. It provides a mathematical framework that further research may eventually complete. This may provide a rational measure of fault displacement probability.

2.2.2 Computation via Earthquake versus Displacement

Earthquake statistics and some form of hazard curve may be used to generate fault displacement data. Conversely, paleo-faulting data may be redefined in terms of the earthquake or earthquakes that may have been associated with the paleo-displacements. If paleo-displacement data are converted to equivalent earthquakes using the moment equation, PSHA may be invoked and the probabilistic earthquake products converted back into displacements. In such an analysis, the PSHA would not be used to calculate ground motions or these calculations could be ignored. Seismic source zones may not be required unless broad areas containing small faults are assumed to be potential random generators of fault displacement. Many small fault offset events might perturb hydraulic permeability of a broad region. They also may have implications regarding the potential for an individual canister being intersected by a displacement event.

There are many empirical relationships between earthquake surface rupture length versus magnitude, e.g., Bonilla et al. (1984) and Slemmons (1977). These relationships are separated into categories by fault type, e.g., thrust, strike-slip and normal faulting. Mahrer and Nur (1979a,b) sound a note of caution, however, in the use of Paleo-fault offsets to determine moment. Crustal rigidity appears to vary with depth. If it is assumed constant with depth, there could be a two-fold overestimate of seismic moment and consequent error in magnitude. Tse (1986) relates crustal instability to variability of fault friction with depth. Fault plane solution polarity patterns cannot distinguish between thrust and normal dip slip faulting without added geological information. However for the purposes of this review, because effective stresses across dip slip or normal faults are less than those of thrusts, the three categories are considered as separate fault types. Hinge faulting results from rocks being cracked as they are bent over a small radius. This results in tearing from the surface to depth and may be a fourth faulting type.

An alternative method of relating fault length and displacement to earthquake magnitude is to use the seismic moment versus fault slip area and stress drop relationship. Magnitudes can be converted to seismic moment and a stress drop can be assumed or determined for a particular source region to make the calculation. For large earthquakes, the fault plane can be assumed to be as "wide" (usually defined as the down-dip extent of the fault) as the thickness of the crust or thickness of the nonviscous crust. An empirical relationship between the short and long axes of rupture areas as a function of region and magnitude can be developed. The relationship can be used to estimate fault dimensions from fault area for small earthquakes whose fault plane does not extend to the brittle-ductile interface, e.g., Kanamori and Anderson (1975). This approach is subject to the comments on the Hanks and McGuire (1981) method which are summarized in section 2.1.5. Because there are substantial uncertainties in paleo-faulting analyses, attempts to address these concerns may not improve fault offset probability estimates. Empirical relationships also exist for amount of fault slip or displacement as a function of magnitude and fault type. Examples of the relationships mentioned are Bonilla et al. (1984 and 1985), Slemmons (1977), Coppersmith and Youngs (1991) (abstract), Wells et al. (1989) (abstract), and Zhang et al. (1989) (abstract). Figure 2-7 is an example of published curves.

Because the hazards from faulting have different implications than those from earthquake ground motion, the hazard curves should provide the probability of a given displacement being exceeded over a specified time. With research, these might be extended to the probability of:

- Generating a hydrologic barrier versus a given displacement,
- Generating a permeable pathway exceeding a certain flow-value versus a given displacement,
- A canister failing from the creation of a new fault, or
- Stress changes from fault slip causing water tables to rise locally.

In literature reviewed to date, however, such extensions were not performed. When and if such efforts are undertaken, they are likely to be fault-system specific.

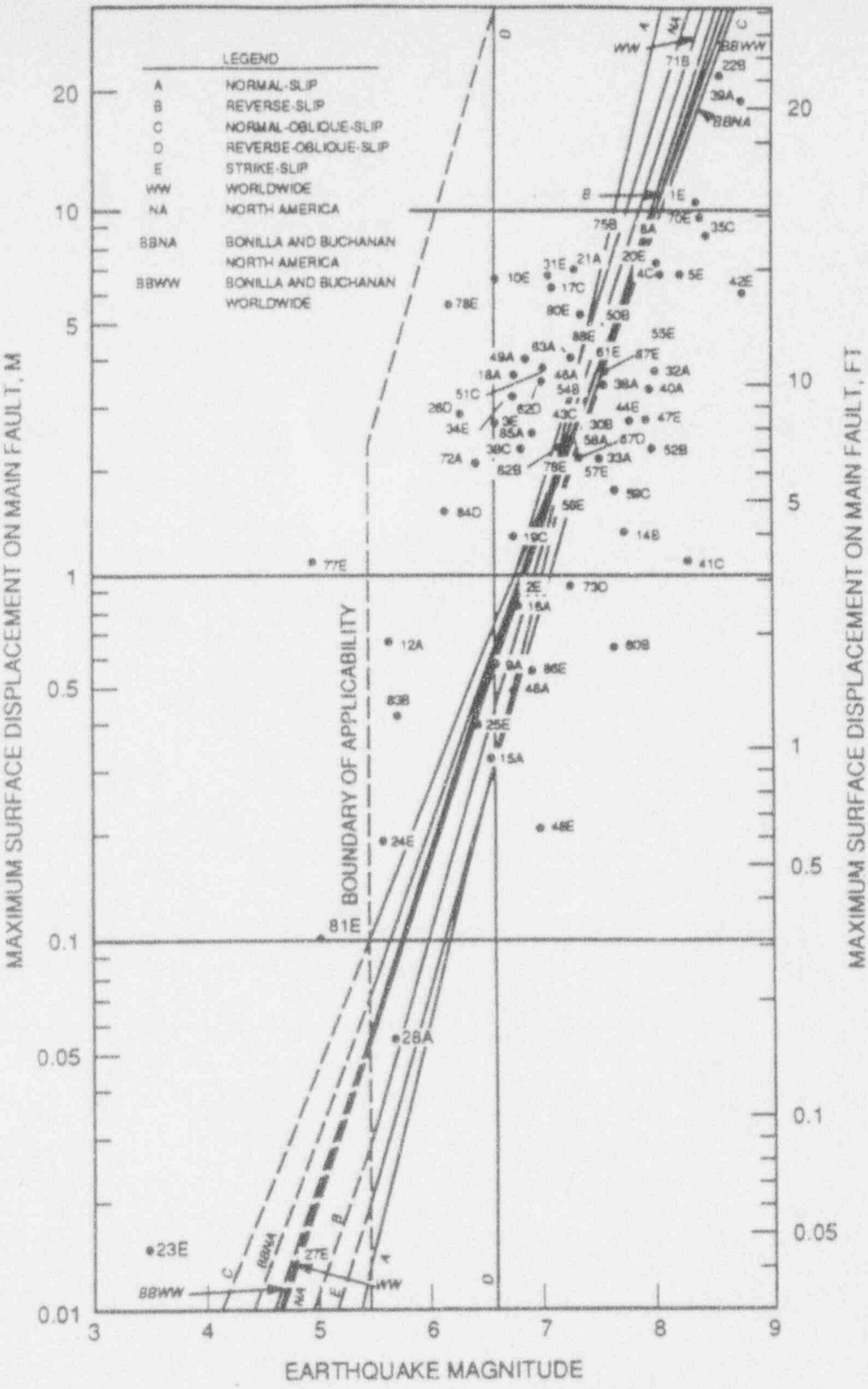


Figure 2-7. Example of maximum fault displacement on a main fault versus earthquake magnitude (from Slemmons, 1977)

2.2.3 Fault Segmentation

The concept of fault segmentation comes from paleo-faulting investigations (e.g., Machette et al., 1991). They indicate that segments of a large fault generate smaller than the maximum possible earthquake for the entire fault. Various criteria are proposed to subdivide a fault into segments without the requirement that paleo-offsets be quantified and dated.

Maximum earthquake magnitudes associated with a segment length are called "characteristic" earthquakes. The amount of slip associated with that earthquake is called the "characteristic" slip. Where age dating of Quaternary displacements on a fault or fault segment clearly demonstrates that only smaller earthquakes have occurred, the concept appears viable. Its extension to other faults without also making a paleo-faulting investigation is questionable.

Based on theories of fault rupture, Aki (1984) and Kanamori and Stewart (1978) agree that eventually all asperities or barriers must be broken. These occurrences, however, may be irregular in time. The history of earthquakes resembles certain categories of chaotic behavior. It has been pointed out that the Gutenberg and Richter recurrence relation is an equation describing a marginal category of chaos (e.g., Hirata, 1989, and Rundle, 1989). Chaos theory may imply long periods of semi-cyclic behavior with sudden catastrophic changes resulting in a period of random or different semi-cyclic behavior, e.g., Shaw (1987). Such patterns are inherent in the recurrence formula and in observations of earthquake behavior. It is unwise to assume that fault segmentation, specified by other than a thorough paleo-faulting study, can accurately predict the maximum slip event on a given fault system.

DePolo et al. (1991) point out that "Fault segmentation has been described at a wide range of scales and with varying criteria. This has led to different definitions of the term 'segment' . . . " These authors define the word as "historical earthquake segments." They conclude, after examining Basin and Range faulting: " . . . in general, only larger features (scales on the order of hundreds of meters to tens of kilometers) appear capable of arresting propagating earthquake ruptures (Sibson, 1989, and Crone and Haller, 1991)." They further conclude that " . . . simple earthquake segmentation models may be inadequate for evaluating larger earthquakes in the Basin and Range province." dePolo et al. (1991) also point out that displacement or rupture may not be confined to individual fault segments, but to multiple geometric or structural segments of a fault system. Faulting may be distributed among parallel faults, where each fault is a segment of a system. This concept is applicable to the Basin and Range.

Crone and Haller (1991), state:

> From our studies in Idaho and Montana, we recognize four characteristics that can help identify important segment boundaries on major, range-front normal faults:
>
> - Prominent gaps or en-echelon offsets in the continuity of fault scarps;
> - Distinct, persistent changes in fault-scarp morphology along strike that likely indicate different ages of faulting;
> - Major salients in the range front; and

- Transverse bedrock ridges that indicate a local decrease in the cumulative throw of the fault.

They further state, in agreement with dePolo et al. (1991), that "Only features whose size is measured in kilometers are likely to be large enough and extend deep enough to physically interfere with a propagating rupture . . . " These two papers are an excellent source of additional references on the topic of fault segmentation. Machette et al. (1991) estimate maximum magnitude on the Wasatch Front using the seismic moment equation and their estimate of displacement surface areas from paleo-faulting. They conclude that M_S of 7.7 is the upper limit for earthquakes on this fault system.

The use of fault segmentation concepts to limit earthquake magnitudes or their equivalent fault displacements to part of a long fault may have utility in probabilistic analyses. However, stating that a "barrier" effectively limits segment length based solely on the premise that it is similar to one observed elsewhere may not be justifiable. In areas where recurrence of large earthquakes is very low, (e.g., 5000 — 10,000 years), the current tectonic regime may not have existed long enough to produce a maximum earthquake. Such a determination would be site specific. Gutenberg and Richter's (1956) recurrence formula predicts a world-wide average of about 8 times as many earthquakes for each succeedingly smaller whole magnitude. Their data sample included only larger earthquakes — greater than magnitude 6. The average inter-occurrence interval has a standard deviation that is approximately 0.5 to 2 times the average interval. Ryall and VanWormer (1980) and Wallace (1985 and 1987) suggest that large events may be clustered with long intervening periods of quiescence. Non-linear equations often demonstrate a similar chaotic behavior when driven at high amplitudes which suggests that earthquake recurrence may be governed by non-linear phenomena and be subject to chaos as well as fractal selfsimilarity. Smalley et al. (1987) present an example of a fractal analysis of an earthquake sequence. A Quaternary record of 1 to 2 million years, however, should be adequate to predict over the next 10,000 years. If 1- to 2-million-year old Quaternary strata are not adequately offset to suggest that large earthquakes have occurred, segmentation theory is acceptable. Often, however, lack of adequate markers in the geologic strata precludes determinations of individual slip events. Under those circumstances a slip rate can be determined over several slip events and displacement distributed in time as would be appropriate for the recurrence of equivalent magnitudes.

2.2.4 Characteristic Slip

A companion concept to fault segmentation is that of a characteristic slip or earthquake. If faults are effectively segmented and these segments support only earthquakes of a size that would rupture the segment, these segments would have a characteristic maximum magnitude earthquake, fault length, and displacement. The concept may be applied to any fault, segmented or not. Schwartz and Coppersmith (1984) summarize characteristics of various alternative models of slip or displacement as shown in Table 2-1.

The San Andreas fault is used as an example for different segments. The central segment has not had large earthquakes in historic times while the northern and southern segments, which contain barriers which must be surmounted by regional strain accumulation, do have large earthquakes. Sieh (1978) is credited with the concept of uniform slip for each of these three segments although the fault, taken as a whole, may appear to fit the variable slip model. Schwartz and Coppersmith (1984) examined slip rates published by Sieh et. al. from 1980 to 1984. They conclude that observed displacements on segments of the San Andreas fault are a better fit to a characteristic earthquake model than to a uniform

Table 2-1. Definition of slip models (after Schwartz and Coppersmith, 1984)

Model	Observations
Variable Slip	Variable displacement at a point
	Constant slip rate along length
	Variable earthquake size
Uniform Slip	Constant displacement per event at a point
	Constant slip rate along length
	Constant size large earthquakes; more frequent moderate earthquakes
Characteristic Slip	Constant displacement per event at a point
	Variable slip rate along length
	Constant size large earthquakes; infrequent moderate earthquakes

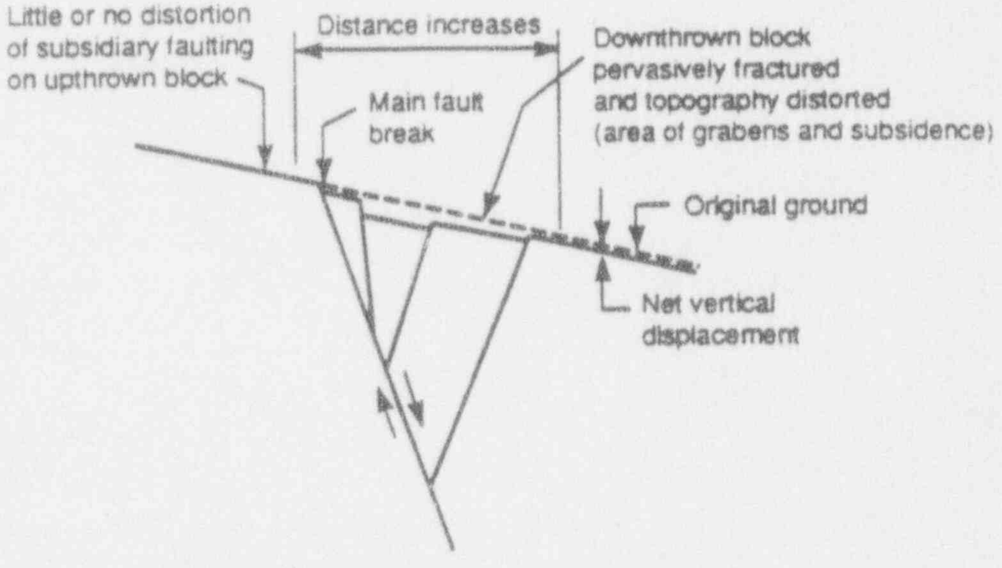


Figure 2-8. Distributed pattern of dip-slip faults with greater displacement at depth than at the surface (from Slemmons, 1977)

slip model. Clearly the segments chosen have differing slip rates over differing periods of time. It is not so obvious that the data discriminate between models. They conclude that recurrence is discontinuous above a certain magnitude. This would, of course, apply to a limited period of observation. For earthquakes, the period of observation is often less than the projected average inter-occurrence interval between large earthquakes. Therefore, this discontinuity may not be justified. However, substantiation by paleo-faulting investigations enhances credibility of the characteristic slip concept. The complexity of Basin and Range faulting makes it difficult to prove that paleo-events are limited in size. According to Slemmons (1977) (Figure 2-8), large fault slips at a depth, below which trenching is impractical, commonly divide into parallel offsets of lesser displacement near the surface. Sibson (1982) shows a correlation of slip and stick-slip segments of the San Andreas fault with heat flow. The central slipping portions are in a region of elevated heat flow. He infers that higher temperatures with depth affect rock strength.

Sykes and Nishenko (1984) propose several possibilities for the manner in which strain may accumulate and be released on a fault (Figure 2-9). These models are further defined by Schwartz and Coppersmith (1984) (Table 2-1).

To summarize, characteristic earthquakes and fault displacements are a matter of scale in both space and time. Over large faults and long periods of time, the variable slip model applies. Over smaller portions of large faults and shorter periods of time, the uniform slip and characteristic earthquake models may apply. In contrast, fractal self similarity is a space concept but is sometimes applied to time functions as well. Geometric patterns at a small scale are similar to those at very large scales. The mathematics of chaos are largely a time concept, e.g., Shaw 1987. Chaotic system behavior is often depicted in three dimensions as an attractor. Figure 2-10 is an example. Similarly a repetition of events may recur in a two-dimensional space for a time, then a "catastrophe" occurs and repetition may continue in another dimensional plane.

A speculative illustration using a plot similar to Figure 2-10 might be the size of earthquakes plotted in space and time for a particular large region. Repetition of a sequence of earthquakes could continue in a place over a long period. The plot would be two dimensional in time and magnitude over several possible cycles of activity. The time axis would be for the maximum length of the cycle. A catastrophe might occur with earthquakes now being spread over a space dimension at nearly the same time. An example might be earthquakes associated with oceanic crust which underthrusts a continent. This is called a down-going slab. Earthquakes occur over many years with some semblance of a time/magnitude relationship that is limited by a characteristic magnitude for a portion of the slab. Then, a major earthquake occurs on a previously quiescent portion of the slab. Aftershocks now appear virtually over the entire slab for a period of a few months, playing in groups over various parts of the slab. This is also a two dimensional plot. This time it is magnitude versus distance where distance is the length of a characteristic segment. As time after the catastrophic earthquake increases only one or more places on the plate remain highly seismic and the plot reverts to the two dimensions of magnitude and of the characteristic time interval between them. Attractors, also called phase diagrams, may be plotted with various axes, not necessarily time and space. A more complete introduction to the concepts of chaos as applied to natural earth phenomena is in Turcotte (1992).

The strictly periodic model requires that strain build at a constant rate over a specified period of time, and then be completely released by a slip event (earthquake). The time-predictable model is similar except that not all the accumulated strain may be released. Stress builds to a certain fixed value before each slip event occurs. Eventually a constant fault strength is assumed but variable slip may

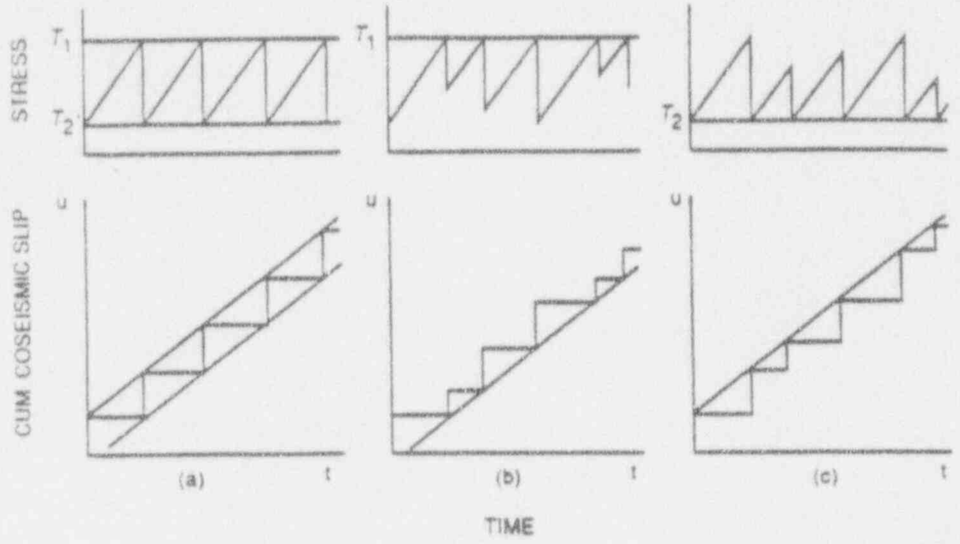


Figure 2-9. Schematic recurrence models: (a) strictly periodic, (b) time-predictable, and (c) slip-predictable (from Sykes and Nishenko, 1984)

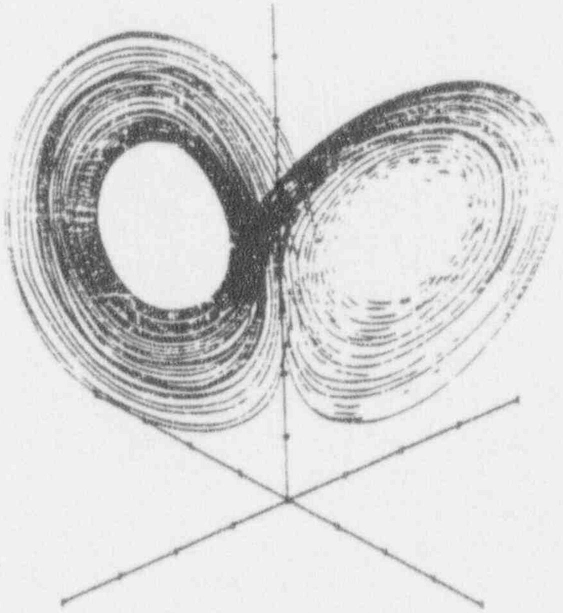


Figure 2-10. Two-dimensional representation of a three-dimensional Lorenz strange attractor (after Crutchfield et al., 1986)

occur. In the slip-predictable model, a slip event may occur at various stress levels (fault strength may vary) but cumulative slip will be bounded by a constant slip versus time function. There will be a constant bounding or base stress level.

The notation "characteristic earthquake" has been in the literature for some time, (e.g., Smith, 1976). Smith used the concept to describe a maximum magnitude associated with a particular fault system. He argued that this magnitude may not be as large as that which would correlate with rupture of the entire surface expression of a fault. Smith advocated the use of geologic slip data to determine the maximum or characteristic magnitude for a particular fault zone. His formula has no term for the time of observation. He stated that his results become increasingly conservative (the maximum earthquake becomes larger) with an increase in the time span covered by the record of seismicity.

A mathematical development, based on Anderson (1979), provides a formula which Schwartz and Coppersmith (1984) argue will allow determination of maximum magnitude on a fault. Truncated recurrence curves which limit maximum magnitude are developed. These curves are stated to fit observed data well. Except for several annual "numbers of earthquakes" in the California Transverse Ranges, observed data is not overlayed on their recurrence curve. Their fit to the limited data presented appears equally good for an exponential magnitude distribution (the Gutenberg and Richter recurrence relation) as for a characteristic magnitude distribution. Evidence is provided that large prehistoric offsets along the Wasatch Front in Utah are all within about a factor of 2.5. This lends credence to their hypothesis that this size earthquake is characteristic of the region and that the concept can be extended in hazard analyses of other faults.

Sykes and Nishenko (1984), who calculate the probability of a major event on each of 19 segments of the San Andreas Fault, state: "Tectonic inhomogeneities on a scale of about 1 to 100 km are much larger than displacement in any single large event and may be regarded as invariant in their effects on earthquake generation over many cycles of large shocks. It is this invariance that appears to lead to a given segment of a fault rupturing repeatedly in events of nearly the same size." Repeat times are estimated from both historic and prehistoric events. They state that two adjacent segments may be nearly in phase in their respective strain loading and may break in a single event (presumably larger than the earthquake characteristic of each individual segment). They also state that the segment from San Juan Bautista to San Jose was calculated to have a high probability of breaking with a magnitude between 6 3/4 and 7 1/4. This segment was one of several that broke simultaneously during the 1906 San Francisco earthquake and probably during the 1838 shock. The northern-most section of this segment ruptured in a non-simple way in the October 1989 $M_s = 7$ Loma Prieta event. This could represent an apparently successful prediction although it was given for a 20 year time span — perhaps the best possible using probabilities. Scholz (1985) also predicted that this general area was a likely one for a substantial earthquake to occur. [See also Working Group on California Earthquake Probabilities (1988)]. The prediction of earthquakes in time may not seem particularly germane to the discussion here but it is the basis for many proposals for other than Poisson probability distributions. That adjacent segments of a long fault can synchronously accumulate and then release strain together, suggests that the fault-segmentation/characteristic-earthquake concept may be of limited utility. Ultimately, the use of the concept must be tied to a time dependent assessment of risk if it is to be meaningful. The length of time that a structure or facility is to remain functional becomes an important element in hazard determination. A prediction must be made for a 10,000-year period from statistical data based upon geologic age dating of paleo-earthquakes. Because geologic age dating is not precise, the fault segmentation and characteristic earthquake concepts may not be very useful in HLW repository siting.

Davidson and Scholz (1985) plot an 18-year record of seismicity recorded with a dense array of instruments and an 85-year data set for large earthquakes on several segments of the Aleutian arc. An example is in section 3.2.4 (Figure 3-2.b). They plot cumulative numbers of earthquakes versus moment. A knee appears in several of their 18-year plots. The "knees" would be expected if characteristic earthquakes limited maximum magnitude. When these data are extrapolated to the horizontal axis (for one cumulative earthquake), a maximum earthquake is predicted. This value is always lower than an extrapolation of the 85-year data set. Only the data set for the entire arc predicts an event as large as the 1964 Alaskan earthquake. Worldwide data predict a maximum moment between 10^{30} and 10^{31} dyne-centimeters, equivalent to the 1960 Chilean earthquake. These data suggest that the size of a cumulative earthquake for a given fault segment can only be predicted from the data for the entire fault. Davidson and Scholz (1985) do not compare their results with maximum earthquakes from the empirical graphs of Slemmons (1977) or Bonilla et al. (1984). The maximum values determined may be less than fault length versus magnitude curves, but they are larger than the values determined from individual segments of a fault.

The likelihood of earthquakes occurring on various fault segments near Borah Peak, Idaho is discussed by Scott et al. (1985). They document slip rates over the Quaternary record from about 0.1 to 1.0 meter per 1000 years. The highest rates appear on faults which bound topography of highest relief. Therefore, they conclude that such faults or fault segments are more likely to rupture than others, although little late Quaternary movement is observed. They use the terms "seismic gap," "surface-faulting gap," and "grouping of events." A seismic gap is defined as a fault segment that has not ruptured in historic times but lies between historic fault scarps. A surface faulting gap is defined as an unruptured segment between segments having evidence of more recent but prehistoric breakage. Grouping of events is a phenomenon whose observation is attributed to Wallace and Whitney (1984) and Wallace (1985). The term groupings is applied to a phenomena similar to Ryall and VanWormer's (1980) observation that, in the Basin and Range, paleo-fault-slip events indicate that a fault becomes active and builds in activity until a large event occurs. That fault then becomes dormant while another, previously dormant fault, becomes active. Scott et al. (1985) propose that slip rates, observed maximum Quaternary offsets, and the period to the last prior displacement episode, may be used to identify fault segments with the highest probability of rupture.

Doser and Smith (1989) determine a greater than 1-meter characteristic slip for $M_s = 7$ earthquakes in the western Cordillera including the Basin and Range and Snake River Plain. They estimate surface ruptures of 12 to 16 km for this characteristic slip. Their conclusions are largely based on a review of historical earthquake source parameters. If a characteristic rupture length can be defined, seismic risk may be calculated. An example is in Loh et al. (1991).

Thenhaus and Barnhard (1989) discuss various kinds of segment barriers and review literature concerning them. They believe that some barriers should be considered seismic gaps. Considering the connotation that seismic gaps in areas of higher deformation, rates imply some of these barriers may be good places for a large earthquake. Because such an earthquake would not be related to either adjacent segment, it would not be characteristic of either one. Following the logic of Sykes and Nishenko (1984), it could include the sum of the adjacent segment slip areas plus slip through the intervening barrier zone.

Several theoretical papers concerning fault mechanics may have relevance to the question of characteristic fault slips or earthquakes. A recent one (Carlson, 1991) builds on the Burridge-Knopoff (1967) sliding spring-block fault model, where behavior appears to have fractal or chaotic characteristics. Carlson attempts to define a characteristic maximum fault slip or magnitude based on the occurrence of smaller earthquakes. A complex methodology which satisfies a one-dimensional quasi-linear wave equation is proposed, but the result is left to the reader, and no quantitative comparison with real data is ultimately attempted. The process is interesting and should be watched for future developments. Other papers which discuss fault dynamics or other characteristics in terms of fractal or chaos are by Brown et al. (1991), McClosky and Bean (1992), Horowitz and Ruina (1989), Beltrami et al. (1991), and Ito (1980).

King et al. (1988) discuss the growth of dip slip structures caused by deformations which accompany repeated characteristic earthquakes. They build a theory involving a thin elastic layer over a deeper viscous layer in Part 1 and apply it to the Basin and Range Province in Part 2, (Stein et al., 1988). In their model, they calculate that seismic slip is greater at a depth of perhaps 1 km or more than it is near the surface. If their theory is correct, seismic moments from paleo-earthquakes in the Basin and Range may be in error. The principal reason is that fault width from near-surface measurement is less than proposed by King et al. (1988). They conclude that theoretical structures resulting from repeated earthquakes of similar size require a thin elastic crust of 2 to 4 km thickness. They point out that this is only about half the depth of the vertical zone in which earthquake hypocenters are determined in the Basin and Range province. (Sibson, 1982, argues that this interface is delineated by the presence or absence of earthquakes of $M_L < 3$. Only the Geysers and Clear Lake, California areas could be interpreted to indicate a transition at less than 5 km.) The underlying viscous layer of King et al. (1988) has viscous properties on a long time scale but not on a short one. Such behavior is well known for shorter time scales, e.g., for tar (when cold), marble window sills and benches, and glass panes. Post seismic rebound in the underlying viscous layer and deformation from eroded and redeposited sediments are involved in their calculations and conclusions. They point out a half-dozen examples of rivers flooding fault-bounded valleys and depositing a significant sediment load after a substantial earthquake. These observations may suggest an increased flow of springs as well as temporary changes of groundwater level. Magnitude-limiting-characteristic earthquakes are adequate, in this theoretical development, to predict the size and shape of geologic structures observed in the Basin and Range. Presumably, without the assumption of characteristic earthquakes, development of the theory would have been less tractable. The requirement of a thin elastic crust, which is not supported by other data, suggests that the characteristic earthquake premise may also not be supported by this development.

Beltrami et al. (1991) conclude that earthquakes have no characteristic size. They state that ". . . earthquakes are unconditionally hard multifractal processes . . . " Aki (1984) states:

> The concept of "earthquake families" or "characteristic earthquakes" defies self-similarity of earthquake phenomena which has been known to hold over a large range of magnitude for the ensemble of earthquakes sampled without regard to specific faults or fault zones . . . For earthquakes from a specific fault or fault zone, however, there may be a departure from self-similarity because of the existence of heterogeneous scale lengths such as the barrier interval.

Aki's barrier hypothesis also requires barriers to eventually be broken. Therefore, the deviation from self-similarity, represented by characteristic slip, is not likely to be extant over very long periods of time. The characteristic earthquake concept is, therefore, consistent with the mathematics of chaos which predicts clustering. It would also predict larger or catastrophic earthquakes to occur, given enough time.

2.2.5 Fault Mechanics

Relevance of fault mechanics to probabilistic methodologies is potentially important to the question of hydrologic barriers, the creation of permeable zones, and disruption of the repository or canisters by fault displacement. From the standpoint of self similarity, that is recognized in all geologic processes, what is learned at a microscopic scale may be an unrecognized subset of regional tectonic phenomena, for example, see Keilis-Borok (1990). From these standpoints, the literature is briefly investigated. Self similarity of scale in geologic phenomena is not a new observation. For example, slump features in road cuts caused by underlying gypsum or salt dissolution have been used to illustrate virtually all known geologic structures which occur at much larger scales. In the past decade, the mathematics of fractals and chaos have formalized self similarity in both space and time. These new mathematical concepts are beginning to provide new tools with which additional information can be derived from observations of self similarity patterns in geological and seismological processes, e.g., Shaw (1987).

Keilis-Borok (1990) discusses self-similarity in faults and the blocks of material that are separated by them. He defines the largest blocks to be major tectonic plates. These are then subdivided into shields and mountain chains. "After 15—20 divisions we come to grains of rock of millimeter scale, if not less. The blocks are separated by less rigid boundary zones, 10—100 times thinner than the corresponding blocks." All boundary zones in the lithosphere are considered to have self-similar properties. His list of boundary zone dimensions is given in Table 2-2.

Keilis-Borok (1990) reintroduces the Rhebinder effect as a mechanism that may have a much wider effect than presently recognized in causing sudden changes in material and fault zone strength. The effect is a consequence of mechanical weakening caused by physical-chemical interactions of a solute with material at a crack tip. It may not be necessary to call upon the Rhebinder effect to argue for chaotic instability of boundary zones, but it is well suited to that purpose. It is a destabilizing mechanism that could lead to catastrophic events.

Keilis-Borok describes the problem of chaotic systems by the following analo

> Chaos arises in deterministic systems because of their specific instability. For example, imagine a billiard game . . . The player sends the ball into the usual array of other balls. The slightest variation in the direction of the original push will send the ball down quite a different path and the difference will not attenuate but will grow with time. Each collision of the balls with each other will further amplify this divergence . . . Newton's laws do determine the trajectory of each ball and the sequence of collisions. But the prediction will be completely wrong after a certain number of collisions even if the initial push is defined with an error as small as the gravitational effect of a single electron on the margins of the galaxy. It is beyond the estimation of necessary precision - it is just a picturesque way of saying that the deviation does not attenuate but grows exponentially in time so that prediction is impossible at any level of precision of the initial conditions . . . With a multitude of such turning points, a dynamic system may display erratic, complicated behavior, which looks and is called, chaotic. Though deterministic, it will be unpredictable, because prediction would require paradoxical precision of the initial conditions . . .

Table 2-2. Boundary zone sizes (after Keilis-Borok, 1990)

Boundary Zone	Size of Blocks, km
Fault Zone	10^{4} — 10^{2}
Fault	10^{1} — 10^{-2}
Crack	10^{-3} — 10^{-5}
Microcrack	10^{-6} — 10^{-7}
Interface	10^{-8} — . . .

> However, this kind of chaos does contain inherent regularities. These regularities can be understood, and some integral traits of chaotic behavior can even be predicted . . . ."

Except for the introduction regarding block sizes, Keilis-Borok does not discuss the fractal self-similarity aspect of chaos, a regularity he mentions. Others discuss fractal self similarity, e.g., Brown (1987), Kumar et al. (1991), Andrews (1980), and Power and Tullis (1991).

Okubo (1989) does not approach the problem of modeling fault rupture with the mathematics of chaos, but his solutions seem to include elements of self similarity. One of his modeling scenarios produces the following interesting observation:

> Rupture models are also calculated for the seismological asperity problem. The problem is defined as the failure of a highly stressed fault patch surrounded by a region of zero stress drop. Dynamic overshoot of slip into the region of zero stress drop roughly agrees with a simple energy balance analysis; the final size of the rupture is proportional to the square of the size of the high stress patch.

If this model is appropriate for a given fault system, one can estimate the size of the fault slip area to accompany the breaking of an identified barrier. Although barriers are defined differently than asperities by Aki (1984), the distinction is not made here. If initiation of barrier breakage requires a characteristic slip on two adjacent segments, the energy released from breaking the barrier is added to the total energy of the event. Seismic moment can be calculated from the anticipated rupture area by formulae in, for example, Kanamori and Anderson (1975), and moment can be related to magnitude through empirical formulae, for example, the figure of Heaton et al. in Campbell (1985) and the figure in Nuttli (1974). An alternative is to use empirical formulae, for example, Bonilla et al. (1984) or Slemmons (1977), for the entire estimate using the total rupture length of the two segments and of the intervening barrier.

Andrews (1980 and 1981), in a two-part paper, utilizes self-similarity and fractals to estimate earthquake recurrence. The 'b' value (slope term) of the recurrence equation is developed from fractal theory to be 2/3. He points out that estimates of 'b' usually range from 1--1.5 for larger earthquakes (Hanks and Kanamori, 1979). The range is smaller, from 0.8 -- 1.2 for magnitudes less than 3, (Bakun and Lindh, 1977 and Grosenbaugh and Lindh, 1978). Pfluke and Steppe (1973) show that smaller 'b' values are obtained on locked portions of the San Andreas fault and larger values on segments where creep occurs. Considering these 'b' values, Andrews reasons that the locked portions of the fault may be following the rules of self similarity. Carlson (1991) develops theoretical 'b' values which are lower than usually observed, 0.5--1.

A basic tenet of Andrews' papers is that fault irregularity is self-similar. It is ". . . statistically invariant under change of length scale . . . ." The implication is that the same statistical description holds for fault surface roughness as it does for an entire fault with larger 'barrier' or 'asperity' irregularities. This is a reiteration of a common theme that earthquakes cluster at various magnitudes depending on the size and distribution of asperities or barriers. Eventually all barriers or asperities on a fault of a given length will break. From this one can conclude that characteristic earthquakes are a real phenomenon but not necessarily an upper limit for a particular fault system, given enough time. Andrews (1981) cites Kagan and Knopoff's (1980) proposal that this self-similarity extends to each individual earthquake which ". . . is an irregular superposition of infinitesimal subevents, and each subevent generates a following subevent with a probability varying as an inverse power of the time interval." He points out that this can be plotted as the familiar "devils staircase" in fractals. Andrews developed a crack model, based in part on self-similarity principals. He finds his results compare well with those of Brune's (1970) relatively simpler approach.

There is little in the Andrews and the Carlson papers which is immediately applicable to regulatory decision making. These may be important papers from the standpoint that they incorporate fractal theory into past developments, particularly the theory of Brune (1970). Those past developments are being proposed as a component of a new standard to define dynamic input to the structural designs for mined repositories (ASCE's draft recommendations, section 2.1.5). There seems little doubt that much in earth science obeys fractal/chaos mathematics. This observation has inspired the imagination of theoreticians in the field. At this point, advantages to be obtained from the theory's use are not broadly obvious. It is obvious, however, that more work of this type is forthcoming and that advances are likely to be made that may be applicable in the licensing process.

Unstable slip induced by slow movement on a fault, with material of differing elastic constants juxtaposed, has been theoretically demonstrated by Weertman (1980). Under these circumstances, Weertman's development indicates that unstable slip can occur with an applied stress that is less than the friction stress. Stress drops may be lower than expected under these circumstances. This suggests lower accelerations but potentially higher frequencies of occurrence. According to this theory, fault instability can occur without regional stress exceeding friction.

Surface roughness of exposed faults was measured in the field at four locations in the Basin and Range and Colorado Plateau provinces by Power et al. (1987). Power spectra of roughness wavelength for each fault were calculated. These are not adequately describable by an rms average. They are fractal in nature. For the San Andreas fault (data from Scholz and Aviles, 1986), the fractal nature of roughness was shown by Power et al. for over 11 orders of magnitude in fault variation: from a few square centimeters of fault plane to kilometers of fault trace. As expected, profile amplitudes parallel to the slip direction were smaller than those perpendicular to it, by at least an order of magnitude. Power spectra of roughness varied by 2 orders of magnitude when comparing those from parallel and perpendicular directions to slip. This property is identified "self-affine" by Power and Tullis (1991). Roughness perpendicular to the direction of slip was found, from direct measurement, to be similar to the roughness observed on rock joints. Power et al. (1987) recommend that surface roughness at the 1-meter wavelength be used to establish predominant slip direction because, at smaller scales, slickensides may be reset by small movements or readjustments that are not in the principal direction of displacement. Power and Tullis (1991) point out that ". . . surface roughness affects frictional strength, the flow of fluids in joints and fractures, the seismic behavior of faults, and the formation of gouge and breccia in fault zones." They do not elaborate. It is worthy of note that these relationships are of concern in a deep geological repository evaluation.

The pore space aspect of crack roughness is addressed by Wong et al. (1989). They correlate crack aperture (openness) with contact pressure for theoretical models of two rock types, a granite and a quartzite. They show that the "Hertzian" model surface roughness (spherical irregularities of varying height), for example, Walsh and Grosenbaugh (1979), is a better representation than the so called "bed-of-nails" model (cylindrical irregularities of varying height), for example, Gangi (1978). As with Power and Tullis (1991), they find surface roughness to have a fractal dimension in the 2.8 range. As expected, pore space varies with pressure and aperture. It is not identical for the two samples. Wang et al. and the papers they cite are a potential starting place for further definition of fault surface roughness and permeability studies.

Brown (1987) discusses two methods for finding the two terms needed to describe self-affine surfaces in fractal mathematics. These models appear to be the beginnings of a methodology to estimate the probability that fault movement may increase permeability in the fault contact zone. These developments are not currently in a state that is useful in assessing HLW repository suitability. It is a topic that may be developed to a useful state before licensing hearings at the Yucca Mountain site are concluded.

Horowitz (1988) and Lomnitz-Adler (1991) discuss slip velocity strengthening and weakening of fault contact zones. Lomnitz-Adler concludes that, for fractally defined surfaces, his model shows ". . . velocity strengthening at low velocities and velocity weakening at high velocities, implying the existence of a stick-slip like instability." Questions regarding strain softening or weakening are discussed by Stuart and Mavko (1979). They believe that mathematical modeling of fault slip can ultimately aid in the prediction of earthquakes. They point out that their model indicates that ". . . average fault stress always decreases before instability . . . ." This may have some meaning in terms of recent stress measurements on the San Andreas fault which suggests surprisingly low stresses (Zoback et al. 1987). McGarr et al. (1982) also points out that there are low limits to the traction at the base of the elastic-brittle layer. The time scales of such stress events which may be related to scale remain undefined. Lomnitz-Adler's model also predicts both dynamic instability (an earthquake) or a rapid quasi-static slip episode (slow earthquakes or intermittent creep). These discussions are relevant to time-related models of the probability of fault slip or earthquakes. The probability of a slip event on a fault segment may be made using such models. The usefulness of time-related models for intervals as long as 10,000 years may be questionable. However, the long periods between major paleo-faulting events reported by Wallace (1987) and Ryall and VanWormer (1980) suggest that such arguments may have potential applicability in PFD estimates for Yucca Mountain. Acceptance of such a rationale would depend on a demonstration that intervals between barrier breakage is very much longer than Yucca Mountain's 10,000-year period of performance concern. Therefore, it is important to be cognizant of time-related recurrence models and their implications.

2.2.6 Adequacy Evaluation Recommendations

Evaluation of the adequacy of PFD analyses or methodologies requires consideration of the following:

- Appropriateness of the probability system employed;
- Length of time over which the result applies;
- Accuracy and precision with which paleo-data can be determined;
- Effects of the fault hazard on facility performance;
- Relevance of personalistic uncertainties to real data and theory; and
- Amount of data (not opinions) used.

Ordinary probability can be used for PFD. This system is used in the EPRI and LLNL PSHA analyses. Truncated probability distributions are desirable where they can be employed by the probability analysis mathematics or their computer code implementation. How the probability functions are truncated becomes another matter for clarification through staff technical positions or standard review plans.

A time-related probability system may be a likely candidate for application to the Basin and Range geologic province because of the long intervals between large earthquakes indicated by paleo-faulting studies. These require careful consideration in the context of the time over which the repository must be functional. After all data become available, a time-related probability may not prove to be appropriate.

Chaos and fractal self similarity as applied to geologic systems is of increasing interest. Its principal utility for PFD&SHA is in time-related probability determinations. However, the concepts do not support the use of characteristic earthquakes and fault segmentation over long periods of time. Taken to its limit, the self-similarity in fault movements proposed by Kagan and Knopoff (1980) might predict that entire continents may, on very rare occasions, move suddenly with great releases of energy. That could be true if planetary collisions with large asteroids occur. Such events are so rare as to be beyond regulatory concern. However, those features which separate faults into segments and limit the segments to characteristic earthquakes may fail with a higher probability than the occurrence of planetary collisions. Arguments may be made that these events, too, are so rare as to be below regulatory concern. Such arguments, if offered, should be judged on their merits. This theory is too new and unrefined, at this point, to project its future potential acceptance.

Amounts and distribution of paleo-faulting data and its potential precision may need to be considered. If data points are so few that only a fault slip rate can be determined, age dating precision could have a high impact on the reliability of probabilistic fault displacement calculations. This may be a potential staff-technical-position topic. A statistically significant sample is necessary for a probabilistic determination. If it is not possible to obtain such a sample, reliance should be placed in deterministic methods and an empirical relationship between maximum magnitude and fault trace length.

The effect of a fault movement or of repeated fault movements on repository performance is an open issue at this time. Can the fault effects associated with a single earthquake cause a serious impairment to hydrologic flow because of increased gouge thickness? Are many offsets that could be attributed to large earthquakes necessary to develop such an impermeable barrier? The same concerns can be expressed about permanent increases in permeability along faults or their intersections. The potential effect of new faulting or recurring fault movement whether or not it is accompanied by earthquakes on a particular repository configuration will influence performance. If it cannot do so, there should be limited concern with regulating the details of PFD calculations. There is no question that changes in stress accompanying an earthquake, and possibly associated shaking, cause temporary changes in groundwater elevation and flow. Over 10,000 years, several such incidents are possible. Their influence on groundwater flow, if any, should be considered, and any potential impact on repository performance estimated.

Use of expert opinions and self appraisals of uncertainty, without a quantitative basis, is not a satisfying way to develop criteria by which HLW repository site suitability is to be determined. It is a useful tool in assessing divergence of opinion and exposing alternate failure mechanisms. By itself, a PFD analysis strongly based on expert opinions becomes less credible as a function of the time that a facility must remain functional. The longer the time of performance the more opportunity there is for effects not currently recognized to develop. A PFD analysis without carefully acquired data should be rejected. This advice may appear superfluous, but perhaps it should be re-emphasized considering the current position of the National Academy of Sciences and review boards favoring the use of subjective probabilistic approaches. These approaches, at this time, have only been implemented with the use of expert opinions. Further, there is a tendency to develop regulations which are not prescriptive, a process that leaves open whether information must be data or may be opinion. Results from a PFD, based only on data (e.g., like the PSHA of Yegian, 1979), should be compared with one based also on opinions. Differences in results should be justified. A PFD based only on data would have seismic source zones and maximum magnitudes, for example, based on paleo-faulting data of Quaternary age or not much older material. The methods or criteria for making such an assessment might not agree with the thinking of all investigators but would provide an anchor for argument. Where expert opinions are used, the rationale for each opinion should be subject to the same scrutiny as the rationale for deterministic analyses used in past licensing decisions.

3 METHODOLOGY VARIABLES AND CODES

A discussion of the various input variables to the probabilistic methods reviewed in Section 2 can provide additional insight into the limitations of the methods. Some inputs have been discussed as a necessary part of the review of the probabilistic methods. Other input variables are further addressed or discussed only in this section. Codes referenced by publications reviewed in the literature search are listed in this section.

3.1 ELEMENTS AND VARIABLES

Some important variables are discussed under other sections of this report. Those not previously addressed are discussed in this section. Computer codes with a significant base of usage in PFD&SHA are listed in Section 3.2. These codes use the variables discussed in the section as input.

3.1.1 Definition of Seismic Source Zones and Alternative Zones

Seismic source zones are areas over which seismic activity is assumed to be of a similar nature. Often the only evidence available to create the boundaries of seismic source zones is the history of earthquakes. Seismicity may also be confined to a tectonic province or a tectonic structure. If a part of a tectonic province or structure is seismically active, the entire structure or province may be a potential seismic source zone. Seismic source zone boundaries must be specified in most PSHA methods, for example, McGuire (1976). Consequently, a review of literature concerning the subject of defining seismic source zones follows.

There are no published rules regarding the definition of seismic source zones. Usually source zone boundaries are based on one or more of the following:

- Geomorphological provinces,
- Areas of similar geological origin,
- Areas undergoing similar tectonic deformation,
- Areas of Quaternary fault displacement,
- Areas of similar historical seismicity.

Seismic source zone boundaries are usually based to a large extent upon historical seismicity. Experts in the LLNL and EPRI studies relied heavily on historic seismicity in estimating the confidence of seismic source zone boundaries, (Bernreuter et al. 1987). If Quaternary fault displacement data is available it may also have a strong influence on confidence. Historical earthquakes and Quaternary fault displacements are the only two *prima facie* examples of evidence that a seismic hazard exists or has recently existed. There is no direct correlation between amplitudes or directions of stress vectors and seismic hazard. There is often a general correlation between regional geology, tectonic styles, and seismicity, particularly in the western U.S.

In a statistical analysis, (e.g., McGuire's, 1976 EQRISK program), reducing the distance from a seismic source zone boundary to a facility in question may raise the probabilistically determined acceleration level. Two alternative seismic source zones, selected by different experts, were analyzed for the coast of British Columbia by Hofmann et al. (1982). The source zones were not greatly different.

For a 475-year period, the site acceleration differed only a few percent. If, however, maximum magnitudes are increased by one unit for one of the zones, site acceleration charged about 17 percent. Other circumstances may produce greater differences when seismic source zone boundaries are changed.

Perkins et al. (1980) and Fitzell (1978) used different source zones for Puget Sound. This resulted in about a 20-percent difference in design acceleration at a site in Vancouver, B.C. Recent publications proposed larger accelerations for Puget Sound, for exmaple, Cohee et al. (1990) because of tectonic interpretations, for example, Heaton and Kanamori (1984), which allow higher maximum magnitudes than the consensus held in 1980.

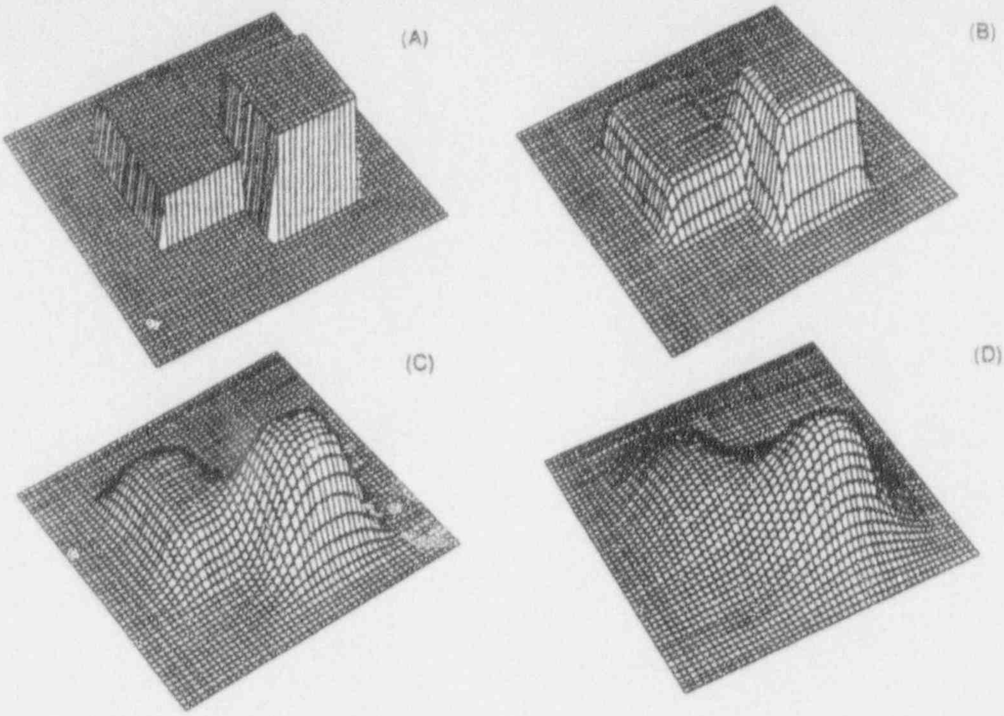
Seismic zone boundaries should be set by Quaternary tectonism and faulting and by historical seismicity. For facilities with a life span similar to that of the historical record, historical seismicity will be the predominant factor. For facilities with a much longer life span, in-depth evaluation of the available Quaternary record and development of a regional tectonic scheme should be elements in determining seismic zone boundaries. However, available seismic data must also be considered in projections of seismic hazard into future periods.

The problem of source zones in the eastern U.S. is particularly vexing. There often is little correlation between earthquakes and known tectonic structures. Six possible seismic zone configurations were examined by Thenhaus et al. (1987) in an attempt to determine the consequences of these varied sources in probabilistic calculations. Acceleration variations of 1.5 to 3 times (at several different sites) resulted from the various characterizations of source zones. Lower ground motion usually resulted from ". . . speculative geologic hypotheses . . . than otherwise implied by accepting historical seismicity as a guide to future hazard." Source zones were derived from geomorphic evidence, geodetic observations, historic seismicity, and various hypothesized geologic correlations.

Although the following observation of Thenhaus et al. (1987) is not particularly germane to the subject at hand, it is based on an analysis which used a collection of widely varying source zones. They believe that although efforts have been concentrated on the Charleston 1886 earthquake, even higher hazard values result for the areas:

- Southeast Maine to Rhode Island,
- Eastern North Carolina along the Cape Fear arch,
- Southeast Georgia.

Bender (1986) suggests that source zone boundaries be determined probabilistically. She allows seismicity to vary continuously over source zone boundaries rather than change abruptly. Bender and Perkins (1982) in their computer program, SEISRISK II, allow zone boundaries and fault zones to be "fuzzy." Figure 3-1 from Bender (1986) illustrates the concept. Rabinowitz and Van Eck (1988) use fuzzy set theory (FST) in an application to earthquake hazard analysis. FST allows more variation in describing fault zone boundaries. The authors point out that earthquake damage analyses have incorporated FST and that it is easier to use computationally than with adjustments to probability. See also Kandel and Byatt (1980), Wang et al. (1986), Shah et al. (1987), Lamarre and Dong (1986) and Frangopol and Hong (1990) for other examples of analyses incorporating FST.



Earthquakes rates at a grid points spaced 10 km apart in the x and y directions. In (A), earthquakes occur only within two well-defined seismically homogeneous source zones. In (B), earthquake locations have a standard deviation $\sigma = 10$ km; in (C), $\sigma = 25$ km; in (D), $\sigma = 50$ km.

Figure 3-1. Method of making seismic zone boundaries fuzzy in SEISRISK II (from Bender 1986)

3.1.2 Earthquake Recurrence Estimates

Rate of earthquake occurrence is set by the 'b' value in the Gutenberg and Richter recurrence formula. It is sometimes specified as β in natural logarithm form, e.g., in EQRISK. The term 'b' usually ranges from 0.8 to 0.9+ but can range regionally from about 0.7 to 1.5. It is questionable whether 'b' values should be allowed to exceed these limits or vary over small areas in which statistically significant samples of earthquakes do not exist. Such a scheme is used in the EPRI methodology discussed in Section 2.1.3. At times, a recurrence is fit to MMI data. Thenhaus et al. (1987) find that the 'b_I' value associated with this kind of recurrence varies between 0.66 and 0.7 for the eastern U.S. Recent topics in the literature are: the form of the recurrence equation, whether it is a straight line or not; whether it is discontinuous or not; and, if it is a straight line in logarithm space, how to determine its slope. Those that argue for characteristic earthquakes or fault slips believe there is a disproportionately high number of characteristic earthquakes compared to smaller earthquakes. They believe that no earthquakes larger than the characteristic earthquake will occur. This results in a leveling-off of numbers of earthquakes at a characteristic magnitude. Numbers of these magnitudes would be larger than indicated by the Gutenberg and Richter relationship, but there would be no earthquakes of larger magnitude. Characteristic earthquake recurrence relationships are usually associated with time-dependant models of recurrence. There is a great deal of interest in time-related statistical models, which may be likened to chaos theory. These suggest that earthquake magnitudes cluster in time until barriers or asperities are broken.

Time-dependent models associated with characteristic earthquakes or fault slip are of interest because they imply a truncation of the recurrence relationship at high magnitudes. Shimazaki and Nakata (1980) propose that there are three basic models of slip on a fault:

- Strictly periodic,
- Time-predictable,
- Slip-predictable.

The periodic model predicts a characteristic earthquake slip which recurs each time a certain tectonic strain level is reached. There are equal intervals between slip events and magnitudes of the same size. The time-predictable model predicts that stress builds to some level and is then released by various amounts of slip. A small amount of slip would relieve only a small amount of stress. Therefore, the time to the next event (of unknown size) could be predicted knowing the average strain rate or stress limit. The slip-predictable model predicts that stress is reduced, or drops, during an earthquake (whatever its size) to a constant level. Therefore, the longer the time without an earthquake, the larger the earthquake would be. They conclude that ". . . the time interval between two succeeding large earthquakes is approximately proportional to the amount of coseismic displacement of the preceding earthquake and not of the following earthquake." Davis et al. (1989) concluded that the longer the time since the last earthquake, the longer the expected time till the next. They propose that the methodology may be useful in predicting the occurrence of earthquakes.

All the above concepts apply to highly seismic areas in California. If applied to the Basin and Range with its lower seismicity rate, intervals between large earthquakes may be longer than the repository performance period. The applicability of these concepts to Yucca Mountain, therefore, appears to rest on whether the probability of a large earthquake is below regulatory concern (e.g. $< 10^{-8}$) and whether this regulatory concept is applicable. Currently, the concept does not appear to be applicable to an HLW repository. Other references relevant to this topic are discussed in Section 2.2.4 (e.g. Figure 2-9) of this report.

Suzuki and Kiremidjian (1991) develop time-related probability methods. Statistical distributions are developed for each earthquake that might return a fault to a prescribed stress level or always yield at some stress level. This development is termed a random slip rate model. They state: "Interarrival times are represented by a Weibull distribution." This distribution is described by Weibull (1949) and for example, Gumbel (1954). Suzuki and Kiremidjian further state, "The parameters of the distribution are usually based on a limited and highly variable data . . . " They attribute the advantage of no model saturation for their development. Saturation is defined as ". . . when probabilities of exceeding a specified magnitude range in some future event in time t given a seismic gap reach 1." They believe that their previously published constant slip model (Kiremidjian and Suzuki, 1987) demonstrated saturation. They conclude that lack of data is a problem but estimates have to be made now. They suggest that a combination of periodic-, slip-, and time-predictable models be examined to make such estimates.

Johnston and Nava (1985) consider the broad requirements of a recurrence model. A cumulative frequency-magnitude distribution and inter-occurrence times for each of several magnitude ranges are needed for their development. Inter-occurrence times are derived from an interval that is longer than the average return period. By definition, then, such models become less reliable for the larger and less frequent earthquakes in the record. Galanopoulos (1988) summarizes this advice, constructs a model with these characteristics, and compares results for two areas in Greece. The interest in this detail of recurrence functions is motivated by a desire to calculate the probability of a forthcoming event in a certain interval. Recurrence models may also be used to define the probable time to the next earthquake of a given size. This problem is not one which would normally be of concern in siting a deep geological repository. However, considering the amount of statistical analysis that is being applied to the recurrence model problem, future advances in this topic are likely to be applicable.

3.1.3 Ground-Motion Attenuation Models (Including Site Specific)

Campbell (1989) recently developed an attenuation model. It is based on accelerograms from small-magnitude earthquakes in California and eastern North America. He found significant differences between accelerograms from sites at the same distance from a given magnitude earthquake. Free-field and deep-soil sites (>10 m) produced similar peak accelerations. Strong-motion instruments in buildings founded on deep soil, however, recorded 30-percent lower accelerations than those in the free field. Accelerograms from shallow soil sites (<10 m) produced 82-percent higher accelerations. Acceleration and velocity attenuation curves for several magnitudes higher than 5 are nearly uniformly spaced on a log plot of peak horizontal acceleration versus epicentral surface distance. The spacing appears to mimic the spacing between empirical curves for magnitudes 3, 4, and 5. The shape of the family of curves of $M>5$ indicates more flattening or lowering of accelerations at close distances than the empirical curve for $M_L = 5$ indicates. This adjustment is apparently made to accommodate effects of finite source size for larger earthquakes.

Joyner and Boore (1981) also developed an empirical attenuation model. It is derived from many strong motion records, mostly from California. A variety of fault source types are represented. These curves should be conservative for use in the Basin and Range Tectonic Province. Joyner and Boore's paper was critiqued by Brillinger and Preisler (1984) who discussed weighting data from various magnitude ranges. Brillinger and Preisler proposed a method that would relieve the reliance on weighting procedures. As always, there is concern with the abundance of data for small shocks and with how to weight the data at large distances for large shocks. There are, of course, no data for large shocks at close distances where strong motions are highest and of greatest concern.

These two recent examples of acceleration attenuation are largely empirical, although attenuation also may be defined theoretically. In summary three approaches to developing ground motion attenuation curves are:

- Source scaling relations where stress drop, corner frequencies, and seismic moment are used to define strong ground motion with distance. This is accomplished with theoretical formulae.

- Spectral scaling where the above methodology is used to compute spectra rather than peak ground motion parameters and its attenuation. Spectral amplitudes vary with both frequency and mean amplitude as a function of distance. It is sometimes applied when the spectral scaling is strictly empirical.

- Attenuation relations which are empirically determined or extrapolated from a given data set. If near-field data are available, these relations infer near-field strong motion behavior.

Several examples may be found in the April 1987 *Bulletin of the Seismological Society of America (BSSA)* entitled: "Source Scaling, Attenuation, and Predictions of Strong Ground Motions for eastern North American Earthquakes."

Donovan (1982) critiques many attenuation functions. A common problem with them is the assumption of equivalency between various magnitude scales and moment-related magnitudes. There is equivalency only over a limited range of magnitudes. The relationship to energy differs for the various magnitude scales. Saturation of magnitude as a function of energy begins to occur and is complete at different magnitudes for different scales, e.g., Chinnery (1978), Hofmann et al. (1982), and Nuttli (1974).

Other problems result from determining large-earthquake acceleration by scaling data from small earthquakes which appear as point sources at close distances. Attempts at correcting this phenomenon were made by Hofmann (1974) who used the directivity function and source geometry to estimate near-field effects. Schnabel and Seed (1973) also refer to apportioning energy release over a large fault in their extrapolation of larger earthquake strong motion to the near-field. Joyner and Boore (1981) have produced a widely used attenuation curve for accelerations. Refinement of their work continues with analysis of recent California earthquakes by the USGS, for example, Borcherdt et al. (1989) and the California Department of Conservation, for example, Shakal et al. (1989).

Another problem with attenuation functions is the common use of the m_b and M_L magnitude scales. Both begin saturating at magnitude 6.5 and are nearly fully saturated at magnitude 7. Some who use these measures of magnitude argue that the range of resonant frequencies of engineered structures is no higher than that generated by a magnitude 6.5. Consequently, there is no need for concern about larger magnitudes. Larger magnitudes, however, have longer durations and impart many more cycles of shaking to a structure that may be in an already overstressed and hysteretically deteriorating stress-strain response situation.

There is a general resistance among the generators of acceleration attenuation functions to the concept that peak accelerations at high frequencies are independent of magnitude. This effect was shown by Brune (1970). There is also resistance to the idea that accelerations at lower frequencies continue to increase with increasing magnitude, as one would have to conclude from the work of Gutenberg and Richter (1956). This resistance has moderated somewhat with strong-motion records from the $M_S = 7$ Loma Prieta event, for example, Shakal et al. (1989) and the special Loma Prieta issue of the BSSA, October, (1991), and many high g recordings in California and elsewhere in recent years. Aki (1985) states that "... the specific barrier model of Papageorgiou and Aki (1983), a hybrid of deterministic and stochastic models, clearly distinguishes the local stress drop responsible for high-frequency generation from the global stress drop corresponding to the average over the fault plane." The letter would affect longer period spectral components. McGarr (1984a) shows that stress drop is a controlling factor in peak acceleration.

Morrison et al. (1966) showed that peak attenuation followed a different attenuation relation than the general level of accelerations during the 1966 Parkfield earthquake. An array of strong-motion instruments perpendicular to the San Andreas fault was triggered. The nearest station was a few feet from the most recent fault trace. That instrument recorded 0.5g on one horizontal component. One of the instrument's horizontal components had failed. Extrapolations from other instruments further away indicated that over 0.8g should have been recorded. A high g pulse, seen propagating across the array, attenuated more quickly than did the general level of acceleration. Ida (1973) also discusses determination of peak acceleration. Weichert et al. (1986) point out that about 2g was recorded within about 5 km of an $M_S = 6.9$ earthquake in Canada's Northwest Territories. Their illustrations suggest that the instrument distance to the fault slip plane may be less than the epicentral distance. An epicenter is defined as the point on the earth's surface vertically above the rupture initiation.

Acceleration attenuation, other than empirical with extrapolations, is offered by the equations of Brune (1970) as implemented by Hanks and McGuire (1981) and others, for example, those listed by Aki (1985). Developments to date have not attempted to include the effects of a non-point source. The method has been employed for the eastern U.S. where useful strong motion records are virtually non existent. This methodology begins with a formulation for determining the moment magnitude of Kanamori (1977), M_W, or of Hanks and Kanamori (1979), M, which is similar. Various relationships between these and the magnitudes M_S, M_L or m_b have been proposed, for example, by Nuttli (1974) and Campbell (1985). Some of them ignore modest but significant differences between magnitude and energy in favor of simplicity. For example, Hanks and Kanamori (1979) point out that M_S, M_L and their proposed moment magnitude, M_W, are approximately related. Plots by Nuttli (1974) and Nuttli and Herrmann (1982), however, indicate that differences between some of these magnitude scales can be substantial. Assuming a one-to-one correspondence between scales introduces consistent errors in relationships between moment magnitude, other magnitudes, and accelerations. Moment related magnitudes are stated by their promoters not to saturate. They do saturate, however, as a function of the frequency bandwidth of the instrument recording them and because of the bandwidth limitations of the S-wave time window used to calculate spectra. Current definitions of S-wave window width may require revisions for very large earthquakes. The largest S-wave amplitudes may result from asperity or barrier breakage, not from gross fault movement. There are enough wideband and very-long-period instruments available that an accurate M_o should be calculable for the largest earthquakes that have been seen worldwide in recent times. It is important to be aware of this saturation when assessing proposed attenuation functions. The question that needs to be asked is whether the higher moment related magnitudes, used to define the attenuation function, were recorded on broadband instruments. If very high magnitudes are not of concern, as may be the situation in the Basin and Range, M_o saturation may not be a concern.

A principal variable in the moment magnitude equation is the corner frequency, f_o. This is determined from the spectra of the S-wave in teleseismic recordings. It is often not entirely clear where the corner frequency is or, as in Jarpe (1989), which of two postulated corner frequencies is the correct one to use. Snoke (1987) recommends alternative formulations for the Brune stress drop which do not require the corner frequency. However, his method would require redefinition of the M_o concept using data from only broadband instruments. The principal variable becomes an integration of the broadband spectra. If, as in Hanks and McGuire (1981), a fixed or prescribed value of stress drop (100 bars) is used, an f_o is not critical. If a constant stress drop is assumed, the corner frequency used in the M_o determination formula may be found. Where corner frequencies cannot be easily discerned, it is often a consequence of multiple shocks or multiple barriers or asperities being broken in a single earthquake. In these circumstances, the moment magnitude shows greater variability than do more familiar magnitude scales, for example, M_S. Snoke (1987) does not see his procedure as a solution for determining stress drop.

Another variable inherent in the moment magnitude, f_{max}, may vary as the bandpass of the seismometer or the frequency band generated by the source or filtered by the path from source to seismometer. It is a subject of considerable interest in the literature, (see Section 2.1.5). Other variables such as stress drop and γ (the coefficient of ω which controls spectral attenuation) are usually considered a constant.

To determine relative energy of earthquakes from teleseismic recordings, Hanks and Kanamori (1979) consider the relationship between the b value for Gutenberg and Richter's recursion formula and the $\omega^{-\gamma}$ and $\Delta\sigma$ of the Brune (1970) relationship. A change in 'b' could be the result of a change in either of the other two variables. Proposals by ASCE in their draft document regarding design bases (see Section 2.1.5), argue for a worldwide constant of $\gamma=2$ and a $\Delta\sigma=50$ bars. EPRI, however (see Section 2.1.3) argues for a continuously variable 'b' over very small areas. This writer believes that 'b' values may change by small amounts over a seismic region but rapid local variations are not likely to be provable or justifiable. Clearly there is a range of stress drops and one can do better than accept a constant 50 or 100 bars. Documentation in the literature (reviewed in Section 2.1.5) provides criteria for using values other than $\gamma=-2$.

Important unresolved items in strong-motion attenuation models are:

- The effect on near-source accelerations of the finite dimensions of the fault source, and

- The large effects on ground motions caused by fault radiation patterns. Variations of 2 to 10+ times in acceleration [e.g. Sommerville and Nelson (1982) and Boatwright and Boore (1982)] have been reported as a function of azimuth from certain fault sources. McCann and Boore (1983), however, report a maximum standard deviation of 1.9 for the 1971 San Fernando earthquake acceleration variation. Bouchon (1978) discusses a theoretical model which may replicate characteristics of these observations. The data are not adequate to distinguish between azimuth and other factors. Joyner (1991) points our that large variations may be effective only for very small ranges of rupture propagation to instrument direction angles.

These factors are not addressed in most published strong-motion attenuation functions. These variables often cannot be predicted because the angle of the source rupture with respect to the site is not known. For an identified fault, however, there may be a limited range of angles. This variation should be considered, particularly in estimating the uncertainty or variability of accelerations expected at a site.

No particular attenuation function is recommended over another at this time. Each is appropriate for the range of magnitudes and distances for which data were used to compile the function. They are likely to be in error for extrapolations beyond the ranges of data used to generate them. Potential variations in acceleration are usually greater than indicated by the values used to generate them. The previously cited studies addressing azimuthal variation support this conclusion.

The large distances over which earthquakes are felt in the eastern and central U.S., compared to the western U.S., suggest that different attenuation functions should apply to these regions. Studies by Atkinson (1984) and Atkinson and Charlwood (1983), however, suggest that damaging-level accelerations, at frequencies above 50 hertz, are similar for both regions. Probably, long-period strong-motion from surface waves has not been sufficiently investigated in either area to conclude whether they differ or are similar. Campbell (1985) provides a summary of site-specific and other attenuation functions. That site-specific attenuation functions can be adequately generated for areas smaller than a broadly defined tectonic province is doubtful. Locations in California where both earthquakes and strong-motion instruments are abundant may be an exception.

Site- or region-specific attenuation functions have been proposed, for example, Campbell (1986) for Utah. Hough and Anderson (1989) point out differences in the attenuation of nuclear test and earthquake waves in western Nevada. Their curves, however, are for low magnitude events. A major element that contributes to hazard at the site is the tectonic style of earthquake faulting. Stress drop is a variable that affects acceleration and stress drop depends on source fault type, McGarr (1984a). Fault types (defined in this report to be normal dip-slip, strike-slip, or thrust) have differing mean stress drops. Whether the effect of the difference is enough to be worthwhile is the subject of some debate. Hanks and McGuire (1981) argue that a constant 100 bars is adequate for all faults worldwide. McGarr (1984a) presents convincing evidence that these differences should be considered in the near-field of strong motion. The Basin and Range is a region of extension. Virtually all fault movement evidence (slickensides) suggests dip-slip, sometimes with a minor strike-slip component. Therefore, development of a site-specific attenuation function, based on normal-fault earthquakes, may be reasonable for this region.

For seismic ground motion in the elastic range, considerable effort has gone into attenuation-function development for the Nevada Test Site (NTS) and for comparable foreign test sites, for example, Hough and Anderson (1989) and Taylor and Denny (1991). The differences in attenuation between the NTS and other foreign test sites apply to nuclear explosive tests which produce higher frequency waves than earthquakes. Some energy released in these tests is in response to the same regional stresses that cause natural earthquakes. Proposed variables which could affect attenuation include the degree of fluid saturation in rocks and the specific layering sequences in the area. Inherent material energy absorption is another possible significant variable. Herrmann and Nuttli (1985) summarize variations of the anelastic attenuation factor, Q, for a frequency of 1 hertz. They determine Q from the tail or 'coda' of earthquake seismograms over the U.S. The lowest coda Q values are found in the Pacific coastal states and the Basin and Range Province. A similar map of η, the frequency dependence factor, shows similar variations. Its highest values are in parts of California and the Basin and Range Province. Herrmann and Nuttli (1985) reference their illustrations to Singh and Herrmann (1983). This information, taken together, suggests that a regional attenuation formula for the Basin and Range may well differ significantly from generalized formulae for either the eastern or western U.S.

Some investigators prefer to attenuate design spectra or power spectra with distance for specific site conditions and source magnitude. These methodologies are summarized by Dunbar and Charlwood (1991). They point out that design spectra differ for different magnitudes and that a significant amount of soil layering versus rock modifies these spectra. Enough strong-motion records are now available that some generalizations can be made. Dunbar and Charlwood particularly address differences between spectra by Blume et al. (1972) and Newmark and Hall (1982). They conclude that the ". . . methods reviewed produce comparable results provided the comparisons are made in a reasonable manner." Spectra are frequently generated from unequally spaced digitizations of strong motion records. Campbell (1987) defends the practice because strong motion peaks are always captured. Schiff and Bogdanoff (1967), for example, point out that unequal digitization introduces uncorrectable errors from spectral foldover caused by an ill-defined Nyquist frequency. Fine enough digitalization to capture strong motion peaks is easily attained with current technology. However, the practice of unequal digitization continues and a sufficiently fine digitization should be specified in requirements for spectra.

3.1.4 Age of Displacement

In paleo-faulting studies, a principal element is age-dating methodology. A variety of methods, from geological inference to radioactive isotopes, are employed. If few fault offsets are observed or if few age dates are possible, estimates of earthquake or fault displacement recurrence may be critically tied to the accuracy of age-dating methods. If there are many age-dates, accuracy may improve as $N^{0.5}$. A requirement for analysis of this effect on probabilistically derived hazard curves should be required. For an HLW repository, interest in uncertainty examples is highest for methods which will resolve dates from a few thousand years through to earliest Quaternary, approximately two million years. Several age-dating methods well outside of this range are listed in Table 3-1 to provide examples of the kind of uncertainties inherent in age-dating methods. The condition and history of the sample are both important for many methods. The listed examples may represent an optimistic assessment of uncertainties. Many methods are not listed, e.g., lead isotope ratios and uranium-lead ratios which tend to be complex and useful only for rocks much older than the Quaternary Period. Uncertainties in age-dating methods are site dependent in some circumstances.

The work of Wells et al. (1990) near the NTS is of particular concern. They believe their age-dating methods indicate an order of magnitude younger age volcanoes than previous determinations. Therefore, the uncertainty between separate age-dating estimates may be much larger than the estimated precision for a particular estimate.

3.1.5 Computer Code Summary

Computer codes mentioned in this literature review and assessment are summarized in Table 3-2.

The only PSHA codes found in this review are SEISM 1, 2, and 3 and EQHAZARD. SEISM 1 is specific to the eastern U.S. It is discussed in section 2.12 of this report. SEISMIC 2 is DOE's proprietary version of the code which they have used to evaluate facilities throughout the U.S. Most of their analyses are not published. Development of SEISM 3 is being funded by NRC/NRR to address NPP siting problems in the western U.S. This version of the code is to have more efficient statistical analyses and the ability to accept thrust and other faults directly as source zones. Its completion date is unknown. EQHAZARD is EPRI's PSHA code and is discussed in section 2.13 of this report. These codes accept expert opinions in addition to data and they aggregate probabilities and uncertainty estimates to produce a seismic hazard curve.

Several SHA codes were mentioned in the literature reviewed. SEISRISK II is a USGS product used to develop seismic source zones for the Uniform Building Code. The Program has evolved from earlier versions which did not consider standard deviations in the data. This code is described in Algermissen et al. (1982). EQRISK is McGuire's (1976) implementation of Cornell's (1968) probabilistic risk procedure. The code uses seismic source zones which are specified by the user. Similar routines are incorporated in the SEISM and EQHAZARD codes. FRISK, (McGuire, 1978) accepts faults as source zones without requiring one or more long narrow source zones with hypocenter depth restrictions as an approximation.

The RASCAL code, Silva and Lee (1987) is used to generate characteristics of strong motion and synthetic time histories (accelerograms). The code is referenced in the literature reviewed but was not separately analyzed. Mentioned also are the SHAKE and LUSH 2 codes of U.C. Berkeley. SHAKE, Schnabel et al. (1972) is a 1D program which simulates the filtering action of flat lying sediments or rock layers on vertically traveling shear waves. The program assumes the input is appropriate for hard rock

Table 3-1. Examples of precision estimates for age dating methods

Method	Representative Age and Precision Estimate	Author
$^{40}Ar/^{39}Ar$	15.50±.02 Ma	Gans (1991)
Thermoluminescence	38.9±5.2 Ka, 4000±400 yrs.	Forman et al. (1991)
^{14}C	2470±80 y.b.p.	Greensmith and Gutmanis (1989)
K/Ar	37 to 570 Ka (different samples)	Wells et al. (1990)
Cinder Cone Slope	20,000 yrs.	Wells et al. (1990)
Cation Ratio of Rock Varnish	14,600±800 yrs.	Wells et al. (1990)
Magnetic Field Direction	~16-29 ka	Wells et al. (1990)
$^{207}Pb/^{206}Pb$(Zircon) (evap.)	744±5 Ma	Kröner et al. (1990)
Rb-Sr	800±43 Ma 642±124 Ma	Kröner et al. (1990)
Re-Os	4.0±.8 Ga	Gunter (1977)
Lu-Hf	3.59±0.22 Ga	Pettingill and Petchett (1981)

Ka = thousands of years ago; Ma = millions of years ago; Ga - billions of years ago; y.b.p. = years before present (1950)

and alters its spectrum in response to the prescribed layering sequence. LUSH 2, Lysmer et al. (1974) is a finite element code which will model plain strain quadrilateral elements for both soils and structures. Unlike SHAKE, it allows differing damping moduli for each element. This 2D program will simulate a 3D analysis. These programs and others permit tailoring of strong motion data recorded on hard rock to sites covered by flat lying continuous sediments. If sediments are not flat lying or if the site is on a topographic high or in a valley, precise results can be obtained only if the 3D geometry is also modeled. This may be possible with LUSH 2 but cannot be accommodated by SHAKE. Other 2D and 3D finite element or finite difference programs may also be employed with a suitable constitutive equation to model the effect of complex geology and material behavior.

SEISM 1 or EQRISK produce a hazard estimate in terms of the variables of the strong motion attenuation function or functions that they employ. If the function is for hard rock, the resulting hazard estimate is for hard rock. If the function is for sites on sediments, the resulting hazard is for a site on an average sedimentary sequence. The acceleration provided by the hazard estimate must be modified

Table 3-2. Computer code summary

Code Name	Purpose	Source of Information
SEISM 1, 2 & 3	PSHA	LLNL or National Software Center, Argonne National Laboratory, IL
EQHAZARD	PSHA	EPRI, Palo Alto, CA
SEISRISK II	SHA	USGS, Denver, CO
EQRISK	SHA	Risk Consultants, Golden, CO
FRISK	SHA	Risk Consultants, Golden, CO
RASCAL	Earthquake Ground Motion	U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS
SHAKE	Soil Response	U. of California, Berkeley, CA
LUSH 2	Soil Response	U. of California, Berkeley, CA

through programs like SHAKE, LUSH 2 or more complex modeling analyses (e.g., Archuleta and Frazier, 1978 and Bard and Bouchon, 1980) if topography or an underground facility is a consideration.

3.2 PROBABILITY CONSIDERATIONS

In this section, the discussion centers on probability related topics. Examples of classes of probability distribution functions and uncertainties regarding several key variables are discussed. A summary of formulae for calculating stress drops follows. Estimates of viability for probabilistic calculations over several ranges of time are discussed. Examples of uncertainties for particular problems reported in the literature are given where possible. The examples may not predict the uncertainties inherent to another problem but are intended to provide an insight into what might be expected.

3.2.1 Probability Distribution Functions

The Poisson distribution is generally adequate if a large data sample is available. Cornell and Winterstein (1988) discuss the applicability of a Poisson distribution for time-dependent predictions. Criteria they identify, for other than a Poisson distribution, are ". . . limited practically to those in which . . . the elapsed time since the last significant event exceeds the average time between such events." An additional condition is that the criteria apply only if events show a strongly "characteristic" behavior. They observe that "Attention is restricted to situations of engineering interest, namely future time windows of about 50 years and magnitudes levels with annual exceedance probabilities of 10^{-3} or less." Additionally, where hazard contributions are from more than one source, the Poisson distribution will provide the best estimate.

The effect of different probability distributions is greatest on the resultant seismic hazard when they are applied to earthquake recurrence relationships. Consequently, some articles reviewed in Section 3.2.2 are also reviewed here, but from a different viewpoint.

Cornell and Winterstein (1988) cite examples of proposed non-Poisson distributions:

- Aki, 1956;
- Vere-Jones, 1970;
- Knopoff, 1971;
- Esteva, 1974;
- Kameda and Ozaki, 1979;
- Patwardhan et al., 1980;
- Anagnos and Kiremidjian, 1984;
- Kiremidjian and Anagnos, 1984;
- Sykes and Nishenko, 1984.

References in this list are either reviewed in this section or they are reviewed elsewhere in this report.

Cornell and Winterstein (1988) separated alternative distributions into several categories: "recurrence," "time predictable," "slip predictable," and "combined predictable" models. Their advantages include permitting the duration between characteristic events, τ, not to be constrained to an exponential distribution as happens for a Poisson process. This permits a dependence between τ and the size of the last event, the next event, or both. Cornell and Winterstein (1988) analyze the consequences and conclude that the alternative distributions really offer little advantage over a Poisson distribution, whose properties are better suited to generalized statistical analysis. Lomnitz (1989) has published comments regarding this paper. He points out that "The Poisson Process is a limiting process for the sum of many point processes - all of which exhibit time and magnitude dependence!" The authors replied to the comments (Cornell and Winterstein, 1989). Their work did not address some ". . . recurrence models in which a recent past event may or may not increase risk . . . which were outside the purview of their study." They also state "Thus in the limit, temporal dependence is not only 'ignored' but 'ignorable.'" Their statement appears to agree with Lomnitz' (1989) view.

Cosentino et al. (1977) develop a doubly truncated probability distribution function which replicates the Gutenberg and Richter recurrence relation when $M_{max} = \infty$. Magnitudes lower than a value of concern in strong-motion seismology, $M=4.4$ in their analysis, are removed from the distribution. Low magnitude earthquakes often follow a different *b* slope in the recurrence formula than do larger magnitudes. Further, such small magnitude earthquakes do not damage structures of reasonable design and condition. Cosentino et al., (1977) state that "considering the dependency of the *b* evaluation on magnitude range (Papazachos, 1974) and the procedure used (Procházková, 1974) that have been observed lately, it seems particularly significant to insert the M_p value in the probability density, so that the *b* estimate becomes less sensitive to the variation in the chosen magnitude range." M_p is Cosentino et al.'s (1977) notation for M_{max}. These observations should probably be reconsidered now that magnitude saturation effects are more broadly recognized than they were at the time this paper was written. Such an analysis is beyond the scope of this review, but this author believes that results could change if moment magnitudes were used for great earthquakes.

Bloom and Erdman (1980) also comment on the dependence of *b* values on the range of magnitudes used to define them. Bloom and Erdman use M_w for larger great earthquakes and found that *b* values were similar for large parts of the world, although they do not attribute this result to the use of M_w. It is likely that some *b* value dependence on magnitude range is caused by magnitude saturation. M_w nearly eliminates the saturation problem. Another part of the dependence may be a function of the change in *b* slope for small earthquakes. The Cosentino et al. (1977) recommendation, combined with their double truncation, would also reduce the dependency problem.

Patwardhan et al. (1980) develop a semi-Markov model for the "waiting times" (inter-occurrence) of large earthquakes. The model relies on data concerning ". . . the magnitude of the most recent large earthquake and the time elapsed since then." This development is a time dependent probability distribution. The distribution was proposed because of the observation ". . . of nonrandomness in location, size, and time of occurrence . . . " of great earthquakes. They cite Schlien and Toksöz (1970) and Esteva (1976) as earlier proposals of clustering of earthquakes in time. Time dependent distributions may provide a multistep memory, dependence on the size of the last and next earthquake, and their inter-occurrence time. The model was tested for large areas, e.g., the Aleutian arc, the west coast of South America, and the Japan-to-Kamchatka Arc. A conjugate prior distribution, the student-*t*, is assumed. Three levels of large earthquake occurrence were assumed: magnitudes 8, 8.4, and 8.75. Magnitudes appear to be M_S, or effectively, M_w for the larger values. A result of parametric analysis of several seismic gaps for the probability of these magnitudes being reached appears to provide an improvement over a simple Poisson distribution. With adequate paleo-fault displacement data near Yucca Mountain, this process or a similar one might provide an improved probability analysis of the time of a future large earthquake. There is a complicating circumstance in the Basin and Range. Regional tectonic extension is accommodated randomly on various faults. Intervals between times of activity on a given fault are about 1000 years, (Wallace 1985 and 1987 and Ryall and VanWormer 1980). This is in contrast to the more predictable or inexorable movement of down-going slabs beneath island arcs or continents. For the Basin and Range Tectonic Province there could be a joint probability that activity would initiate on a particular fault and that a particular earthquake magnitude could occur. Obtaining enough paleo-faulting information to make such a calculation may be exceedingly difficult.

Kijko and Sellevol (1981) develop a triple exponential distribution for large earthquakes. By application of the X^2 test, they show that the goodness of fit of data is improved by an order of magnitude from simpler distributions. As with a third Gumbel's distribution, used by Yegulalp and Kuo (1974), a maximum magnitude is implied. They tested their distribution, using data of earthquakes felt in Norway, and found their distribution to fit the data more closely than a Poisson distribution. The maximum magnitude in this data set was 6.5.

Sykes and Nishenko (1984) also discussed in Section 2.2.4 of this report, apply probability techniques to their characteristic earthquake models of San Andreas fault segments. Their calculations are based on Nishenko (1982 and 1985). The concept of normalized repeat-times (repeat-time divided by average repeat-time) is employed. For the Chilean Coast, the standard deviation of the normalized repeat-time was ". . . characteristically 14 to 25 percent of the average repeat-time." Similar results were graphed for paleo-displacement derived data for Parkfield and Pallett Creek, California and indicated similar results.

Kiremidjian and Anagnos (1984) list references to several memoryless Poisson or non-Poisson probability distributions. They present a slip-predictable, semi-Markovian process. Inter-arrival times are considered Weibull distributed. This permits the hazard rate to increase with time, unlike the often used exponential distribution for inter-arrival times. The hazard rate indicates the probability of an event occurring in a small interval. For large earthquakes, this value increases with increasing time from the last event. Tests of the model for 300 km segments of the trench opposite the west coast of Mexico suggests the slip predictable model produces a better fit to data than a time predictable model. The model was more sensitive to slip rate than minimum or maximum magnitude. The model assumes that strain energy will accumulate along a fault segment and will be released later by a large earthquake. The time dependence of earthquakes is represented by a Markov renewal process. With this model, the longer the elapsed time since the last earthquake, the larger the next earthquake will be.

Kiremidjian and Suzuki (1987) extend this concept by adding empirical attenuation functions to the probabilistic process, thereby obtaining a risk or probability of an acceleration over a stated period. Their model is more or less conservative than a memoryless Poisson distribution depending on whether the time of interest is shortly after or a long time after a major earthquake.

Kiremidjian et al. (1989) use the Markov renewal process of Kiremidjian and Anagnos (1984) assuming slip-predictable earthquake behavior. Thatcher (1984) showed that fault stress accumulation may be nonlinear. Consequently, Kiremidjian et al. (1989) modified their procedure to accept such information. Their analysis employed published attenuation functions but they were not specified. Kiremidjian and Suzuki (1987) used the attenuation functions of Campbell (1981), Joyner and Boore (1981), Woodward-Clyde Consultants (1978), and Kawashima et al. (1984) to predict strong ground motion. An interesting aspect of Kiremidjian et al. (1989) is the proposed use of a ". . . geophysical ground motion model . . ." or ". . . normal mode method . . ." as an alternative to empirical attenuation functions. It is built upon the asperity model of Kanamori and Stewart (1978) which is based upon a determination of the earth's free oscillations combined with a site response analysis. They reference Suzuki and Kiremidjian (1988) for additional information on the method. Aki (1985) briefly summarizes several modeling procedures which could be similarly employed.

Johnston and Nava (1985) derive conditional probabilities for recurrence of an earthquake like those in the 1811-1812 New Madrid sequence. They assume both a large and small source volume for strain storage and several probability distributions including Gaussian, lognormal, Weibull, and Poisson. Lower standard deviations are between a third and half the mean recurrence time. The highest sensitivity of the procedure was to the assumed source area or volume, although very large differences resulted from the choice of distribution function as well. They assume a time-predictable model which they deem appropriate for intraplate earthquakes. Problems addressed by this analysis are likely to be similar to those for Yucca Mountain, which is also an intraplate zone.

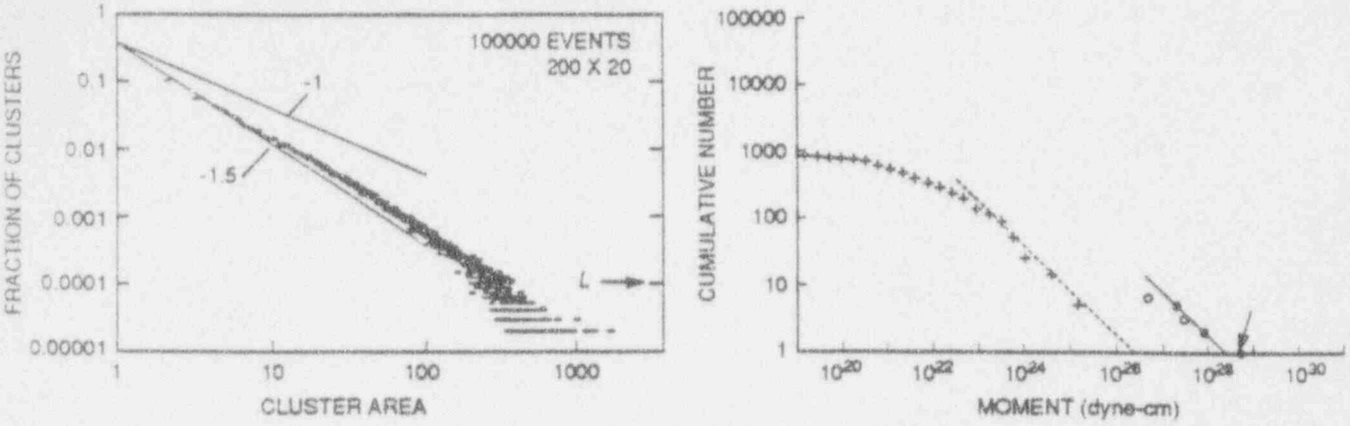
Galanopolos (1988) reiterates Johnston and Nava's (1985) observation that the inter-occurrence times for given magnitude ranges must be known. Numbers of earthquakes versus magnitude for a specified time and area are not sufficient. This would apply to slip- or time-predictable methods. He states that "In each seismic cycle, large events of any possible magnitude may occur. There is no tendency for association of larger events with higher classes (seismic cycles) of actual repeat times."

Davis et al. (1989) are concerned with seismic "droughts." These are defined as unusually long periods of time without the occurrence of a given magnitude earthquake. They build upon the model of Nishenko and Buland (1987) which determines a dimensionless coefficient of variation of 0.21 for worldwide recurrence. Davis et al. (1989) determine the coefficient of variation ". . . independently for each fault segment from its earthquake history . . . " They state that it varies depending on the fault or segment, and its uncertainty strongly affects seismic risk. They adopt a characteristic earthquake approach and a lognormal distribution of inter-occurrence times. These assumptions result in the risk dropping after the mean interval between characteristic earthquakes is reached. This opposes the concept that the longer it has been since the last large earthquake, the larger the next one will be. It does so simply by assuming that earthquakes reach a limiting magnitude for a given segment of a fault. Over long enough periods of time, inter-segment barriers may break, resulting in a higher than characteristic magnitude. Therefore, these assumptions appear reasonable only for relatively short periods of time.

Brown, et al. (1991) attempt to model slip- and time-predictable phenomena using a simple cellular automaton or self-organized-criticality model which accommodates clustering of magnitudes. Their model is patterned after the Burridge and Knopoff (1967) spring-block frictional sliding model and later similar developments, e.g., Rundle and Brown (1989 and 1991). See also Newman and Knopoff (1983). Although not noted by the authors, self-organized-criticality is one of several possible states of chaotic behavior as listed by Shaw (1987). They state: "By introducing a lattice geometry reminiscent of the geometry of a strike-slip fault, we have introduced a characteristic time in the system behavior. This leads to striking similarities with established earthquake statistics . . ." They compare their results in terms of fraction of clusters versus cluster area with the Davidson and Scholz (1985) cumulative number versus moment for Aleutian arc earthquakes (Figure 3-2b). There is a "knee" in each curve, as expected for characteristic earthquakes, but the upper limit of Brown et al. (1991) looks more like the Gutenberg and Richter relationship (Figure 3-2a). Events which involve all blocks (the large events) account for most slip. Their model behavior for large events does not exactly fit the time- or slip-predictable models of Shimazaki and Nakata (1980). However some sequences of small slip events appear to fit one or the other. They note also that large events are usually preceded by a period of quiescence. Brown et al. (1991) conclude:

> . . . recurrence times greater than the mean are often followed by recurrence times shorter than the mean, and vice versa . . . If this pattern can be learned, say through training a neural network [e.g., Koons and Gorney, 1990], and some degree of universality holds, then one should be able to improve the ability to predict events over that given by simply knowing the standard deviation of the recurrence time ...

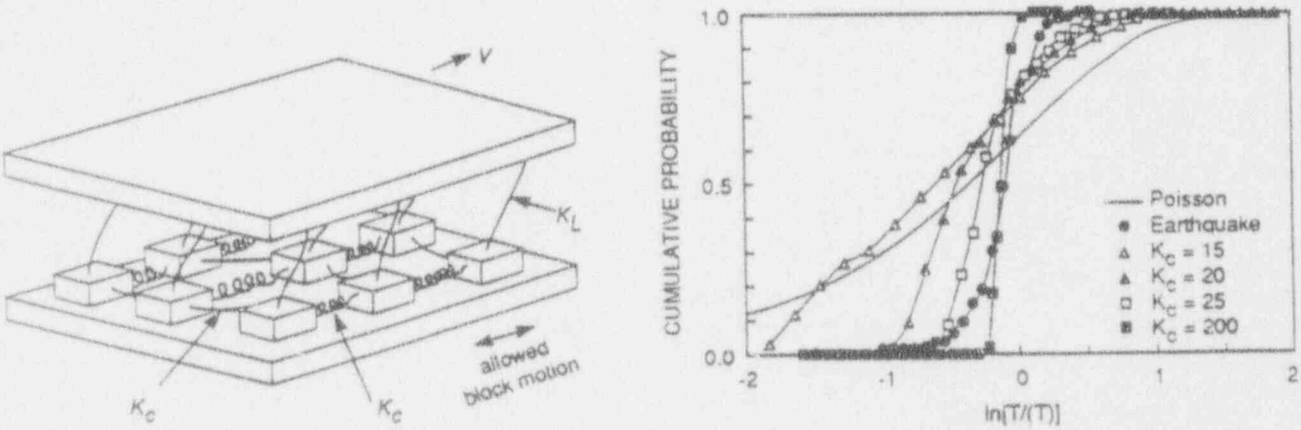
Another interesting analogy by Brown et al. (1991) involves the cumulative probability of events versus $\ln[T/\langle T\rangle]$. T represents interoccurrence times of large slips and $\langle T\rangle$ is the mean recurrence time of large slip events in their model. Several curves are plotted for various spring constants. The softer the spring constant, the more nearly the model approaches pure Poissonian behavior (Figure 3-3). An analogous constant for Basin and Range dip-slip faulting in an extensional tectonic regime would be for a soft spring because rocks are weaker in tension than in compression. Strike-slip or compressional faulting, however, could be thought of as having more strength or a higher spring constant with a consequent greater potential for deviating from a pure Poisson distribution. This analogy might suggest that, for tensional faulting, a Poisson distribution could be expected to fit well for large events. It should be kept in mind, however, that the analogy also predicts various behaviors for individual sequences. Therefore, this consequence would be best tested for a long time span with many large events. Such a data set is not presently extant in the Basin and Range. Additional paleo-faulting studies may eventually provide such data.



a. Fraction of total number of clusters versus cluster area.
(from Brown et al. 1991)

b. Cumulative number of earthquakes versus their M_0 for the Yakataga seismic gap of the Aleautian Island Arc.
(from Davidson and Scholz, 1985)

Figure 3-2. Comparison of spring-block model 'earthquakes' to observed seismicity



a. Geometry of the spring-block model of Brown et al. (1991)

K_C = Effective spring stiffness

K_L = Effective leaf spring stiffness

V = Velocity

$K_L \langle\langle K_C$

b. Cumulative probability function for ln(T/⟨T⟩) versus spring stiffness.
(from Brown et al., 1991)

T = event interoccurrence times
⟨T⟩ = mean interoccurrence time

- earthquakes are from Nishenko and Buland (1987) These are primarily interplate thrust events and some interplate strike-slip events.

– solid line, is more closely approximated by low spring constant model events which may be analogous to extensional Basin and Range province earthquakes.

Figure 3-3. Earthquake spring-block model and implications for a Poisson distribution

Whether time-dependent models of any kind are sufficiently conservative for use over a 10,000-year period is a concern to regulators. What may be relevant for a 50-year projection may not be relevant for a 10,000-year projection. Without analysis of specific Yucca Mountain hazards, this author does not believe that time predictable models are adequately conservative. A Poisson distribution is reasonable where a large data sample is available. If only a small data sample is available for a given site, a larger area or a longer period for paleo-studies must be used to obtain an adequate sample. However, a non-Poisson distribution is not justifiable when only a few data points are available. Distributions equivalent to truncated Poisson distributions, however, may be preferred to Poisson for long periods or when a high level of confidence is desired. Truncation or its equivalent will remove physically impossible values, at the extremes of the function, and prevent propagation through a statistical analysis.

Cornell and Toro (1989) show that a Poisson distribution is appropriate in a highly seismic area. He expresses doubts, however, concerning its applicability for repositories with a much longer lifetime than nuclear power plants:

> Current practice, which is applicable at least to the operational phase of a repository, is based almost solely on the memoryless Poissonian earthquake recurrence model. Its data needs are relatively limited, although low-hazard, long-time-window estimates will be subject to significant, if quantifiable, uncertainty. Adequacy of this Poisson model for long-window hazard predictions has not yet been well investigated. Questions of seismicity stationarity become more dominant in the long-window case; nonstationarity and/or stochastically changing parameter values have not been well studied or applied.

Time-dependent models are even less well investigated for long-term predictions. A saving feature of long-term analyses is that multiple sources of earthquake shaking, each of which may have some time dependency, combine to produce a hazard which appears Poissonian. The longer the period, the more likely it will be that several sources will contribute to the hazard, and the less likely that predictions based on a weak time dependence will be accurate. Of concern, however, is the unconstrained nature of the Poisson distribution. For unlikely events, the extremes of the function may predict values which are physically unrealizable. If an analysis is sensitive to Poisson distribution extremes, efforts to truncate distributions, or replace them with equivalent distributions which do not have such extremes, will be worthwhile.

3.2.2 Uncertainties

Uncertainties are defined here as encompassing both uncertainties in professional opinion and uncertainties in data. The latter uncertainties have been defined as randomness (see Section 2.1.3). The discussion that follows is not quantitative, although quantitative measures of randomness, e.g., standard deviations assuming a Poisson distribution, are often given with curves derived from data. These standard deviations are sometimes assumed to apply to extrapolations beyond the range of data. In that event, they are a measure of one investigator's estimate of uncertainty. A definition of uncertainties inherent in an analysis is attempted by McGuire and Shedlock (1981) using several attenuation relationships and other input estimates derived from available data.

3.2.2.1 Seismic Source Zones

If seismic source zones are faults, major earthquakes often correlate with them and the uncertainty in size and shape of the source zone may be minimal. Geophysical exploration methods can determine the shape of the source zone (fault) at depth. However, for smaller earthquakes also associated with the fault, the width of the fault zone on the surface, which includes branching faults, must also be considered. If the individual branches are not specifically mapped, the entire surface width of the fault zone must be considered as a source zone for all earthquakes of less than maximum magnitude. This is usually taken as earthquakes of one magnitude unit less than the maximum and lower. A study of the surface width of fault zones versus fault length or segment length has been made by Slemmons (1977) and Bonilla et al. (1984).

If observed seismic source zones are broad areas, there may be differences in opinions concerning the boundaries of the zone. Rationales for describing zone boundaries usually include the observation of seismicity. A list of bases for establishing zone boundaries follows:

- Area or volume over which seismicity is located;
- Any fault on which seismicity has been observed;
- Area of a tectonic feature other than a fault, some part of which has associated seismicity, e.g., an anticline;
- Broad area of similar geology, some part of which has associated seismicity;
- Any fault that has demonstrated Quaternary movement or which has movement that cannot be demonstrated to be preQuaternary; and
- Any structure or geologic feature that the investigator believes can control seismicity, e.g., round basic plutonic intrusions, Kane (1977).

An expert system could be constructed to develop source zone boundaries in a manner similar to that of a particular investigator or team of investigators, at least for one point in time. When the expert system is developed to the point that it will reproduce the gross features of past source zone descriptions, it could be used to create new ones at new sites. The uncertainties in the boundaries as estimated in published work can be carried along in the expert system. Because several boundary configurations are incorporated in any final hazard estimation, any particular source zone boundary in a probabilistic seismic hazard analysis similar to EPRI's or LLNL's may not be critical.

An alternative to the expert system or team/panel approach is to require that source zone boundaries be generated using quantitative physical criteria, for example:

- An area or volume encompassing a certain level of seismicity;
- An area encompassing Quaternary fault offsets of a given displacement;
- An area encompassing a certain number of a particular tectonic feature per square mile, for example, grabens with bounding dip-slip faults;

- An area encompassing a continuous lineation of strike-slip faults;

- An area overlying a down-going slab; and

- Seismic gaps or paleo-fault displacement gaps.

Boundaries may be specified with a certain technically justifiable "fuzziness" or uncertainty as proposed by Bender (1986).

Evaluation of uncertainty requires evaluation of the basis for the "expert's" opinion for "uncertainty" in the boundary. It may require a weighting based on potential motivation of expert teams or expert panel members if the matter is litigious. Such a process is antithetical to the precepts of science and engineering. That is, what can be quantified with assurance should be quantified and used. These precepts, however, must not be violated. What cannot be quantified, but is held as an expert opinion of merit, could be used to generate boundaries and to evaluate the uncertainty in them.

3.2.2.2 Source Zone Magnitude Minima and Maxima

Varying the minimum and maximum earthquake prescribed for a source zone changes the hazard derived from a statistical analysis. Therefore, means of establishing these values are of interest.

Minimum earthquakes are usually defined as those which could damage a given structure. In their initial studies, EPRI chose $M_{min} = 5$ and LLNL chose $M_{min} = 3.75$. Bernreuter et al. (1987) state that the difference in M_{min} was a significant factor for differences in initial seismic hazard estimations of the eastern U.S. This results from an assumed Poisson distribution of peak accelerations for a given distance for a given magnitude. Damaging-level accelerations are predicted, at low probability levels, for magnitude 3.75 earthquakes. However no damage to well-engineered structures has been documented. Damage of ordinary structures is usually considered to begin at the M = 4.5 level. Apparently EPRI believes that the damage seen from this magnitude results from outliers in associated acceleration and outliers in presumed structural response. Hence they deem a higher minimum magnitude to be appropriate. If the standard Gutenberg and Richter recurrence relation is assumed, $M_L = 3.75$ is about an order of magnitude more frequent than an M = 5.0 earthquake. The use of $M_{min}=3.75$ moves some outlying acceleration predictions from the M = 3.75--4.9 group of earthquakes into the damaging acceleration range. In later studies, the minimum earthquake magnitude was set at 5.0 for both the LLNL and EPRI analyses. Substantial differences in results remained, e.g. Bernreuter et al. (1989b).

Truncation of probability distribution functions is about the only way to eliminate these disparities. However, the truncation process is an anathema to any probabilistic analysis. Such analyses assume that there is a continuous and unlimited range of probability and virtually any value may occur. Truncated distributions have been investigated by Cosentino et al. (1977) and applied by Kijko and Dessokey (1987) and by Kijko and Sellevoll (1989), who found that a double truncation of a Poisson distribution produced an equivalent to the first Gumbel's asymptote of extremes. Kijko and Sellevoll reference Tinti and Mulargia (1985a), who had made similar conclusions. Tinti and Mulargia (1985b) examined the effects of magnitude uncertainties on the Gutenberg-Richter frequency-magnitude law. They concluded that apparent numbers of earthquakes exceeding a given magnitude tend to be larger than the real value, perhaps twice as large. They use a truncated exponential probability distribution function which essentially becomes unbounded if the maximum magnitude is allowed to approach infinity. This paper is a good source of earlier references on the topic of bounded probability distribution functions for earthquakes, e.g., Cornell and Vanmarcke (1969) who appear to be the first to seriously address the topic. Kijko and Sellevoll (1989) believe their method accurately evaluates an earthquake catalogue in a very active part of Italy. They believe that it will accommodate the combined use of years of complete data and years for which only large magnitude data are available. They state that their method will produce an estimate of maximum magnitude.

Bender and Campbell (1989) use a tapered distribution to define the minimum magnitude and resolve the conflict or produce a compromise regarding this topic. The taper corresponds, in effect, to the number in each range of small magnitudes between some M_{min} (where damage occurs) and a level below which no damage occurs. This has the effect of steepening the Poisson distribution slope where curvature changes sign and an asymptote is approached.

Maximum earthquakes have been typically assigned as one magnitude unit higher than the highest value observed except for major faults, e.g., the San Andreas, or for down-going slabs. For these, only the maximum magnitude observed has been assigned. If Quaternary fault displacements indicate that larger earthquakes had occurred on a fault than had been observed historically, the paleo-event would be used as the maximum event. Slemmons (1982), Youngs and Coppersmith (1989), and dePolo and Slemmons (1990) review many methods currently used for setting maximum magnitude including McGarr's (1987) strain rate method.

McGuire and Shedlock (1981) address the effect on uncertainty caused by a maximum magnitude variation between 7 to 8 in a test analysis. They do not separate this effect from others but do recommend procedures for incorporating this variability in a probabilistic analysis.

Bender (1984) shows the effect of varying minimum and maximum magnitudes on a probabilistically determined acceleration. Effects from fixing source-to-site distance or letting it vary over a region were investigated. Truncating acceleration probability distributions at the 1.5 to 3.0 standard deviation levels rather than integrating over the distribution function was tested. In the example given, a median acceleration of 0.41g for a 10^{-7} yearly exceedance became 1.18 g when integrated over the distribution function. The acceleration became 0.82 g when the distribution function was truncated at a 1.5 standard deviation. McCann and Boore (1983) propose that a standard deviation corresponding to 1.35 times acceleration is claimed irreducible and that it corresponds to source variations in dynamic stress release. They state that other factors may be improved upon, e.g., amplification by soft soil or variability imposed by instrument embedment depth.

Berrill and Davis (1980) explore entropy which they describe as a measure of uncertainty or as "missing information." They imply that through the maximum entropy principal, a best fit to existing recurrence data will result in a truncated maximum magnitude. The concept was tested only on very large Circum-Pacific data sets and found accurate.

Uncertainties in maximum magnitude were approached by Doser and Smith (1989) using a comparison of seismic moments derived from seismograms and from fault displacement characteristics. This information could presumably be used to determine the uncertainty in magnitudes derived from paleo-earthquake information in the western Cordillera of the United States. Data are not presented in an easily accessible form but the development in this paper suggests that useful information regarding maximum magnitude uncertainty could be obtained from western U.S. fault slip measurements and 3D plots of aftershocks.

Wyss (1979b) proposes that a maximum expectable rupture area is a better means of estimating maximum magnitude than through maximum trace length. He shows a comparatively tight distribution of earthquake source area versus magnitude in the 5 to 9 range. He indicates that the reduced scatter supports his concept.

Anderson and Luco (1983) attempt to estimate maximum magnitude, M_{max}, from the seismic moment release rate of small magnitude earthquakes. They use a truncated exponential function such that the rate goes to zero at M_{max}. The method could also be applied to paleo-fault displacement data. The method is sensitive to the completeness and quality of the historical data used. These data always have a probability distribution associated with their respective recurrence function. Therefore there is a range of maximum magnitudes based on the number of standard deviations in the data from which they are derived. The nature of probabilities is that there are probabilities of probabilities being correct The pursuit of these probabilities of probabilities is not likely to be warranted for expert opinions which are substituted for data. M_{max} and M_{min} may have associated probability distributions whether they are derived from expert opinion or from a quantitative analysis of data.

Davidson and Scholz (1985) plot cumulative numbers of earthquakes for segments of the Aleutian arc (Figure 3-2b) versus moments for an 18- and an 85-year data set. A cumulative number of 1 represents a maximum earthquake. Therefore an extrapolation of moment versus cumulative numbers to the cumulative "unity" predicts the maximum earthquake. The 85-year data set, comprised only of very large earthquakes, always indicated a larger number than the 18-year data set, comprised of a broad range of magnitudes. Only data from the entire arc predicts a maximum magnitude equal to that which occurred in 1964. Therefore, maximum magnitude on a fault segment can be predicted only from the entire fault over a long period. See also the discussion in section 3.2.1.

3.2.2.3 Ground-Motion Attenuation

Problems associated with empirical ground motion versus distance versus magnitude curves are numerous. Among them are data sets from a few large earthquakes and a few critical data points for magnitudes at near-field distances, mostly recorded at far-field distances. There are many strong-motion records of modest earthquakes at non-near-field distances. There are few strong-motion records for large earthquakes at distances less than source dimensions. Analyses of radiation patterns imply that accelerations could vary as much as 10 times for certain source configurations, e.g., Sommerville and Nelson (1982) and Boatwright and Boore (1982). Soil response adds another dimension to empirical curves. An additional axis with soil thickness could be added to acceleration versus distance curves for particular magnitudes. However, this effect is site-specific and difficult to generalize.

Topographic effects are also reported to be substantial, for example, Boore (1972) or Kawase and Aki (1990). It is not surprising that some estimates of confidence in ground motion attenuation curves are not reassuring. Brillinger and Preisler (1984) analyze Boore and Joyner's (1982) and Bolt and Abrahamson's (1982) relationships based on the same data. The standard deviations in horizontal acceleration that each investigator used are given in Table 3-3.

Boore and Joyner (1982) multiply Campbell's (1981) accelerations by 1.13 to compare his average-of-two-horizontal components with their largest-of-two-horizontal components.

Table 3-3. Examples of statistical variation in acceleration (from data of Brillinger and Preisler, 1984)

Author	Statistical	Measure of Variation
Boore and Joyner (1982)	0.26 g	One SD for ML = 5 to ML = 7
Bolt and Abrahamson (1982)	0.09 g	One SD for ML = 6 to ML = 7
Brillinger and Preisler (1984)	0.256--0.934 g	95 percent Conf. Interval for MS = 7 and D = 5 km

The measures described in this section and in Table 3-3, are not directly comparable but provide an estimate of variability. Brillinger and Preisler (1984) find that the earthquake-to-earthquake variance at the same magnitude is about one fourth the record-to-record variance for a single earthquake.

Typically earlier recurrence relations were developed from less data than are now available. Often they had higher standard deviations than those published more recently. However, Schnabel and Seed (1973) selected their data carefully from records of larger earthquakes at the shortest distances available and only from hard-rock recording sites. They did not provide a standard deviation value for acceleration, but it was estimated by Hofmann et al. (1982) as approximately 0.1 *g*. This was about one fifth of the value reported by McGuire (1976) for his relationship, which was derived from a larger, less selective database. A problem in constructing these relationships is the definition of the distance from site to source. This subject is discussed in the last topic of Section 3.2.2.4.

Campbell (1987) developed an attenuation function purportedly for the Wasatch Front in Utah, an extensional dip-slip environment. His data are from California and some worldwide sources. He argues that strike-slip data from California are close enough to dip-slip data that it is reasonable to use it for a dip-slip fault. Campbell (1986) also uses strong motion data from the 1971 San Fernando earthquake that has a thrust fault source. He believes that McGarr (1984a) is not supported in his contention that tensional faulting should produce lower ground motion than thrust or strike-slip faults. Campbell cites the 1975 Oroville, California, earthquakes, which were in a tensional environment. These data do not show reduced ground motion. It might be pointed out that the Oroville faulting situation is different from the Basin and Range extensional environment. The Foothills fault zone at Oroville is a hinge fault, not a simple tensional fault. The "hinge" is between the Sierra Nevada massif and the Central Valley. Hinge faulting is conceptually a different specie than Basin and Range dip-slip faulting. As surficial rock layers are bent over the hinge, cracks propagate from the surface to the base of the layer. This occurs because the outside radius of the layer is larger than the inner radius at the bottom of the layer. Publications regarding the effect of bending earth material over a small radius were not found in this review. This kind of material failure may be researched in metal forming literature.

Characteristics causing ground motion to be theoretically lower will also reduce earthquake magnitude estimates according to Campbell (1987). Therefore, there can be no difference between the ground motion generated by different fault types. This is correct, but if seismic moment equations are correct, stress drop and fault area both contribute to energy release. Paleo-fault offsets then may well represent lower magnitudes in the Basin and Range in a compressive stress regime because stress drops are lower. An adequate earthquake record for a 10,000-year period must be based largely upon paleo-earthquakes. A critical component of the calculation is the relationship between fault rupture area and magnitude. The unknown in this relationship is stress drop. This variable may significantly affect magnitude estimates from paleo-faulting data.

Campbell (1987) shows only two data points at less than a five km source-receiver separation. However, he restricted his data to distances less than 30 km for magnitudes less than 6.25 and to 50 km for magnitudes greater than 6.25. He uses the average of two horizontal components of acceleration, not the largest one. He believes the average to be more statistically significant than the largest component, which is more commonly used. Joyner and Boore (1981) point out that this measure can be modified to produce an attenuation curve equivalent to one derived from the largest horizontal component. Campbell's method doesn't consider that peak high-frequency accelerations in the near-field are controlled by stress drop, rather than magnitude, as predicted by Brune (1970) and others, for example, McGarr (1984a). Campbell disputes McGarr's idea based on the limited near-field data available. This attenuation function is from data recorded at distances less than 50 km. It is not specific to Utah, the Basin and Range, or the types of faulting in these areas. Campbell argues that a region-specific attenuation function is not needed. McGuire (1985) summarizes many of these ground-motion uncertainties.

Apsel et al. (1983) derive ground motion (pseudo-velocity) spectra from modeling fault parameters for the eastern U.S. Wave propagation is modeled with a frequency-wave number integration algorithm. A source time function for each grid element of the analysis is represented by an empirical scaled value from a near-field accelerogram. They find that Q has a strong influence on results. Model parameters include magnitudes of 4.5 to 6.6, strike-slip and dip-slip source mechanisms, hard rock to soft soil sites, and distances from 2.5 to 35 km. In addition, several rupture depths and rupture configurations were modeled. This work results from ground-motion modeling of a presumed Hosgri fault strike-slip rupture offshore from California. The modeling was performed for the San Onofre and Diablo Canyon nuclear power plants. It is a Green's function approach.

Several large strong-motion arrays are providing additional information of acceleration variability. Examples are Higashimatsuyama and Chiba Experiment Stations in Japan (e.g., Nagata et al., 1990), the Lotung large scale test (LLST)-Tai Power, Abrahamson et al., (1990), and the SMART 1 arrays in Taiwan (Niazi and Bozargnia 1990). Vanmarcke and Rosenblueth (1989) briefly discuss results for a single event recorded at each of two arrays. They do not have enough data from which to draw quantitative conclusions, but a direction of improved assessment of strong-motion attenuation is indicated by using such array data. The density of strong-motion stations in California virtually provides array status for many locations. Improving ground motion prediction is problematical because the location of a future event on a fault may be in an area of limited instrumentation and identification of asperities prior to an earthquake may not be possible. High-amplitude high-frequency pulses are predicted to emenate from asperities.

3.2.2.4 Source Variables

This section is intended to summarize input variables that are likely to be required for the SEIM 1 code. These variables will also apply to other probabilistic seismic hazard analysis codes. Some inputs, like the latitude and longitude of source region polygon nodes or, in some cases, end points of linear faults, will vary for each site and possibly for each expert. Expert estimates of uncertainty in their respective estimates will also vary for each expert and for the region of the site being investigated.

The largest number of potential variables are associated with ground motion attenuation functions both empirical and theoretical. Many of these variables are already summarized in sections of this report which discuss either empirical or theoretical attenuation functions. They are summarized again here en-masse. Although the list of potential variables that might be used is extensive, it is not necessarily all encompassing. It may be impossible to anticipate every theoretical formulation that might be preferred by a particular expert concerning ground motion attenuation but certainly a majority of those available at the date of this revision are included.

Uncertainties in source variables for both earthquakes and fault displacement can be considerable. Variables which may be input to a PSHA include but may not be limited to the following.

- Stress drop,
- γ, the exponent of ω (attenuation coefficient),
- Maximum frequency,
- Minimum frequency,
- Age of fault displacement,
- Source mechanism,
- Site to source distance, and
- Seismic efficiency.

The first four of these variables apply to the "stochastic method" of Hanks and Boore (1984). The next three could apply in the implementation of any of the methods considered.

Stress drops have already been discussed. To summarize, several kinds of stress drops are defined in the literature, e.g., see Boatwright (1984a) and Table 3-4.

Boatwright (1984a) defines $M_o = 4\pi[\rho(\xi)\rho(\mathbf{x})\beta(\mathbf{x})]^{1/2}\beta^{5/2}(\xi)(\mathbf{R}/F^*)\bar{u}$. Definitions of terms for this equation and those in Table 3-4 follow:

a	final source radius,
β	shear velocity,
$\beta(\xi)$	shear velocity at the source, e.g., 3.6 km/sec,
$\beta(\mathbf{x})$	shear velocity at the source, e.g., 3.0 or 2.0 km/sec,
D	slip at the center of a fault dislocation,
$\Delta\sigma$	stress drop,
$\Delta\sigma'$	$=\Delta\sigma/\tau_e$, non-dimensional stress drop,
$\Delta\sigma_{rms}$	dynamic stress drop or root-mean-square stress drop,
e	usually rupture slip eccentricity, see Boatwright (1984b),
E_s	radiated energy,
$\eta\bar{\sigma}$	$=\mu E_s/M_o$ apparent stress of Madariaga (1976),
f_o	corner frequency,
F^*	vector magnitude of horizontal shear waves, e.g., 0.85,
f_{max}	maximum S-wave corner spectral frequency,
$g(v_R)$	energy release rate for the self-similar circular shear crack of Madariaga (1976),
M_o	seismic moment,
ν_0^s	average corner frequency of Madariaga (1976), e.g., $0.21\beta/a$,
ρ	correlation coefficient of Hanks and McGuire (1981), e.g., 0.11 - 0.95,
$\rho(\xi)$	density at the source, e.g., 3.0 g/cm^3,

Table 3-4. Stress drop formulae

Stress Drop Type	Author	Formula
Dynamic stress drop	Boatwright, 1980	$\tau_e = \{[\sigma(\xi)\sigma(\mathrm{x})]^{1/2}\beta^{5/2}(\xi)\nu^{-3}\}\bullet$ $(\mathbf{R}/\mathrm{F}^s)(1-\zeta^2)^2\langle\dot{\mathrm{u}}/\mathrm{t}\rangle$
Apparent stress	Madariaga, 1976 Wyss, 1979a	$\eta\bar{\sigma} = \frac{1}{2}\tau_e\{2-\Delta\sigma'-\mathrm{g}(\upsilon_R/\mathrm{D}\}$ $\tau_a = \mu\mathrm{E}_s/\mathrm{M}_o$
a_{rms} Stress drop	Hanks & McGuire, 1981	$\Delta\sigma = 2.7(\rho\mathrm{R}/\langle\mathrm{F}^s\rangle)(\mathrm{f}_o/\mathrm{f}_{max})^2 a_{rms}$
Brune stress drop	Brune, 1970	$\Delta\sigma = 8.5\mathrm{M}_o(\mathrm{f}_o/\beta)^3$
Avg. static stress drop	Chinnery, 1969 rectangular fault	$\Delta\sigma = (1+e)\mathrm{M}_o/2\mathrm{aw}^2$
Stress drop	Keilis-Borok, 1957, circular fault	$\Delta\sigma = \mu(7\pi/16)(\bar{\mathrm{u}}/r)$

$\rho(\mathrm{x})$	density at the strong motion instrument, e.g., 2.5 g/cm^3,
r	radius of a circular fault,
R	geometrical spreading factor,
$t^*/2$	attenuation correction factor,
τ_a	apparent stress,
τ_e	effective stress,
τ_R	dynamic stress drop,
$\bar{\mathrm{u}}$	average slip,
μ	rigidity,
$\langle\dot{\mathrm{u}}/\mathrm{t}\rangle$	vector slip,
v	average rupture velocity,
v_R	rupture velocity of Madariaga (1976),
w	usually rupture width - see Boatwright (1984b),
ζ	$=\mathrm{v}/\beta_{\sin\theta}$ where θ is the angle between the normal to the fault and the S-wave take-off direction.

Boatwright (1984a) estimates the uncertainties in estimates of stress drop for the Oroville earthquake study. The uncertainties apply to individual calculations. Actual variations of stress drops among earthquakes are larger than the estimated uncertainties for each calculation. See Table 3-5 for a summary of his uncertainty estimates.

Only the shear-wave dynamic stress drop or the a_{rms} stress drop is used in the Hanks and McGuire (1981) approach. Depending on the tectonic situation, various authors have reported stress drops of a few to about 1000 bars. Most of these estimates are discussed in this review. Therefore, there may be differences compared to the Hanks and Boore method of calculation. Boatwright (1984a) determines stress drops for the five different definitions of stress or stress drop above for a suite of aftershocks of the 1975 Oroville, California, earthquake. Values of a_{rms} varied between 87 and 195 bars.

Table 3-5. Table of uncertainties

Variable	Examples of Uncertainties in Calculation
Moment estimates	Standard deviations ranged from 0.25 to 0.55 of the moment estimates for data from 6 to 11 stations. Uncertainties are about 0.1. Dynamic stress of Boatwright uncertainty is about 0.15.
a_{rms} stress drops of Hanks and Boore	Uncertainty is about 0.15
Apparent stress	Uncertainty is about 0.2
Brune stress drop	Uncertainty is about 0.1. However, Boatwright (1984a) states that "...this apparent stability is misleading because it correlates poorly with both the static stress drop...and the three dynamic stress drop estimates...."
Comparison of a_{rms} stress drop and dynamic stress drop	For simple events, the a_{rms} stress drop underestimates dynamic stress drop by 0.10 to 0.35. For complex events (several asperities), dynamic stress drops are 0.56 larger than a_{rms} stress drops. This reduces to 0.25 if f_{max} is more accurately determined, Boatwright (1984a).
Comparison of Brune stress drop and static stress drop	If uncertainty in individual Brune stress drop measurements is 0.15; the uncertainty in the relationship to the static stress-drop is 0.5.

If the range in individual estimates is included, the total spread is 73 to 217 bars. The range of values for all aftershocks determined by all the stress-drop definitions is 28 to 286 bars.

Clearly the measure of stress drop used by Hanks and Boore (1984) varies between about 20 bars and 200 bars. A stress drop of 20 bars is proposed for Basin and Range dip-slip events, McGarr (1984a). McGarr discusses these variations with source type and depth and concludes that a particular stress-drop calculation could vary as a function of azimuth relative to a source. The higher value would apply to certain thrust-type events. Hanks and Boore propose that a constant value of 100 bars is adequate to carry out their method of determining peak acceleration and spectra. A penalty of up to a four-fold increase in scatter of results must be accepted with this assumption.

Variations in stress drop observed for a given event may result from inherent source anisotropy, for example, rupture velocity variations and/or relationship to the focal mechanism. Other variations result from a difference in source type, for example, dip-slip, strike-slip, or thrust. Further, not all earthquakes have simple source mechanisms, for example, Loma Prieta, California, events. See, for example, a description of the 1964 Corralitos event in Hofmann (1969). During the 1989 event, Loma Prieta peak apparently lurched permanently northwestward with strike-slip movement on either side and thrusting beneath. Such a complex mechanism would not produce any of the simple patterns of first-motion polarity presently used to define source mechanisms. An ambiguous stress drop as a function of azimuth would also be expected.

Analyses of stress drop scatter about particular simple-source mechanisms were not found in the literature. If all Oroville aftershocks are of the same mechanism, Boatwright's (1984a) data could be used to estimate scatter for that mechanism. Observed stress drop scatter for the Orville earthquake aftershocks combined with Hanks and McGuire (1981) stochastic method might produce an estimate of the variation in peak acceleration to be expected with azimuth.

Attenuation Coefficient, γ

The exponent of ω, γ, in Hanks and Boore's (1984) development, controls spectral attenuation. It varies slightly with magnitude. Observed variations can be incorporated into the stochastic model and any improvement in estimates quantified. The model is too simple to account for near-field effects at recording distances less than a fault dimension. Changing the stochastic model to accommodate near-field effects would be difficult. However, a postcalculation correction factor could be developed for particular faulting configurations. Frankel (1991) shows that if a b-value of 1.0 and a γ of 2 are assumed, a scale-invariant strength along fault zones is indicated. It does not matter whether the falloff of individual subevents is best represented by a γ of 2 or 3. This is a further indication of the fractal nature of earthquake processes and is contrary to the b value analyses reviewed in Section 2.2.5.

Maximum Frequency

The maximum frequency, f_{max}, enters the calculation of peak acceleration and dynamic stress drop. Maximum frequency is known to vary with source depth, rock compressibility, and instrument response, e.g., Hanks (1982). However it is assumed to be a constant in the Hanks and McGuire (1981) stochastic model. Hanks believes that for most earthquakes this assumption appears adequate. For locations at depth in hard rock, however, higher values may improve accuracy. Boatwright (1984a) suggests that an additional 25-percent error could result from failing to let this term vary in his analysis of the 1975 Oroville aftershocks. The effect of f_{max} is to produce increasing differences in peak acceleration, a_p, with respect to decreasing magnitudes, (Boore, 1983b). At smaller magnitudes, peak accelerations were higher when he chose higher values of f_{max}. McGarr et al. (1981) used $f_{max} = 400$ hz when analyzing mine tremors of less than magnitude 2.4. They also found that a Q of 600 was appropriate. Yucca Mountain tuff is not as hard as the rock in the South African mines. Consequently, both f_{max} and Q will probably have lower values than those of McGarr et al. (1981). However, higher values at depth are a possibility, because tuff that has been under compaction will be more cohesive and may attenuate less than weathered tuff at the surface. Investigations should be undertaken to determine the values of these parameters at the mined repository depth.

Minimum Frequency

The minimum corner frequency, f_o, depends on source size and the width of the shear wave window in the stochastic method. Energy is generated at longer wavelengths than defined by Hanks and Boore (1984) for the shear wave window for very large earthquakes. Currently, large earthquakes are not anticipated in the Basin and Range province. Consequently, this limitation can probably be ignored for Yucca Mountain analysis. An STP designed to encompass this methodology may be desired for a wide range of tectonic environments. If so, effects of greater magnitudes than 8.0 might be addressed.

Should future investigations suggest that very large earthquakes are potential at Yucca Mountain, an investigation into the minimum corner frequency would be appropriate.

Source Mechanisms

Source mechanisms are not usually indicated as an input parameter. However, other variables take on different mean values depending on the source mechanism. Stress drop for example, increases from normal through strike-slip to reverse faulting. The shape of the fault displacement surface will vary with the type of faulting. Rupture velocities are closer to the shear velocity for simple single asperity breaks than are multiple asperity complex sources according to Boatwright (1984b). This factor causes a discrepancy between the stress drops of Boatwright (1980) and of Hanks and Boore (1984). Normal and thrust fault slip surfaces are more compact and nearly equidimensional than the ribbon-like large events on strike-slip faults. Ground-motion radiation patterns are distinctly different between normal and strike-slip faulting. Although radiation patterns may cause ground motion to vary more than ten times with azimuth, most investigators do not consider them in PSHA. This additional refinement may narrow the range of motions from a given source and is a logical further step in the development of PSHA. Requiring consideration of azimuthal effects, on the final hazard, is prudent. The problem of complex sources like the Loma Prieta event requires discrete element analyses to anticipate near-field ground motion. Few such analyses are available, but more on this topic is expected in the future. The state-of-the-art in anticipating ground motion from complex sources is too rudimentary at this point to address in an STP. However, should this issue arise in a license application, additional research and development will, no doubt, be applied. Therefore, this is a topic for consideration during the review of an HLW repository application.

Site to Source Distances

Common measures of recording site to source distance are "epicentral distance" and "distance to nearest point on the causative fault." Shakal and Bernreuter (1981) point out that for high frequencies (e.g., >15 Hz), an appropriate distance might be "the distance to a high stress zone." The high stress zones are barriers or asperities that are broken in the rupture process. Such zones are difficult to identify before a rupture. Terminations of fault segments with which characteristic earthquakes have been associated are candidate barrier locations. However, if paleo-earthquake studies prove that no larger earthquakes have occurred during the Quaternary, their rupture may occur only with a probability that is below regulatory concern. Recent data and analysis are less ambiguous regarding source to site distance for example, Campbell (1985 and 1989). Higher levels of field research and higher densities of sensitive seismic and strong motion stations are now used to define rupture zones of earthquakes, particularly in California, e.g., Joyner and Boore (1988). However, some time will be required to accumulate enough of this high quality data to improve the current data set which has less rigorous distance definitions.

Source-to-site distances are defined in several ways as they relate to the near- and far-field of earthquake sources. For far-field estimates of ground motion, epicentral distances are convenient as a measure, and are usually appropriate. For estimates closer to the potential source, a distance to fault or likely fault-rupture zone is a better measure. Far-field can be defined as a distance that is an order of magnitude larger than the largest dimension of the fault plane rupture area. Near-field can be defined as a distance shorter than the maximum fault rupture dimension. Therefore, definition of near-, mid- and far-field strong motions are related to magnitude and faulting type. There are other definitions. Aki and

Richards (1980), for example, define near-, intermediate-, and far-field as functions of the number of terms required in Green's functions to describe the motion.

Theoretical fault modeling is a procedure for defining near-field ground motion in addition to comparison with a limited database. It was undertaken to predict possible future shaking at the Diablo Canyon and San Onofre nuclear power plants. Near-field can be defined as distance to the center of energy release or to the nearest point on the rupture plane, whichever provides the largest ground motion value. For dynamic modeling, the definition of near-field distance is less tractable than for empirical methods. In practice, distances to all parts of the rupture plane enter the integration of ground-motion over the rupture surface. A distance parameter based on the nearest point of the rupture plane is useful for preparing lists and seismic hazard curves. However, for dynamic computer fault modeling, this value has less meaning than in the usual application.

3.2.3 Sensitivity Analysis Recommendations

Sensitivity studies are common in Type II probabilistic analyses, e.g., Hofmann et al. (1982). The purpose of these analyses is to determine the sensitivity of output to input parameter variations or errors. Inputs having a high error sensitivity are targets for extra attention to improve confidence in output. Parameters examined were peak magnitude, source zones, source-zone boundaries, and acceleration attenuation functions. Where results differ, they are summarized and discussed. Other parameters of interest are the probability distribution function, minimum magnitude assigned to each source zone, and the 'a' and 'b' values of the recurrence relation.

Other potential variables in strong motion assessment, whose sensitivity may influence results, are the methods of assigning randomness or uncertainty and an assumption that a characteristic earthquake is or is not exceeded. Hazard curve sensitivity to time or slip-predictable probability distributions compared to Poisson or other conventional distributions should be analyzed. If there is a high sensitivity but low confidence in such distributions, their use should be restricted. For a 10,000-year period, the use of time or slip variable probability distributions or models may not be practical. Several cycles of seismic activity may have occurred during that period. Time or slip predictable model validity over a long period may be uncertain. A different, larger cycle may be invoked after several smaller cycles that produce only a characteristic earthquake. If a variable has a negligible effect on results, there is little purpose in assigning more complex probability distributions to it. Methods used to calculate ground-motion parameters within a source dimension from a rupturing fault could also be studied by sensitivity analyses.

Type II analyses, which include sensitivity studies, are similar to, but less formalized and complex, than Type III and IV analyses. In sensitivity analyses, expert opinion is frequently obtained from referenced publications. A statistical analysis of the variation in results is appropriate if there are enough inputs for each element of the analysis. Sensitivity analysis, therefore, has at least two purposes:

- It points out which variables require the most attention for the configuration of a particular problem, and

- It can provide preliminary insights into the variability to be expected in a more formal hazard analysis.

Such a process is described in some detail by Rabinowitz and Steinberg (1991) for an application to Jerusalem. In their process, all parameters are varied simultaneously. This permits evaluation of any interdependencies between variables. They used the Joyner-Boore (1981) and the Campbell (1981) attenuation relations, with standard deviations of 0.6 and 0.3, respectively. The Cornell-McGuire method (e.g., McGuire, 1976) was used for each permutation of the probability computation.

Rabinowitz and Steinberg (1991) found variations in attenuation standard deviation to greatly affect results for their problem. The choice of attenuation function was the second largest factor, followed by maximum magnitude and recurrence relationship. The rank of the latter two depends on the attenuation relationship. Choosing a line instead of a zone source produces a large effect when the recurrence interval is large. This may apply to analyses for the Yucca Mountain area, but the experience of this author is that every evaluation is different because of the many variables involved. That the form and standard deviation of the attenuation function are the two most critical factors corroborates the single parameter analyses of Bender (1984) and Atkinson and Charlwood (1983). Rabinowitz and Steinberg (1991) believe their approach allows them to better discern input variable interactions than does a single parameter analysis like that of McGuire and Shedlock (1981). Their conclusion clearly applies to interrelationships between variables ranking just below the most sensitive ones.

A similar approach in PA methodology is the use of Latin Squares or the Latin Hypercube, e.g., Iman et al. (1980). These methods facilitate deriving output from changes in input, without a total recalculation of the problem each time. With approaches like these, recurrence relations are a series of terms with coefficients and exponents, all of which may vary within accepted ranges.

3.2.4 Fault Displacement and Seismic Hazard Curve Generation

The hazard is usually displayed as an annual probability of exceedance of peak acceleration or other ground-motion parameter. This form of hazard representation would also apply to fault displacement. Variability of this curve is in expert opinion limits or a percentile deviation. Sometimes the range is displayed for various numbers of experts employed, e.g., Coppersmith and Youngs (1990c). In each case randomness or mathematical uncertainty of data scatter is carried along with the "personalistic" uncertainty.

3.2.4.1 Methods

Type III probabilistic analyses, similar to the proposal of Yegian (1979), are sufficiently complex that a seismic hazard curve could result. A single model is normally constructed for a given site. A probability distribution is developed from the data used to define the input parameters. Yegian discusses the subjective weight assignment method of Cornell and Merz (1975), however, which is an early example of a multiple-model Type IV procedure. Type IV procedures incorporate expert opinions regarding most aspects of the analysis. This permits any expert's opinion to be input, whatever the rationale's quality. Also discussed is a means for incorporating a fault rupture model. Several derivations in Yegian (1979) are also incorporated in McGuire's EQRISK (1976) and FRISK (1978) programs.

Two extensive Type IV probabilistic analysis procedures have been developed for earthquake applications. They are the LLNL and EPRI studies developed for the eastern U.S. Bernreuter et al. (1987) concluded that the methodologies with the same inputs would produce similar results. The reasons that early results were different are summarized in Section 2.1.4. Although the methods are similar, there are variations in detail. Large differences in the hazard estimates reported by Bernreuter et al. (1984) result from choices in minimum magnitude, type and number of attenuation functions, and expert opinion elicitation rules. However, in analyses reported by Bernreuter et al. (1989b), the minimum magnitude was held to the same value for both methods. There were still significant differences in results. Although not specifically addressed, a potential factor in the difference may be the choice of experts. Details of this method are in the preceding Sections 2.1.2-2.1.4 of this report. Later comparisons of PSHA evaluations (Bernreuter et al. 1989b), in which minimum magnitude was the same, still produced differences of concern (e.g. NRC SECY-92-122).

A possible alternate method to the SOG/EPRI and LLNL expert opinion/analyses is the use of Delphi Theory. In Delphi Theory questions asked must be simple. In some original examples of Delphi, the "experts" were not subject matter experts, but randomly selected respondents. Questions must be carefully posed using rules. Feedback to the panel of "experts" is in two forms: (1) convergence of panel estimates and (2) factual data germane to the problem. Later Rand Corporation analyses continued to elicit opinions in writing only, to avoid interpersonal dynamics. However, they used experts in the subject of the study instead of experts randomly selected from the general population. EPRI and LLNL's analyses also use subject matter experts but do not necessarily adhere to Delphi protocol. In the Delphi process a solution is obtained by noting convergences in opinion, feeding those convergences and additional data back to the experts, and reassessing. Eventually there is convergence on one result. That is, many respondents will have the same result, although there may be many other diverse opinions retained by some experts. The consensus or converged upon result is taken as the answer, usually without consideration of the unconvinced remainder of the panel. Such information as standard deviations, degree of confidence in the result, etc. could be separate Delphi topics.

The Delphi method has had demonstrable successes although it is more cumbersome and expensive to implement than the teams-of-experts used by the SOG/EPRI method in which personal discussions are required within the teams to develop consensus. The Delphi method does not allow personal discussions. Smith and Hytler (1985) quote Dalkey (1969) to summarize Delphi precepts:

> Traditional polling of individual opinions is by face-to-face discussion. Numerous studies by psychologists in the past two decades have demonstrated some serious difficulties with face-to-face interaction. Among the most serious are: (i) Influence by dominant individuals. The group opinion is highly influenced, for example, by the person who talks the most. There is very little correlation between pressure of speech and knowledge. (ii) Noise. By noise is not meant auditory level (although in some face-to-face situations this may be serious enough) but semantic noise. Much of the "communication" in a discussion group has to do with individual and group interests, not with problem solving. This kind of communication, although it may appear problem-oriented, is often irrelevant or biasing. (iii) Group pressure for conformity. In experiments at Rand and elsewhere, it has turned out that, after face-to-face discussions, more often than not the group response is less accurate than a simple median of individual estimates without discussion.

Strict Delphi methodology has not been used in earthquake uncertainty evaluations. Use of the Delphi method, as originally developed, would be more cumbersome for an application requiring uncertainties and probabilities than the methods used by LLNL and SOG/EPRI. The methods so far employed for earthquake problems have entailed the averaging, in some way, of real experts' opinions and their estimated confidences in those opinions.

Acceleration and spatial attenuation functions, used by these methods, seldom incorporate a rational theory for adjusting accelerations in the near-field to account for the finite size and shape of the fault displacements that initiate them. Most attenuation functions arbitrarily accommodate near-field effects with a term that causes a leveling-off of accelerations as a fault is approached. Part of this leveling off is justified because the source area is a zone of slip on a fault plane that is centered at some substantial depth. Therefore, a site is never closer than the depth to the center of the fault displacement area where accelerations are assumed to be the highest. Such attenuation models rarely attempt to distinguish between fault types and their associated stress drops, both of which influence acceleration.

None of the methods attempts to determine probabilities of acceleration based on the radiation patterns known for particular fault types. This effect is substantial and may be accommodated, where the source zone is a known fault, through a modification of the method of Cornell and Merz (1975).

A hazard curve has an additional dimension compared to a probabilistically determined acceleration. That dimension is "exceedance," e.g., Ang and Tang (1984). Instead of a single value of probability and associated acceleration, e.g., the 10,000-year acceleration, there is a curve. Its dimensions are acceleration versus the probability of exceedance per unit time. If a very low probability of exceedance per year is desired, a high value of acceleration will be indicated. Such curves require only one set of source zones and one 'best' attenuation function. The curve results from repeated calculations for different probability levels using, e.g., McGuire's (1976) method. Known data uncertainties may be incorporated. Some uncertainties are difficult to quantify. Examples are differences in opinion concerning source-zone boundaries or extrapolating acceleration attenuation near a fault. This sociological aspect of finding the center and dispersion in opinion has become the focus of Type IV methods.

3.2.4.2 Attendant Uncertainties

The attendant uncertainties with the above method are clearly influenced by intangibles. LLNL experts have more freedom of expression resulting in higher hazards than EPRI's teams. EPRI team expressions of uncertainty in their own opinions are limited to a multiple choice selection. The most influential variables reported in Bernreuter et al. (1987) are the choice of minimum magnitude, use of a site soil correction, and type of attenuation function. Bernreuter et al. (1989b) reports comparisons of later EPRI and LLNL PSHA in which minimum magnitudes are the same. Substantial differences still result, (Bernreuter et al. 1989b) and NRC, (1992). Attenuation functions do not extrapolate to higher magnitudes and close distances in an equally competent manner.

Two problems tend to frustrate accurate extrapolations. Most data come from a few recent large earthquakes. The balance of data are one or a few recordings from each of many small earthquakes. Proposed extrapolations do not use equally effective weighting schemes for these two classes of data. Two recent empirical attenuation functions really do not employ the same variable. The Joyner and Boore (1981) method uses peak horizontal acceleration on one of two horizontal components of a recording instrument. Campbell (1981) uses the average acceleration from the two components of horizontal motion. It is not entirely clear what the stochastic method uses. The spectra from the horizontal component with the peak horizontal acceleration appears to be the definition used. Other measures could be proposed, e.g., the peak-vector-sum acceleration or the peak-horizontal contribution to the peak-vector-sum of three components. When the two PSHA studies use the same data for the most influential variables (Bernreuter et al., 1987), results were more similar for most sites, perhaps remarkably so. Although results in uncertainty varied, they all plotted on the same semi-log scale and usually overlapped one another. Although median LLNL and EPRI hazard curves are similar, the mean and 85th percentile curves vary by as much as half an order of magnitude, (Figure 3-4).

3.2.5 Probabilistic Data Viability Estimates

The viability of estimates for extended periods of time is, in part, a function of the time span of the database used. It is also a function of technology. What appears viable today for an extended period may not be an acceptable approach decades hence. It is also a function of how close the estimate of recurrence patterns and of the maximum earthquake are to reality. If the database encompasses many earthquake cycles as in China and Iran (Persia), a predictive scheme should propagate well into the future. If the database does not encompass a single earthquake cycle, predictive capability is limited and analogs must be employed. The recent idea that earthquakes and faulting may be chaotic processes, for example, Brown et al. (1991), Levi (1990) and Ito (1980) may well change the manner in which probabilities for future events are viewed.

3.2.5.1 Data Viability for a Probability of Occurrence During a 100-Year Period

Two near maximum earthquakes have occurred in California, near San Francisco in 1906 and near Los Angeles in 1857. Consequently, instrumentation is extensive and estimates of earthquake hazard for 100 years hence should be reliable for the San Andreas fault and associated features. Seismic activity rate is high and San Andreas fault characteristics have been investigated since the 1906 earthquake, e.g., Lawson (1908). Paleo-seismic studies are necessary for less seismic areas like the Basin and Range, if hazard estimate reliability is to equal that of California. Ryall and VanWormer, (1980), and Wallace, (1985 and 1987) discuss Basin and Range province paleo-seismicity. They indicate that it ends quickly with a substantial earthquake on a fault, only to resume on another formerly quiet fault. To ensure an accurate 100-year or longer hazard estimate in the Basin and Range, more detailed study is required. In short, this author believes that the viability of Basin and Range hazard analyses, with the current state of knowledge, is only slightly better than for the eastern U.S.

3.2.5.2 Data Viability for a Probability of Occurrence During a 300- to 1000-Year Period

Paleo-earthquake studies of the San Andreas fault in California provide adequate information concerning major past events. Hence, there is reasonable confidence in forecasting future hazard. However, for areas in California where seismicity is not as high, and paleo-studies not as frequent or intensive, there is little knowledge regarding earthquake magnitudes or repetition during the past 300—1000 years. Hazard estimates are virtually unconstrained on features such as the Transverse Ranges, the White Wolf, Garlock, and offshore faults.

For the Basin and Range, sufficient knowledge to make a viable PSHA is lacking without additional paleo-studies and a consensus concerning expected patterns of seismicity. Work on the Yucca Mountain repository by DOE is adding to the knowledge base. Tectonic similarity throughout the Basin and Range province may lend more confidence to predictions than for parts of California where tectonic styles change and are confusing or hidden.

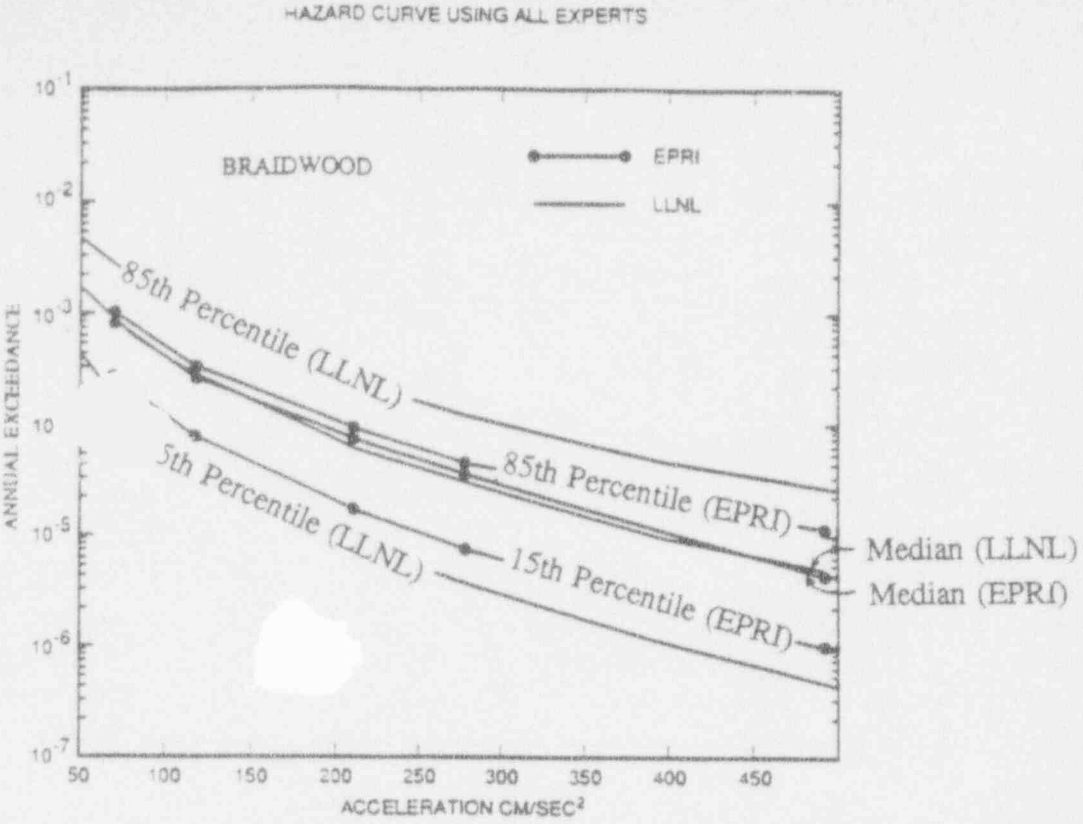


Figure 3-4. Example of spread in hazard results from the SOG/EPRI and LLNL PSHA methods after input variables we [illegible]malized (from Bernreuter et al., 1987)

For the Basin and Range, sufficient knowledge to make a viable PSHA is lacking without additional paleo-studies and a consensus concerning expected patterns of seismicity. Work on the Yucca Mountain repository by DOE is adding to the knowledge base. Tectonic similarity throughout the Basin and Range province may lend more confidence to predictions than for parts of California where tectonic styles change and are confusing or hidden.

3.2.5.3 Data Viability for a Probability of Occurrence During a 10,000-Year Period

This author believes that an important area for investigation is paleo-evidence of broken barriers and how frequently they may occur. In the 10,000-year time range, probabilistic hazard analysis becomes increasingly dependent on geologic history and less on the limited earthquake record. Major features of both California and Basin and Range tectonism have been in place for much longer periods of time than the available seismic record. Cycles of seismicity become important for a 10,000-year period but whether a single cycle exists or has run its course is questionable. Concern over self similarity of earthquakes and faulting begins to have larger potential consequences. Less can be said about characteristic earthquakes and fault segmentation with any confidence. Time related probability distributions become less consequential. The methodology remains the same but major inputs are different. Viable PSHA are possible for the Basin and Range but broad studies are needed to better understand the details of tectonism and estimate a maximum earthquake.

4 CONCLUSIONS AND RECOMMENDATIONS

Conclusions and recommendations are given in sections 4.1 — 4.4. The first two sections discuss the scope and limitations of the present study and the general technical areas that would benefit from prelicensing guidance. Section 4.3 introduces specific recommendations regarding particular technical items consequent to the literature search conducted under this effort. The last section lists several items that would benefit from research or further development in the processes of creating an STP concerning PFD&SHA.

4.1 INTRODUCTION AND QUALIFICATION

Several points regarding this review provide an introduction to and a qualification of the conclusions and recommendations made in this document:

- Items requested for review constitute a large part of earthquake seismology. Consequently, the intent of the study is a general overview and is not an in-depth technical analysis.

- The review attempted to emphasize those elements that may have an impact on development of an STP for PFD&SHA. It is difficult to anticipate which technical items will be important in the future as developments in these areas proceed.

- Several computer codes were cited in the review. It would be beneficial to obtain and examine them. Not all of them are accessible to CNWRA. If this kind of effort is desired, NRC may wish to obtain the codes through its offices.

- This review is extensive. It represents an attempt to review a significant portion of U.S. literature. There may or may not be a significant body of foreign literature on these topics. However, foreign authors publish in U.S. journals to the extent that their published works are usually broadly referenced in U.S. literature. This author believes that there are no oversights of significant work, foreign or domestic in this review.

4.2 TOPICS OF CONCERN IN STP DEVELOPMENT

Several concerns are summarized as conclusions of this review, as listed below. Their impact on a future STP is of a general nature. They are not necessarily specific recommendations but they flag topics to consider in an HLW repository STP.

- Probabilistic fault displacement methods are not well developed nor, consequently, benchmarked in the literature reviewed. Therefore, PFD should be mathematically formalized and its concepts tested.

  The literature reviewed did not indicate the development of a direct probabilistic fault displacement methodology. The literature implied only that PFD analyses could be performed. Only Sommerville et al. (1987) attempted to utilize faulting data directly. Even so, magnitude-moment relations and fault length and width formulae for moment with an assumed stress drop were used in the analysis. Although a potential methodology appears simple, it cannot be tested until it is formulated and data are supplied.

- The chaotic or fractal nature of earthquakes, e.g. Ito (1980), Levi (1990), Scholz and Aviles (1986) and Hirata (1989) suggests that characteristic earthquakes and fault segmentation are time-limited concepts that should always be tested against paleo-fault displacement investigations at each proposed site.

  The concept that barriers or asperities all eventually break suggests that a characteristic earthquake may not define a limiting magnitude over long periods of time. An HLW repository must function over a long period. Therefore, the paleo-faulting record near such a repository should be investigated to determine if barriers have been broken. If they have, the characteristic earthquake concept is not applicable.

- Normal faults are less energetic than strike-slip or reverse faults. This suggests that a Basin and Range specific ground-motion attenuation function may be appropriate. Such a relationship may have to draw on data from other extensional tectonic areas. Paleo-earthquake magnitudes are derived from fault displacement area and stress drop. For dip-slip faulting, stress drops, and the magnitude associated with a given fault area, will be lower than for other types of faulting. This can be verified by observations of recent larger earthquakes in the Basin and Range. However, there probably are not enough strong-motion data from only the Basin and Range to verify a region-specific ground-motion attenuation function.

  Campbell (1982) points out that if ground-motion amplitudes are affected by stress drops, the magnitude of an earthquake derived from such an amplitude is also affected. Therefore, he reasons that stress drop is really not critical in estimating ground-motion parameters. If paleo-faulting data must be used to determine magnitudes, however, stress drop becomes an important parameter. For low stress drops, a larger slip area is required to produce the same magnitude that a smaller slip area would produce with a higher stress drop. Therefore, at least a correction factor to account for this difference should be employed for the Basin and Range tectonic province. Strong-motion data from dip-slip faults are few. Consequently, this reasoning should be checked, if possible, by looking at other parts of the world where such data might be available.

- That two separately developed PSHA methodologies can produce similar results when input variables are constrained suggests that hazard analyses using expert opinion may be workable. However, ground rules should be developed concerning an acceptable span of inputs. Rationales for expert judgments used in PSHA should be acceptable in the same way that rationales supporting a deterministic analysis must be acceptable.

  Expert opinions, if not correct, may have unacceptable results on the outcome of a PFD or PSHA. A wide range of technically unjustified expert opinions may radically increase standard deviations in ground-motion. Therefore, if a greater than mean ground-motion is desired, outliers in opinions can strongly increase the predicted ground motion (see the first 2 paragraphs under the rationale for Section 2.1.7).

4.3 POTENTIAL ITEMS IN STP DEVELOPMENT

In addition to the broader topics of concern discussed in Section 4.2 there are several more specific items for which guidance in an STP may be helpful or which may contribute to establishing staff positions. Several of these items are discussed in the following text.

- If PSHA, as formulated by LLNL and SOG/EPRI, is to be accepted as a generator of licensing criteria for a mined repository, a staff position on restraint of input opinions or a requirement for their rationale should be considered.

  PSHA, as presently defined by LLNL and EPRI, requires expertly estimated parameters and more estimates regarding the expert's confidence in those estimates. Groups of experts are used to define ranges for both parameters and confidences. When probability distributions of data are added to the analysis, uncertainties in risk curves grow even larger. The broader the range of expert opinions permitted, the more likely it is that extremes in probability distributions will contribute to the resultant hazard estimate. Risk will appear to be higher. If estimates are restrained by preselecting experts or limiting their choices of parameters and confidence estimates, resulting hazard curves will be lower and standard deviations reduced. Currently, PSHA does not provide high levels of confidence in results. EPRI and LLNL methodologies are similar. Consequently, a similar median hazard results from similar input restrictions. Different experts were used in the two studies and standard deviations did not remain similar, e.g. Bernreuter et al. (1989b). Whether this difference depends on statistical methodology, the elicitation process, or the choice in experts remains unknown. However, the similarity in median hazard with similar input restrictions suggests that potential restraints are likely topics in an STP. It may be reasonable to limit values to the physically possible or to those that are observed world-wide under similar circumstances.

- Considering the high level of effort for siting at Yucca Mountain, it is not unreasonable to develop a Basin and Range specific STP with attenuation functions or stochastic methodology developed for this province and its peculiarly extensional tectonics.

  If an STP is to have application over a variety of tectonic situations, any restraints should be broad. However, a site or tectonic regime specific strong-motion data set may limit standard deviations to realistic values. A problem with this is that there are fewer data from a particular tectonic province than from global sources. The more limited data may not be statistically significant. The broad database used by Campbell (1986) implies that data are not statistically significant for the Basin and Range province. Additional analysis is required to verify this implication. Dynamic modeling by fault type that simulates available mid- and far-field seismic data will add credibility to near-field predictions. It also may justify the selection of a site-specific attenuation function over the generalized functions available.

- If stochastic methods are used to determine peak acceleration and design spectra, some means of modifying the inherent attenuation function should be required to compare it with available data, e.g. in Sommerville, et al. (1987). This should be addressed by an STP or other staff guidance.

Deterministic analyses pay considerable attention to the applicability of various ground-motion attenuation functions for particular sites. Hanks and McGuire's (1981) procedure implies an attenuation function. That function is not well documented or compared with empirical functions. The Hanks and McGuire attenuation appears adequate for teleseismic use within the limitations of the method. Available literature does not demonstrate its usefulness in the near-field of faulting. Hanks and McGuire's inherent attenuation function should be as thoroughly understood as empirical attenuation functions, if the method is to be applied to an HLW repository.

- "Testing the validity of applications of PSHA is difficult" according to the National Research Council (1988). Therefore, PSHA should remain one of several means of quantifying judgment regarding the probability of seismic hazard and its contribution to radionuclide release. PFD&SHA cannot be a sole criterion for this judgment.

  Reliance on expert opinion in lieu of data does not provide a high level of confidence. PFD&SHA has the advantage of quantifying the spread in expert opinion that a deterministic procedure ignores. For a deterministic procedure, usually a 'best' expert opinion is selected. That opinion may or may not be conservative compared to others but presumably it has the best technical justification. Expert opinions have changed over time and will change over a future 10,000-year time span. Interpretations of the meaning of data, in terms of conceptual models, is also subject to expert opinion. Additional data may not reduce the uncertainties in conceptual models. Data however, remain fact even if ultimately shown to be inadequate. Therefore, data should be strongly weighted compared to opinion, in any ultimate assessment of repository performance.

- Workshops on the variables that contributed significant differences in results between the LLNL and EPRI eastern U.S. seismic risk calculations are one way to further investigate how such variables might be constrained. Some staff who participated in these studies should also be participants in the workshops.

  NRC approved EPRI's and LLNL's methods of determining seismic design criteria at eastern U.S. nuclear power plants, provided they are not used in the near-field. This does not imply similar approval for the western U.S. or for a long-lived geological nuclear waste repository. These methods applied to the eastern U.S. do provide a regulatory background upon which to build a possible Yucca Mountain application. Development of a rationale limiting or not limiting the range of elicited expert opinions might improve credibility in PSHA Type IV analyses. The concept of limiting opinions is unpopular because PSHA can accept all opinions in a democratic fashion with the hope that a reasoned majority will produce a correct answer. However, the much lower probability levels required by a long-lived HLW repository may not allow an unlimited spread in probability distributions and still produce reliable hazard values. There is often an expressed desire for conservatism to be attained by using a standard deviation from the mean or median. A totally democratic procedure for a long-performance-period HLW repository may yield results that are conservative beyond the bounds of all observations be they historic or geologic.

- A staff technical position can request dynamic fault modeling or that an independent assessment be made to validate the applicant's work.

Near-field, dip-slip faulting will be a significant contributor to seismic hazard at Yucca Mountain. Therefore, a resolution of results from separate near-field strong-motion prediction methods should be required.

- Other topics that may influence HLW repository siting and design which could be addressed in an STP include the following:
    - ○ Apply time-dependent probability models including concepts from chaos and fractal theory. This has implications for fault segmentation and characteristic earthquakes that may or may not be resolved on a below-regulatory-concern probability basis. It may be desirable to perform scoping calculations to anticipate whether these concepts should be addressed in an STP applicable to Yucca Mountain. Because seismic activity is low and the 10,000-year period of concern is long, it is not obvious whether time-dependent models are applicable.

    - ○ PFD analyses must show relevance to the mechanisms by which it will affect repository performance. Principal mechanisms for fault displacement are opening of fractures, which increases potential for hydrologic flow, generation of gouge that may divert hydrologic flow, and canister rupture. Such relationships are necessary and should be in probabilistic form. There is little that can be stated in an STP at this time except that such a relationship must be demonstrated by the applicant. NRC staff would be prudent to conduct or support related research because there is a high level of uncertainty and an attendant potential for noncompliance with the regulation.

    - ○ Establish mechanisms for groundwater elevation changes caused by earthquake shaking or attendant changes in rock stress. DOE and others support research in this area. If dynamic computer modeling is employed, the STP should require the modeling to be benchmarked against observations.

    - ○ A proposed model of faulting limits the width or down-dip extent of a large earthquake rupture surface to the depth to the viscous layer. Tectonic modeling efforts, currently under way (e.g. Young et al. 1992) should help establish a bound for fault width. Fault segmentation and characteristic fault displacements require that maximum earthquake calculations be based on fault width and fault-slip area moment. If segmentation concepts are accepted for the 10,000-year period of HLW repository performance, fault width determination may become a critical item. The definition of fault width is the down-dip extent of the fault plane. Based on aftershocks locations of larger Basin and Range earthquakes, the fault width of their sources represents the distance to the elastic/viscous interface, e.g. Boatwright (1984c), and Doser and Smith (1985). This parameter may become critically important. Conversely if the major risk contributors are small faults, which limit maximum magnitude, this concept may not be important. These parameters are potential topics for an STP.

    - ○ Maximum magnitudes may be estimated from the rupture of one segment barrier and two adjacent segments. The area of the combined barrier and adjacent segments plus the fault width allows moment calculation. This estimate may serve as a maximum magnitude on large faults. This concept is a candidate for further development.

- ○ Although there is over an order-of-magnitude acceleration variation relative to azimuth about a fault (a radiation pattern), seismic risk analyses do not consider it. For a given fault or fault segment, the position of a site within the radiation pattern may be described probabilistically. This variable should be addressed and should be required by the STP.
- ○ The maximum magnitude earthquake that could be caused by mining the repository. Formulations are given by McGarr (1976 and 1991).

These technical items are considerations in the performance potential of Yucca Mountain. Some of them are discussed further as potential research topics. These items are not adequately addressed in the literature and are therefore identified here as topics that eventually could be covered in an STP or other staff/guidance.

4.4 POTENTIAL RESEARCH TASKS

This review suggests several areas that require further definition, clarification, or formalization in Staff Technical Position on PFD&SHA applicable to Yucca Mountain. That there are few examples of expert-opinion use in PFD analyses compared to PSHA contributes to these areas.

Examples of PSHA in the western U.S. are Coppersmith and Youngs (1990c) for a Pacific Northwest site and the Diablo Canyon nuclear power plant study by Pacific Gas and Electric (PG&E), reported in NRC (1991). The latter reference became available at the time of this report revision. A discussion of expert opinion does not appear in the NRC (1991) Safety Evaluation Report. However, it is likely that experts were used to carry out the PG&E event-tree/fault-tree approach. Coppersmith and Youngs (1990c) also used an event tree approach in which 14 experts estimate probabilities of various fault mechanism scenarios, maximum magnitude earthquakes, etc. They do not reference a computer code for manipulation of expert opinion data. Unpublished studies for DOE facilities in Idaho and Washington may exist. No published PSHA or PFD analyses are extant for the Basin and Range tectonic province where fault traces are often observable on the surface or detectable by geophysical methods. However, Beavers, et al. (1990) present PSHA efforts for DOE facilities in the midwest. There is precedent for analysis of geologic faults using event-tree methods. However, paleo-faulting data augments seismicity data rather than directly supporting reconstruction of seismic or fault displacement history. A list of potential research items which also are potential STP or STP amendment items regarding PFD&SHA follows.

- Evaluate Type IV PSHA methodologies for application to a long-lived mined repository.

  Published Type IV methodologies are only for short-lived nuclear facilities, e.g., several decades. Effects of high standard deviations, associated with expert opinion uncertainties, have not been evaluated for seismic or faulting hazards over the much longer periods required for a mined repositor,. High uncertainties may render these longer time span hazard estimates too unreliable for use in regulating a mined repository.

- Evaluate the adequacy of stochastic models to synthesize ground-motion or fault slip and compare results to those obtained by other methods.

The stochastic method under consideration by the ASCE as a design standard has not been broadly tested. Certain elements of the methodology have been widely used by seismologists. However, the efficacy of the method for nuclear facility siting has not been benchmarked. The same may be said for the other methods listed by Aki (1984), (see Section 2.1.5.1).

- Search for analog earthquakes to aid in the evaluation of groundwater changes that have accompanied earthquakes and that may accompany earthquakes at Yucca Mountain.

  There are many variables that could effect a rise in groundwater caused by strain changes accompanying an earthquake. Investigation of a historic analog event with similar source and site properties to the anticipated event may improve understanding of this phenomenon. So little has been studied concerning changes in groundwater elevation occurring with earthquakes that a broad program of study could be undertaken. At least one such program is said to be under way, Wood (1991). An investigation into suitable analogous earthquakes with hydrologic changes should provide some preparation for evaluating submissions on this topic.

- Formalize probabilistic fault displacement procedures. It may be appropriate to establish an agreed-upon approach and create or modify an existing computer code as an aid to statistical calculation and aggregation of results.

  See the rationale for the first item under Section 4.2. It is repeated here as a potential research or development effort. It could also be carried out as part of STP development.

- Develop the probabilities and conditions for the formation of fault gouge or for more highly permeable conduits consequent to fault slip. This could be an extensive effort that would interface with the ongoing Seismic Rock Mechanics Research Project at CNWRA.

  The literature searched reports no information concerning the amount, number, or characteristics of movements required to generate hydrologic-flow-resisting gouge. Ideally, information should be obtained from Basin and Range dip-slip faults if it is to be applied to Yucca Mountain.

- Perform a scoping calculation to improve viability of PSHA estimates for various periods of time. The calculation would include historic seismicity, paleo-faulting studies, and geodetic and geologic estimates of Basin and Range extension. If the calculated potential for seismic risk over 10,000 years is low, viability of HLW repository analyses may be equivalent to that for shorter lived nuclear power stations. Sommerville, et al. (1987) and Rogers et al. (1977) report some efforts in this area. Rogers et al. (1987) depict contours of seismic energy release for the historical record. Schedlock et al. (1980), for example, use seismic moment to determine slip rate. An inverse of this type of analysis could produce seismic moment from slip. The proposed study would use these works as a starting point. A probability estimate based on a random distribution of regional extension over major fault zones of the Basin and Range tectonic province for 10,000 years would be added to the risk assessment parameters.

Without such a calculation, estimates of the viability of PSHA calculations are largely a matter of opinion. That consensus among scientists can change over a span of a few years makes this kind of estimate difficult. The usefulness of such estimates is site dependent.

5 SELECTED BIBLIOGRAPHY

Abrahamson, N.A., and J.J. Liteheiser. 1989. Attenuation of vertical peak acceleration. *Bulletin of the Seismological Society of America (BSSA)* 79:549-567.

Abrahamson, N.A., J.F. Schneider, and J.C. Stepp. 1990a. Spatial variation of strong motion for use in soil-structure interaction analyses. *Proceeding of the Fourth U.S. National Conference on Earthquake Engineering*. Vol. 1. El Cerrito, CA:EERI:317-326.

Abrahamson, N.A., P.G. Sommerville, and C.A. Cornell. 1990b. Uncertainty in numerical strong motion predictions. *Proceedings of the Fourth U.S. National Conference on Earthquake Engineering*. Vol 1. El Cerrito, CA:EERI:407-416.

Aki, K. 1956. Some problems in statistical seismology. *Zisn (Japanese)*. 8:205-228.

Aki, K. 1982. Strong motion prediction using mathematical modeling techniques. *BSSA* 72:S29-S41.

Aki, K. 1984. Asperities, barriers, characteristic earthquakes and strong motion prediction. *Journal of Geophysical Research (JGR)* 89B:5867-5872.

Aki, K. 1985. An overview and issues: Review of simulation procedures. *Strong Ground Motion Simulation and Application*. Pub. No. 85-02. R.E. Scholl and J.L. King, eds. El Cerrito, CA: EERI.

Aki, K. 1987. Magnitude-frequency relation for small earthquakes: A clue to the origin of f_{max} of large earthquakes. *JGR* 92B:1349-1355.

Aki, K., and P.G. Richards. 1980. *Quantitative Seismology*. Vols. 1 and 2. San Francisco, CA: W.H. Freeman.

Algermissen, S.T., D.M. Perkins, P.C. Thenhaus, S.L. Hanson, and B.L. Bender. 1982. *Probabilistic Estimates of Maximum Acceleration and Velocity in Rock in the Conterminous United States*. USGS Open-File Report (OFR) 82-1033. Washington, DC: Department of the Interior.

Anagnos T., and A.S. Kiremidjian. 1984. Time-predictable model of earthquake occurrence. *BSSA* 74:2593-2611.

Anderson, J.G. 1979. Estimating the seismicity from geological structure for seismic-risk studies. *BSSA* 69:135-158.

Anderson, J.G. 1991. Strong motion seismology: Reviews of Geophysics, Supplement. *U.S. National Report to International Union of Geodesy and Geophysics 1987-1990*. Washington, DC: AGU:700-720.

Anderson, J.G., and J.E. Luco. 1983. Consequences of slip rate constraints on earthquake occurrence relations. *BSSA* 73:471-496.

Anderson, J.G., and S.E. Hough. 1984. A model for the shape of the Fourier amplitude spectrum of acceleration at high frequencies. *BSSA* 74:1969-1993.

Andrews, D.J. 1980. A stochastic fault model, 1. Static case. *JGR* 85B:3867-3877.

Andrews, D.J. 1981. A stochastic fault model, 2. Time dependent case. *JGR* 86B:10821-10834.

Ang, A.H.S., and W.H. Tang. 1984. *Probability Concepts in Engineering Planning and Design. Volume II - Decision, Risk, and Reliability.* New York, NY: John Wiley and Sons.

Apsel, R.J., D.M. Hadley, and R.S. Hart. 1983. *Effects of Earthquake Rupture Shallowness and Local Soil Conditions on Simulated Ground Motion.* NUREG/CR-3102, UCRL-15495. Washington, DC: NRC.

Archuleta, R.J. and G.A. Frazier. 1978. Three dimensional simulation of dynamic faulting in a half-space. *BSSA* 18:541-572.

Atkinson, G.M. 1984. Attenuation of strong ground motion in Canada from a random vibrations approach. *BSSA* 74:2629-2653.

Atkinson, G.M., and R.G. Charlwood. 1983. Uncertainties in probabilistic seismic hazard assessment as a function of probability level: A case history of British Columbia. *BSSA* 73:1225-1241.

Bakun, W.H., and A.G. Lindh. 1977. Local magnitudes, seismic moments and coda durations for earthquakes near Oroville, California. *BSSA* 67:615-629.

Bard, P.-Y. and M. Bouchon. 1980. The seismic response of Sediment Filled Valleys, Part I. *BSSA* 70:1263-1286.

Beavers, J.E., R.D. Hatcher, and R.J. Hunt. 1990. The Application of the Electric Power Research Institute (EPRI) and the Lawrence Livermore National Laboratory (LLNL) seismic hazard methodologies at two nonreactor sites. *Seismological Research Letters* 61.

Beltrami, H., D. Lavallée, C. Hooge, S. Lovejoy, D. Schertzer, and C.J. Mareschal. 1991. Abstract for the April 23rd AGU meeting in Washington DC: Universal multifractals in earthquakes. EOS, 1991 Spring Meeting Supplement.

Bender, B. 1984. Seismic hazard estimation using a finite-fault rupture model. *BSSA* 74:1899-1923.

Bender, B. 1986. Modeling source zone boundary uncertainty in seismic hazard analysis. *BSSA* 76:329-341.

Bender, B., and D.M. Perkins. 1982. *SEISRISK II - A Computer Program for Seismic Hazard Estimation*. USGS OFR 82-293. Washington, DC: Department of Interior.

Bender, B., and K.W. Campbell. 1989. A note on the selection of minimum magnitude for use in seismic hazard analysis. *BSSA* 79:199-204.

Bender, M. 1977. *Memorandum from M. Bender, Chairman of the ACRS to Marcus A. Rowden, Chairman of the US Nuclear Regulatory commission, Subject Report on Perkins Nuclear Station, Units 1, 2, and 3 and Cherokee Nuclear station, Units 1, 2 and 3.* Dated April 14. Washington DC: NRC.

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

Bernreuter, D.L., J.B. Savy, R.W. Mensing, J.C. Chen, and B.C. Davis. 1985. *Seismic Hazard Characterization of the Eastern United States*. UC/LLNL UCID 2041, V 1 and 2. Livermore, CA: LLNL.

Bernreuter, D.L., J.B. Savy, and R.W. Mensing. 1987. *Seismic Hazard Characterization of the Eastern United States: Comparative Evaluation of the LLNL and EPRI studies*. NUREG/CR-4885. Washington, DC: NRC.

Bernreuter, D.L., J.B. Savy, R.W. Mensing, and J.C. Chen. 1989a. *Seismic hazard characterization of 69 Nuclear Plant Sites East of the Rocky Mountains* NUREG/CR-5250 (UCID-21517) V 6 and 7. Washington DC: NRC.

Bernreuter, D.L., J.B. Savy, and R.W. Mensing. 1989b. *Seismic Hazard Characterization of the Eastern United States: Comparative evaluation of the LLNL (Lawrence Livermore National Laboratory) and EPRI (Electric Power Research Institute) studies*. NUREG/CR-4885 (UCID-20696). Washington DC: NRC.

Berrill, J.B., and R.O. Davis. 1980. Maximum entropy and the magnitude distribution. *BSSA* 70:1823-1831.

Bingham, F.W., and G.E. Barr. 1979. *Scenarios for Long-Term Release of Radionuclides from a Nuclear Waste Repository in the Los Medanos Region of New Mexico*. SAND78-1730. Albuquerque, NM: SNL.

Blackman, R.B., and J.W. Tukey. 1958. *The Measurement of Power Spectra.* New York, NY: Dover Publications.

Bloom, E.D., and R.C. Erdmann. 1980. The observation of a universal shape regularity in earthquake frequency-magnitude distributions. *BSSA* 70:349-362.

Blume, J.A., R.L. Sharpe, and J.S. Dalal. 1972. *Recommendations of Shape of Earthquake Response Spectra*. WASH-1254. Washington, DC: U.S. Atomic Energy Commission.

Boatwright, J. 1980. A spectral theory for circular seismic sources: simple estimates of source dimensions, dynamic stress drop and related seismic energy. *BSSA* 70:1-27

Boatwright, J. 1982. A dynamic model for far-field accelerations. *BSSA* 72:1049-1068.

Boatwright, J. 1984a. Seismic estimates of stress release. *JGR* 89B:6961-6968.

Boatwright, J. 1984b. The effect of rupture complexity on estimates of source size. *JGR* 89B:1132-1146.

Boatwright, J. 1984c. Aftershock sequence of the Borah Peak. Idaho Earthquake. *BSSA* 15:1205-1284.

Boatwright, J., and D.M. Boore. 1982. Analysis of the ground accelerations radiated by the 1980 Livermore Valley earthquakes for directivity and dynamic source characteristics. *BSSA* 72:1843-1865.

Bolt, B.A., and N.A. Abrahamson. 1982. New attenuation relations for peak and expected accelerations of strong ground motion. *BSSA* 72:2307-2321.

Bonilla, M.G. 1985. *Surface Faulting Studies:* USGS OFR 85-464. Washington DC: Department of the Interior.

Bonilla, M.G., R.K. Mark, and J.J. Lienkaemper. 1984. Statistical relations among earthquake magnitude, surface rupture length, surface fault displacement. *BSSA* 74:2379-2411.

Boore, D.M. 1972. A note on the effect of simple topography on seismic SH waves. *BSSA* 62:275-284.

Boore, D.M. 1983a. Strong-motion seismology. *Reviews of Geophysics, Supplement: U.S. National Report to International Union of Geodesy and Geophysics 1979-1982.* Washington DC: AGU:1308-1318.

Boore, D.M. 1983b. Stochastic simulation of high-frequency ground motions based on seismological models of the radiated spectra. *BSSA* 73:1865-1984.

Boore, D.M. 1986. Short period P- and S-wave radiation from large earthquakes: Implications for spectral scaling relations. *BSSA* 76:43-64.

Boore, D.M., and G.M. Atkinson. 1987. Stochastic prediction of ground motion and spectral response parameters at hard-rock sites in Eastern North America. *BSSA* 77:440-467.

Boore, D.M., and W.B. Joyner. 1982. The empirical prediction of ground motion. *BSSA* 72:S269-S286.

Borcherdt, R.D., G. Glassmoyer, A. Der Kiureghian, and E. Cranswick. 1989. *Results and Data from the Seismologic and Geologic Studies Following Earthquakes of December 7, 1988 near Spitak, Armenia, SSR.* USGS OFR 89-163A. Washington, DC: Department of the Interior.

Bouchon, M. 1978. A dynamic source model for the San Fernando earthquake. *BSSA* 68:1555-1576.

Bouchon, M., and K. Aki. 1980. Simulation of long-period, near-field motions for the Great California Earthquake of 1857. *BSSA* 70:1669-1682.

Brillinger, D.R. 1982. Seismic Risk Assessment: Some Statistical Aspects. *Earthquake Prediction Research* 1:182-195.

Brillinger, D.R. 1985. *Review of Draft EPRI/SOG Report: Seismic Hazard Methodology for Nuclear Facilities in the Eastern United States.* Consulting report to the USGS. Washington, DC: Department of the Interior.

Brillinger, D.R., and H.K. Preisler. 1984. An exploratory analysis of Joyner-Boore attenuation data. *BSSA* 74:1441-1450.

Brown, S.R. 1987. A note on the description of surface roughness using fractal dimension. *Geophysical Research Letters* 14:1095-1098.

Brown, S.R., C.H. Scholz, and J.B. Rundle. 1991. A simplified spring-block model of earthquakes. *Geophysical Research Letters* 18:215-218.

Brune, J.N. 1968. Seismic moment, seismicity and rate of slip along major fault zones. *JGR* 73:777-784.

Brune, J.N. 1970. Tectonic stress and the spectra of seismic shear waves. *JGR* 75-B:4997-5009.

Brune, J.N. 1991. Seismic source dynamics, radiation and stress. *Reviews of Geophysics, Supplement: U.S. National Report to International Union of Geodesy and Geophysics 1987-1990.* Washington, DC: AGU: 688-699.

Burridge, R., and L. Knopoff. 1967. Model and theoretical seismicity. *BSSA* 57: 341-371.

Callender, J. 1989. Tectonics and seismicity. *Techniques for Determining Probabilities of Events and Processes Affecting the Performance of Geologic Repositories, Literature Review.* Vol. 1. R.L. Hunter and C.J. Mann, eds. SAND86-0196 NUREG/CR-3964. Washington, DC: NRC:89-126.

Campbell, K.W. 1981. Near source attenuation of acceleration. *BSSA* 71:2039-2070.

Campbell, K.W. 1982. A preliminary methodology for the regional zonation of peak ground attenuation. *Proceedings of the 3rd Microzonation Conference,* Seattle, Washington. 1:365-376.

Campbell, K.W. 1985. Strong motion attenuation relations: A ten year perspective. *Earthquake Spectra.* 1:759-804.

Campbell, K.W. 1987. Predicting strong ground motion in Utah. W.W. Hays and P.L. Gori, eds. *Evaluation of Regional and Urban Earthquake Hazards and Risk in Utah.* USGS Professional Paper 87-585II, L1-L90. Washington, DC: Department of the Interior.

Campbell, K.W. 1989. The dependence of peak horizontal acceleration on magnitude, distance, and site effects for small magnitude earthquakes in California and Eastern North America. *BSSA* 79:1311-1346.

Carlson, J.M. 1991. Time intervals between characteristic earthquakes and correlations with smaller events: An analysis based on a mechanical model of a fault. *JGR* 96B:4225-4267.

Chinnery, M.A. 1969. Theoretical fault models. *A Symposium on Processes in the Focal Region*. Vol. 37. K. Kasahara and A.E. Stevens, eds. Ottowa, Canada: Dominion Observatory:211-223.

Chinnery, M.A. 1978. Measurement of m_b with a global network. *Tectonophysics*. 49:139-144.

Chouet, B., K. Aki, and M. Tsujiura. 1978. Regional variation of the scaling law of earthquake source spectra. *BSSA* 68:49-79.

Cohee, B.P, P.G. Summerville and N.A. Abrahamson. 1990. Simulated ground motion from subduction earthquake in the Pacific N.W. *Proceedings of the Fourth U.S. National Conference on Earthquake Engineering*. Vol 1. EL Cerrito, California: EERI:567-576.

Coppersmith, K.J., and R.R. Youngs. 1990a. Improved methods for seismic hazard analysis in the western United States. *Proceedings of Fourth U.S. National Conference on Earthquake Engineering*. Vol. 1. El Cerrito, CA: EERI:723-732.

Coppersmith, K.J., and R.R. Youngs. 1990b. Earthquakes and tectonics. *Demonstration of a Risk-Based Approach to High-Level Waste Repository Evaluation*. EPRI NP-7057. R.K. McGuire, Principal Investigator. Palo Alto, CA: EPRI.

Coppersmith, K.J., and R.R. Youngs. 1990c. Probabilistic seismic-hazard analysis using expert opinion; An example from the Pacific Northwest. *Reviews in Engineering Geology: Neotectonics in Earthquake Evaluation*. Vol. III. E.L. Krinitzsky and B.B. Slemmons, eds. Boulder, CO: GSA:29-46.

Coppersmith, K.J., and R.R. Youngs. 1991. Modeling fault rupture hazard for the proposed repository at Yucca Mountain, Nevada. (Abstract) *Seismological Research Letters* 62:54.

Cornell, C.A. 1968. Engineering seismic risk analysis. *BSSA* 58:1583-1606.

Cornell, C.A., and H.A. Merz. 1975. Seismic risk of Boston. *Journal of the Structural Division ASCE* 101:2027-2043.

Cornell, C.A., and N.M. Newmark. 1978. On the seismic probability of nuclear power plants. *Proceedings of the American Nuclear Society Topical Meeting on Probabilistic Analysis of Nuclear Reactor Safety*. Vol. 3: XXIVI-1—1-14.

Cornell, C.A., and G. Toro. 1989. Seismic hazard assessment. *Techniques for Determining Probabilities of Events and Processes Affecting the Performance of Geologic Repositories: Literature Review*. R.L. Hunter, and C.J. Mann, eds. SANDS86-0196, NUREG/CR-3964, Vol. 1. Washington, DC: NRC.

Cornell, C.A., and E.H. Vanmarcke. 1969. The Major Influence of Seismic Risk. *Proceedings, 4th World Conference on Earthquake Engineering*. Santiago Chile 1:69-83.

Cornell, A., and S.R. Winterstein. 1988. Temporal and magnitude dependence in earthquake recurrence models. *BSSA* 78:522-1537.

Cornell, A., and S.R. Winterstein. 1989. Reply to C. Lomnitz's comment on temporal and magnitude dependence in earthquake recurrence models. *BSSA* 79:1663-1664.

Cosentino, P., V. Ficara, and D. Luzio. 1977. Truncated exponential frequency-magnitude relationship in earthquake statistics. *BSSA* 67:1615-1623.

Cranwell, R.M., J.E. Campbell, and S.E. Stuckuash. 1982 *Risk Methodology for the Geologic Disposal of Radioactive Waste:* The DUET Computer Code User Manual. SAND 81-1663, NUREG/CR,. Albuquerque, NM.

Cranwell, R.M., R.W. Guzowski, J.E. Campbell, and N.R. Ortiz. 1990. *Risk Methodology for Geologic Disposal of Radioactive Waste - Scenario Selection Procedure.* SAND80-1429, NUREG/CR-1667. Washington, DC: NRC.

Crone, A.J., and K.M. Haller. 1991. Segmentation and the coseismic behavior of basin and range normal faults: Examples from East-Central Idaho and Southwestern Montana, USA. *Journal of Structural Geology* 13:151-164.

Crutchfield, J.P., J.D. Farmer, N.H. Packard, and R.S. Shaw. 1986. Chaos. *Scientific American* 255:46-57.

Dalkey, N.C. 1969. *The Delphi Method; An Experimental Study of Group Opinion.* Memorandum RM-5888 PR. Santa Monica, CA: Rand Corporation.

Davidson, F.C., Jr., and C.H. Scholz. 1985. Frequency-moment distribution of earthquakes in the Aleutian arc: A test of the characteristic earthquake model. *BSSA* 75:1349-1361.

Davis, P.M., D.D. Jackson, and Y.Y. Kagan. 1989. The longer it has been since the last earthquake, the longer the expected time till the next? *BSSA* 79:1439-1456.

dePolo, C.M., and D.B. Slemmons. 1990. Estimation of earthquake size for seismic hazards. *Reviews in Engineering Geology: Neotectonics in Earthquake Evaluation Vol. VIII.* E.L. Krinitzsky and B.B. Slemmons, eds. Boulder, CO: GSA: 8:1-28.

dePolo, C.M., D.G. Clark, D.B. Slemmons, and A.R. Ramelli. 1991. Historical surface faulting in the basin and range province, Western North America: Implications for fault segmentation. *Journal of Structural Geology* 13:123-136.

Di Bona, M., and A. Rovelli. 1988. Effects of bandwidth limitation on stress drops estimated from integrals of the ground motion. *BSSA* 78:1818-1825.

Donath, F.A., and R.M. Cranwell. 1981. Probabilistic treatment of faulting in geologic media. *Mechanical Behavior of Crustal Rocks: Handin Volume. Geophysical Monograph 24.* N.L. Carter, M. Friedman, J.M. Logan, and D.W. Stearns, eds. Washington, DC: AGU:231-241.

Donovan, N.C. 1982. Strong motion attenuation equations - A critique. *Proceedings of the 3rd International Earthquake Microzonation Conference.* V 1. Seattle, WA:377-388.

Doser, D.I., and R.B. Smith. 1985. Source parameters of the 28 October 1983 Borah Peak, Idaho earthquake, from body wave analysis. *BSSA* 75:1041-1051.

Doser, D.I., and R.B. Smith. 1989. An assessment of source parameters of earthquakes in the cordillera of the Western United States. *BSSA* 79:1383-1409.

Dunbar, W.S., and R.G. Charlwood. 1991. Empirical methods for the prediction of response spectra. *Earthquake Spectra* 7:333-353.

EERI Committee on Seismic Risk (McGuire et al.). 1989. The basics of seismic risk analysis. *Earthquake Spectra* 5:675-702.

EPRI. 1988. *Seismic Hazard Methodology for the Central and Eastern United States, Volume 1, Part 1: Theory and Part 2: Methodology (Revision 1).* EPRI NP-4726. Palo Alto, CA: EPRI.

Esteva, L. 1974. Geology and probability in the assessment of seismic risk. *Proceedings of the 2nd Congress of the International Association of Engineering Geology (IAEG).* Paris, France: IAEG.

Esteva, L. 1976. Developments in geotechnical engineering ser.: 15. *Seismic and Risk Engineering Decisions*. New York, NY: Elsevier.

Fitzell, T.P. 1978. *Seismic Risk in the Lower Mainland Region of Western Canada*. MS Thesis. London, England: Univ. of London, Imperial College of Science and Technology

Frangopol, D.M. and K. Hong. 1990. A probabilistic-fuzzy model for seismic hazard applied to the Wasatch Front Range in Utah. *Proceedings of the 4th U.S. National Conference on Earthquake Engineering*. 20-24 May 1990, Palm Springs, CA. El Cerrito, CA: EERI.

Frankel, A. 1991. High-frequency spectral falloff of earthquakes, fractal dimension of complex rupture, b value, and the scaling strengths on faults. *JGR* 96B:6291-6302.

Galanopoulos, A.G. 1988. A new version of earthquake recurrence model. *BSSA* 78:1375-1379.

Gangi, A.F. 1978. Variation of whole and fractured porous rock permeability with confining pressure. *International Journal of Rock Mechanics and Mining Science* 15: 249-257.

Gans, P.B. 1991. Extensional rates in the basin and range province. *Seismological Research Letters* 62:44.

Gariel, J.C., and M. Campillo. 1989. The influence of the source on the high-frequency behavior of the near-field acceleration spectrum: A numerical study. *Geophysical Research Letters* 16:279-282.

Gomberg, J. 1991a. Seismicity and shear strain in the southern great basin of Nevada and California. *JGR* 96B: 16383-16399.

Gomberg, J. 1991b. Seismicity and detection location threshold in the southern Great Basin seismic network. JGR 96B:16401-16414.

Green, G. 1839. On the laws of reflection and refraction of light at the common surface of two non crystallized media. Cambridge Philosophical Society Transactions. Vol. 7.

Greensmith, J.T. and J.C. Gutmanis. 1990. Aspects of the late Holocene depositional history of the Dungeness area, Kent. *Proceedings of the Geologists Association*. 101:225-237.

Grosenbaugh, M., and A. Lindh. 1978. The spatial distribution of seismicity near Parkfield, California: 1969-1976. *Earthquake Notes* 49:41.

Gumbel, E.J. 1954. *Statistical Theories of Extreme Values and Some Practical Applications*. National Bureau of Standards (NBS) Applied Mathematics Series, No. 33. Washington DC: NBS.

Gunter, F. 1977. *Principles of Isotope Geology*. New York, NY: John Wiley & Sons.

Gutenberg, B., and C.F. Richter. 1956. Earthquake magnitude, intensity, energy and acceleration. *BSSA* 32:163.

Hanks, T.C. 1982. f_{max}. *BSSA* 72:1867-1879.

Hanks, T.C., and H. Kanamori. 1979. A moment magnitude scale. *Journal of Geophysical Research* 84-B:2348-2350.

Hanks, T.C., and R.K. McGuire. 1981. The character of high frequency strong ground motion. *BSSA* 71:2071-2075.

Hanks, T.C., and D.M. Boore. 1984. Moment magnitude relations in theory and practice. *JGR* 89B:6229-6235.

Hartzell, S.H., and T.H. Heaton. 1988. Failure of self-similarity for large ($M_w > 8.25$) earthquakes. *BSSA* 78:478-488.

Heaton, T.H., and R.E. Heaton. 1989. Static deformations from point forces and force couples located in welded elastic poissonian half-spaces: Implications for seismic moment tensors. *BSSA* 79:813-841.

Heaton, T.H. and H. Kanamori. 1984. Seismic potential associated with subduction in the northwestern United States. BSSA 71:933-941.

Herrmann, R.B., and O.W. Nuttli. 1985. Regional variation in ground motion attenuation: Current models, consequences, and problems. *Strong Ground Motion Simulation and Earthquake Engineering Applications: A Technological Assessment*. EERI Publication 85-02. Oakland, CA: EERI: 13-1—13-9.

Hirata, T. 1989. A correlation between the b value and the fractal dimension of earthquakes. *JGR* 94B:7507-7514.

Hofmann, R.B. 1969. Geodimeter and laser ranging measurements across the San Andreas fault system. *Laser Applications in the Geosciences*. J. Gauger and F.F. Hall, eds. Huntington Beach, CA: McDonnell Douglas.

Hofmann, R.B. 1974. *Factors in the Specification of Ground Motions for Design Earthquakes in California*. Report No. 3, Miscellaneous Paper S-73-1 series: State-of-the-Art for Assessing Earthquake Hazards in the United States. Vicksburg, MS: U.S. Army Corps of Engineers Waterways Experiment Station.

Hofmann, R.B., K.F. Jones, G.W. Rawlings, and N.R. McCammon. 1982. *Seismic Analysis for Proposed LNG Site; Grassy Point, British Columbia*. Consulting report to Associated-Kellogg Ltd. and Dome Petroleum Ltd., Vancouver, B.C., Canada: Golder Assoc. Ltd.

Horowitz, F. 1988. Mixed states variable friction laws: Some implications for experiments and a stability analysis. *Geophysical Research Letters*. 15:1243-1246.

Horowitz, F., and A. Ruina. 1989. Slip patterns in a spatially homogeneous fault model. *JGR* 94B:10279-10298.

Houston, H., and H. Kanamori. 1990. Comparison of strong motion spectra with teleseismic spectra for three magnitude 8 subduction-zone earthquakes. *BSSA* 80:913-934.

Hough, S.E., and J.G. Anderson. 1989. Attenuation in Western Nevada: Preliminary results from earthquake and explosion sources. *Geophysical Research Letters* 16:207-210.

Hunter, R.L. 1983. *Preliminary Scenarios for the Release of Radioactive Waste from a Hypothetical Repository in Basalt of the Columbia Plateau*. SAND83-1342, NUREG/CR-3353. Albuquerque, NM: SNL.

Hunter, R.L., and C.J. Mann. 1990. *Techniques for Determining Probabilities of Events and Processes Affecting the Performance of Repositories*. SAND86-0020, NUREG/CR-3964. Albuquerque, NM: SNL.

Ida, Y. 1973. The maximum acceleration of seismic ground motion. *BSSA* 63:959-968.

Ito, K. 1980. Periodicity and chaos in great earthquake occurrence. JGR 85:1379-1408.

Iman, R.M., W.J. Conover, J.E. Campbell. 1980. *Risk Methodology for Geologic Disposal of Radioactive Waste: Small Sample Sensitivity Analysis Techniques for Computer Models, with an Application to Risk Assessment.* NUREG/CR 1397. Washington, DC: NRC.

Jarpe, S.P., L.J. Hutchings, T.F. Hauk, and A.F. Shakal. 1989. Selected strong- and weak-motion data from the Loma Prieta earthquake sequence. *Seismological Research Letters* 60:167-176.

Jeffries, H. and B.S. Jeffries. 1956. Mathematical Physics. London, Cambridge University Press.

Johnston, A.C., and S.J. Nava. 1985. Recurrence rates and probability estimates for the new Madrid seismic zone. *JGR* 90B:6737-6753.

Joyner, W.B. 1984. A scaling law for the spectra of large earthquakes. *BSSA* 74:1167-1188.

Joyner, W. B. 1991. Directivity for non-uniform ruptures. *BSSA* 81:1391-1395.

Joyner, W.B., and D.M. Boore. 1981. Peak horizontal acceleration and velocity from strong motion records including records from the 1979 Imperial Valley earthquake. *BSSA* 71:2011-2038.

Joyner, W.B. and D.M. Boore. 1988. Measurement, characterization, and prediction of strong ground motion. *Proceedings, Earthquake Engineering and Soil Dynamics II*, GT Div./ASCE, Park City Utah:43-102.

Kagan, Y.Y., and L. Knopoff. 1980. Spatial distribution of earthquakes: The two-point correlation function. *Geophysical Journal of the Royal Astronomical Society* 62:303-320.

Kameda, H., and Y. Ozaki. 1979. A Renewal Process Model for Use in Seismic Risk Analysis. *Memoirs of the Faculty of Engineering Kyoto University* XLI:11-15.

Kana, D.D., B.H. Brady, B.W. Vanzant, and P.K. Nair. 1991. *Critical Assessment of Seismic and Geomechanics Literature Related to a High-Level Nuclear Waste Underground Repository*. NUREG/CR-5400, CNWRA 89-001. Washington, DC: NRC.

Kanamori, H. 1977. The energy release in great earthquakes. *JGR* 82B:2981-2987.

Kanamori, H. 1979. A semi-empirical approach to prediction of long-period ground motions from great earthquakes. *BSSA* 69:1645-1670.

Kanamori, H., and D.L. Anderson. 1975. Theoretical basis of some empirical relations in seismology. *BSSA* 65:1073-1075.

Kanamori, H., and G.S. Stewart. 1978. Seismological aspects of the Guatemala earthquake of February 4, 1976. *JGR* 83B:3427-3434.

Kandel, A., and J. Byatt. 1980. Fuzzy procedures. *International Journal of Fuzzy Sets Systems* 4:117.

Kane, M.F. 1977. *Correlation of Major Eastern Earthquake Centers with Mafic/ Ultramafic Basement Masses*. USGS Prof. Paper 1028. Washington, DC: Department of the Interior: 151-166.

Kasahara, J. 1981. *Earthquake Mechanics*. Cambridge, England: Cambridge University Press: 248.

Kawase, H., and K. Aki. 1990. Topographic effect at the critical SV-wave incidence: Possible explanation of damage pattern by the Whittier Narrows, California, earthquake of 1 October 1987. *BSSA* 80:1-22.

Kawashima, K.K., K. Aizawa, and K. Takahashi. 1984. Attenuation of peak ground motion and absolute acceleration response spectra. *Proceedings 8th World Conference on Earthquake Engineering*. El Cerrito, CA: EERI.

Keilis-Borok, V.I. 1957. On the estimation of the displacement in an earthquake source and of source dimensions. *Annali di Geofisica* 12:205-214.

Keilis-Borok, V.I. 1990. The lithosphere of the earth as a nonlinear system with implications for earthquake prediction. *Reviews of Geophysics* 28:19-34.

Kijko, A., and M.A. Sellevol. 1981. Triple exponential distribution, a modified model for the occurrence of large earthquakes. *BSSA* 71:2047-2101.

Kijko, A., and M. Dessokey. 1987. Application of extreme magnitude distribution to incomplete earthquake files. *BSSA* 77:1429-1436.

Kijko, A., and M.A. Sellevol. 1989. Estimation of earthquake hazard parameters from incomplete data files. Part I. Utilization of extreme and complete catalogs with different threshold magnitudes. *BSSA* 79:645-654.

King, G.C., R.S. Stein, and J.B. Rundle. 1988. The growth of geological structures by repeated earthquakes 1. Conceptual framework. *JGR* 93B:13307-13331. (See Stein et al., 1988 for part 2).

Kiremidjian, A.S. 1984. Reliability of structures subjected to fault slip. *Earthquake Engineering and Structural Dynamics* 12:603-618.

Kiremidjian, A.S., and T. Anagnos. 1984. Stochastic slip-predictable model of earthquake recurrence. *BSSA* 74:739-755.

Kiremidjian, A.S., and S. Suzuki. 1987. A stochastic model for site ground motions from temporarily dependent earthquakes. *BSSA* 77:1100-1126.

Kiremidjian, A.S., H.C. Shan, E. Rosenblueth, and S.K. Singh. 1989. Non-poissonian characteristics of earthquakes along the Mexico subduction zone. *Reducing Earthquake Hazards. Lessons Learned from the 1985 Mexico Earthquake*. V. Bertero, ed. Palo Alto, CA: EPRI: 18-23.

Knopoff, L. 1971. A stochastic model of occurrence of main-sequence earthquakes. *Reviews of Geophysics and Space Physics* 9:175-187.

Koons, H.C., and D.J. Gorney. 1990. A Sunspot Maximum Prediction Using a Neural Network. *EOS*. 71:677-688.

Kröner, A., M. Eyal, and Y. Eyal. 1990. Early Pan-African evolution of the basement around Elat, Israel, and the Sinai Peninsula revealed by single-zircon evaporation dating, and implications for crustal accretion rates. *Geology* 18:545-548.

Kuhn, M.J. 1985. A numerical study of Lamb's problem. *Geophysical Prospecting* 33:1103-1137.

Kumar, S., G. Bodvarsson, and J. Boernge. 1991. Fractal characteristics of fracture roughness and aperture data. *Proceedings of the 2nd Annual International Conference on High-Level Radioactive Waste Management.* Las Vegas, NV: ANS/ASCE:279-284.

Lamarre, M., and W.M. Dong. 1986. Evaluation of seismic hazard with fuzzy algorithm. *Proceedings of the 3rd U.S. International Conference on Earthquake Engineering*. Vol. 1. Charleston, SC:221-231.

Lamb, Sir H. 1904. *On The Propagation of Tremors over the Surface of an Elastic Solid*. Philosophical Transactions of the Royal Astronomical Society (RAS). London, England: RAS 203:1-42.

Lawson, A.C. 1908. *The California Earthquake of April 18, 1906*. 1: Washington, DC: Carnegie Institute.

Levi, B.G. 1990. Are fractures fractal or quake chaotic? *Physics Today*. November:17-19.

Loh, C.H., Y.T. Yeh, W.Y. Jean, and Y.H. Yeh. 1991. Seismic hazard analysis in the Taiwan area using a bounded fault-rupture model. *BSSA* 81:265-272.

Lomnitz-Adler, J. 1991. Model for steady state friction. *JGR* 94B:6121-6131.

Lomnitz, C. 1989. Comment on temporal and magnitude dependence in earthquake recurrence models. *BSSA* 79:1662.

Lysmer, J., T. Udaka, H.B. Seed, and R. Hwang. LUSH2 - A Computer Program for Complex Response Analysis of Soil-Structure Systems. Earthquake Engineering Research Center, EERC Report 74-4. Berkeley, CA. University of California.

Lyzenga, G.A., K.S. Wallace, J.L. Fanselow, A. Raefsky, and P.M. Groth. 1986. Tectonic motions in California inferred from very long baseline interferometry observations, 1980-1984. *JGR* 91B:9473-9487.

Machette, M.N., S.F. Personius, and A.R. Nelson. 1991. The Wasatch fault zone, Utah: Segmentation and history of holocene earthquakes. *Journal of Geology* 13:137-149

Madariaga, R. 1976. Dynamics of an expanding circular fault. *BSSA* 66:639.

Mahrer, K.D., and A. Nur. 1979a. Strike-slip faulting in a downward varying crust. *JGR* 84B:2296-2302.

Mahrer, K.D., and A. Nur. 1979b. Strike-slip faulting in a horizontally varying crust. *BSSA* 69:975-1009.

McCann, M.W., Jr., and D.M. Boore. 1983. Variability in ground motions: Root mean square acceleration and peak acceleration for the 1971 San Fernando, California earthquake. *BSSA* 73:615-632.

McClosky, J. and C.J. Bean. 1992. Time and magnitude prediction in shocks due to chaotic fault interactions. *Geophysical Research Letters.* 19:119-122.

McGarr, A. 1976. Seismic moments and volume changes. *JGR* 81B:1487-1494.

McGarr, A. 1980. Some constraints on levels of shear stress in the crust from observations and theory. *JGR* 85B:6231-6238.

McGarr, A. 1984a. Scaling of ground motion parameters, state of stress, and focal depth. *JGR* 89B:6969-6979.

McGarr, A. 1984b. Some applications of seismic source mechanism studies to assessing underground hazard. *Proceedings of the 1st International Congress on Rockbursts and Seismicity in Mines.* N.C. Gay and E.H. Wainwright, eds. Johannesburg 1082, South African Institute of Mines and Metalurgy (SAIMM):99-208.

McGarr, A. 1987. Contribution to EPRI's proceedings on intraplate maximum earthquakes. *Methods for assessing Maximum Earthquakes in the Central and Eastern U.S.* K.J. Coppersmith, A.C. Johnson, A.G. Metzger, and W.J. Arabasz, eds. EPRI Research Project 2556-12. Palo Alto, CA: EPRI: 4-63—4-68.

McGarr, A. 1991. On a possible connection between three major earthquakes in California and oil production. *BSSA* 81:948-970.

McGarr, A., and N.C. Gay. 1978. State of stress in the earth's crust. *Ann. Review Earth and Planetary Sciences* 5:405-436.

McGarr, A., W.E. Green, and S.M. Spottiswood. 1981. Strong ground motion of mine tremors: Some implications for near source ground motion parameters. *BSSA* 71:265-319.

McGarr, A., M.D. Zoback, and T.C. Hanks. 1982. Implications of an elastic analysis of *in situ* stress measurements near the San Andreas fault. *JGR* 87B:7797-7806.

McGuire, R.K. 1976. *EQRISK: Evaluation of Earthquake Risk to Site, FORTRAN Computer Program for Seismic Risk Analysis.* USGS OFR 76-67. Washington, DC: Department of the Interior.

McGuire, R.K. 1978. *FRISK-Computer Program for Seismic Risk Analysis Using Faults as Earthquake Sources.* USGS OFR 78-1007. Washington, DC: Department of the Interior.

McGuire, R.K. 1985. A note on interpreting the uncertainties in ground motion estimation. *Strong Ground Motion Simulation and Earthquake Engineering Applications - A Technological Assessment.* R.E. Scholl and J.L. King, eds. EERI Pub. 85-02. Oakland, CA:EERI: 28-1—28-4.

McGuire, R.K. 1990. *Demonstration of a Risk-Based Approach to High-Level Waste Repository Evaluation*. EPRI NP-7057. Palo Alto, CA: EPRI.

McGuire, R.K., and K.M. Shedlock. 1981. Statistical uncertainties in seismic hazard evaluations in the United States. *BSSA* 71:1287-1308.

McGuire, R.K., A.M. Becker, and N.C. Donovan. 1984. Spectral estimates of seismic shear waves. *BSSA* 81:1427-1440.

Mahin, S.A. 1976. *Response of the Olive View Hospital Main Building During the San Fernando Earthquake*. EERC 76-22. Berkeley, CA: University of CA.

Milne, W.G., and A.G. Davenport. 1969. Distribution of earthquake risk in Canada. *BSSA* 59:729-754.

Morrison, P.W., R.B. Hofmann, and J.E. Wolfe. 1966. Parkfield earthquakes. *Earthquake Notes* 27:3.

Nagata, S., T. Katayama, F. Yamazaki, L. Lu, T. Türker. 1990. A dense seismograph array in Chiba Japan and its strong motion database. *Proceedings of the Fourth U.S. National Conference on Earthquake Engineering*. Vol. 1. El Cerrito, CA:EERI:357-356.

National Research Council. 1988. *Probabilistic Seismic Hazard Analysis*. Washington, DC: National Research Council. Page 97.

Newman, W.I., and L. Knopoff. 1983. A model for repetitive cycles of large earthquakes. *Geophysical Research Letters* 10:305-309.

Newmark, N.M., J.A. Blume, and K. Kapur. 1973. Seismic design spectra for nuclear power plants. Journal of the Power Division, *ASCE* 99:287-303.

Newmark, N.M., and W.J. Hall. 1982. *Earthquake Spectra and Design*. Oakland, CA: EERI.

Niazi, M., and Y. Bozargnia. 1990. Observed ratios of PGV/PGA and PGD/PGA for deep soil sites across SMART 1 2D Array, Taiwan. *Proceedings of the Fourth U.S. National Conference on Earthquake Engineering*. Vol. 1. El Cerrito, CA: EERI: 367-374.

Nishenko, S.P. 1982. *Seismic Hazards Evaluation in Interplate and Intraplate Environments*. PhD Thesis. New York, NY: Columbia University.

Nishenko, S.P. 1985. Seismic potential for great interplate earthquakes along the Chilean and Southern Peruvian Margins of South America: A quantitative reappraisal. *JGR* 90B:3589-3615.

Nishenko, S.P., and R. Buland. 1987. A generic recurrence interval distribution for earthquake forecasting. *BSSA* 77:1382-1399.

NRC. 1991. *Safety Evaluation Report related to the operation of Diablo Canyon Nuclear Power Plant Units 1 and 2*. NUREG-0675, Supplement No. 34. Washington DC: NRC

NRC. 1992. *Resolution of Differences Between Probabilistic Seismic Hazard Methodologies for the Eastern United States*. SECY-92-122. Washington DC: NRC.

Nuttli, O.W. 1974. *The Relation of Sustained Maximum Ground Acceleration and Velocity to Earthquake Intensity and Magnitude*. Report No. 13 in the Miscellaneous Paper S-73-1 series: State-of-the-Art for Assessing Earthquake Hazards in the United States. Vicksburg, MS: U.S. Army Corps of Engineers Waterways Experiment Station.

Nuttli, O.W., and R.B. Herrmann. 1982. Earthquake magnitude scales. *Journal of the Geotechnical Engineering Division, ASCE* 108:783-786.

Nuttli, O.W., and R.B. Herrmann. 1984. Ground motion of Mississippi Valley earthquakes. *Journal of Technical Topics in Civil Engineering* 110:54-69.

Nybakken, S. 1991. Sealing fault traps —an exploration concept in a mature petroleum province: Tampen Spur, Northern North Sea. *First Break*. 9:209-222.

Okubo, P.G. 1989. Dynamic modeling with laboratory-derived constitutive relations. *JGR* 94B:12,321-12,335.

Ou, G-B., and R.B. Herrmann. 1990. A statistical model for ground motion produced by earthquakes at local and regional distances. *BSSA* 80:1397-1417.

Papageorgiou, A.S. 1988. On two characteristic frequencies of acceleration spectra: Patch corner frequency and f_{max}. *BSSA* 78:509-529.

Papageorgiou, A.S., and K. Aki. 1983. A specific barrier model for the quantitative description of inhomogeneous faulting and the prediction of strong ground motion, Parts I and II. *BSSA* 73:693-732 and 953-978.

Papazachos, B.C. 1974. Dependence of the seismic parameter b on the magnitude range. *Pure and Applied Geophysics* (Pageophys) 113:447-460

Patton, H.J., and G. Zandt. 1991. Seismic moment tensors of Western U.S. earthquakes and implications for the tectonic stress field. *JGR* 96B:18245-18259.

Patwardhan, A.S., R.B. Kulkarni, and D. Tocher. 1980. A semi-Markov model for characterizing recurrence of great earthquakes. *BSSA* 70:323-347.

Perkins, D.N., P.C. Thenhaus, S.L. Hansen, J.I. Ziony, and S.T. Algermissen. 1980. *Probabilistic Estimates of Maximum Seismic Horizontal Ground Motion on Rock in the Pacific Northwest and the Adjacent Outer Continental Shelf*. USGS OFR 80-471. Washington, DC: Department of the Interior.

Perkins, D.M., B.K. Bender, and P.C. Thenhaus. 1988. *Seismicity Owners Group-Electric Power Research Institute Seismic Hazard Methodology*. USGS report to the NRC in EPRI NP-4726. Washington, DC: NRC.

Pettingill, H.S. and P.J. Petchett. 1981. Ln-Hf total-rock age for the Amitsoqgneiss, West Greenland. Earth and Planetary Science Letters. 55:150-156.

Pfluke, J.H., and J.A. Steppe. 1973. Magnitude-frequency statistics of small earthquakes from San Francisco Bay to Parkfield. *Proceedings of the Conference on Tectonic Problems of the San Andreas Fault System*. R. Kovach and A. Nur, eds. Palo Alto, CA: Stanford U. Press: 13-23.

Power, W.L., and T.E. Tullis. 1991. Euclidean and fractal models for the description of rock surface roughness. *JGR* 96B:415-424.

Power, W.L., T.E. Tullis, S.R. Brown, G.N. Boitnott, and C.H. Scholz. 1987. Roughness of natural fault surfaces. *Geophysical Research Letters* 14:29-32.

Procházková, D. 1974. Test for differences of magnitude-frequency relation parameters due to different calculation procedures. *Pageophys* 112:727-736.

Rabinowitz, N., and D.M. Steinberg. 1991. Seismic hazard sensitivity analysis: A multi-parameter approach. *BSSA* 81:796-817.

Rabinowitz, N., and T. Van Eck. 1988. A note on the fuzzy set theory concept with an application to seismic hazard analysis. *BSSA* 78:1603-1610.

Rankin, D.W. 1977. *Studies Related to the Charleston Earthquake of 1886—Introduction and Discussion.* USGS-OFR 80-471. D.W. Rankin. ed. Washington DC: Department of the Interior.

Reiter, L. 1985. Earthquake ground motion scaling: A regulatory perspective. *Strong Ground Motion Simulation and Earthquake Engineering Applications*. R.E. Scholl and J.L. King, eds. EERI 85-02. Oakland, CA: EERI: 8-1—8-5.

Richardson, R.M., and S.C. Solomon. 1979. Tectonic stress in the plates. *Reviews of Geophysics and Space Physics* 17:981-1019.

Richardson, R.M., and L.M. Reding. 1991. North American plate dynamics. *JGR* 96B:12,201-12,223.

Rogers A.M., D.M. Perkins, and F.A. McKeown. 1977. Preliminary Assessment of Seismic Hazard at the Nevada Test Site. *BSSA* 77:1587-1606.

Rogers, A.M., S.C. Harmsen, and M.E. Meremonte. 1987. *Evaluation of the Southern Great Basin and its Relationship to the Tectonic Framework of the Region.* USGS Open File Report 87-408. Washington D.C., Department of Interior.

Rovelli, A., O. Bonamassa, M. Cocco, M. Di Bona, and S. Mazza. 1988. Scaling laws and spectral parameters of the ground motion in active extensional areas in Italy. *BSSA* 78:530-560.

Ruble, T.A. 1988. *Letter from the Chairman of the SOG Licensing Steering Panel, of October 26th to Mr. James E. Richardson of the NRC.* In EPRI 1988 1: part 1. Birmingham, Alabama Public Services Inc.

Rundle, J.B. 1989. Derivation of the complete Gutenberg-Richter magnitude-frequency relation using the principle of scale invariance. *JGR* 94B:12337-12342.

Rundle, J.B., and S.R. Brown. 1991. Origin of rate dependence in frictional sliding. *Journal of Statistical Physics* (in press).

Ruthenberg, A., P.C. Jennings, and G.W. Housner. 1979. *The Response of the Veterans Hospital Building 41 in the San Fernando Earthquake*. Earthquake Emergency Research Laboratory (EERL) Report 79-03. Pasadena, CA: CA Institute of Technology.

Ruthenberg, A., P.C. Jennings, and G.W. Housner. 1980. *The Response of Veterans Hospital Building 41 in the San Fernando Earthquake*. EERI Report 80-03. Oakland, CA: EERI.

Ryall, A.S., and J.D. VanWormer. 1980. Estimation of maximum magnitude and recommended seismic zone changes in the Western Great Basin. *BSSA* 70:1573-1581.

Schedlock, K.M., R.K. McGuire, and D.G. Herd. 1980. *Earthquake Recurrence in the San Francisco Bay Region, California from Fault Slip and Seismic Moments.* USGS OFR 80-999. Washington, DC: Department of the Interior.

Schiff, A. and J.L. Bogdanoff. 1967. Analysis of Current Methods of Interpreting Strong Motion Accelerograms. *BSSA* 57:857-874.

Schnabel, P.B., and H.B. Seed. 1973. Acceleration of rock for earthquakes in the Western United States. *BSSA* 63:501-516.

Schnabel, P.B., J. Lysmer, and H.B. Seed. *SHAKE — A Computer Program for Earthquake Response Analysis of Horizontally Layered Sites.* Earthquake Engineering Research Center Report No. EERC 72-12. Berkeley, CA. University of California.

Schlien, S., and M.N. Toksöz. 1970. A clustering model for earthquake occurrences. *BSSA* 60:1765-1788.

Scholz, C.H. 1985. Earthquake prediction and seismic hazard. *Earthquake Prediction Research* 3:11-23.

Scholz, C.H. 1991. Fractal Scale-Breaking in Earthquakes and Faulting. *EOS Supplement. AGU Spring Meeting April 23, 1991, Baltimore, Maryland.*

Scholz, C.H., and C.A. Aviles. 1986. The fractal geometry of faults and faulting. *5th Ewing Symposium on Earthquake Source Mechanisms*. S. Das, J. Boatwright, and C.H. Scholz, eds. Geophysical Monograph Series 37:147-156.

Schwartz, D.P., and K.J. Coppersmith. 1984. Fault behavior and characteristic earthquakes: Examples from the Wasatch and San Andreas fault zones. *BSSA* 89:5681-5698.

Scott, W.E., K.L. Pierce, and M.H. Hait, Jr. 1985. Quaternary tectonic setting of the 1983 Borah Peak Earthquake, Central Idaho. *BSSA* 75:1053-1066.

Shah, H.C., W.M. Dong, and A.C. Boissinnade. 1987. Use of knowledge-based expert systems in seismic hazard and risk analysis. *Engineering Aspects of Earthquake Phenomena*. A. Koridze, ed. Corte Madera, CA: Omega Scientific.

Shakal, A.F., and D.L. Bernreuter. 1981. *Empirical Analyses of Near-Source Ground Motion*. NUREG/CR-2095. Washington, DC: NRC.

Shakal, A.F., M. Huang, M. Reichele, C. Ventura, T. Cao, R. Sherbourne, M. Savage, R. Darragh, and C. Petersen. 1989. *CSMIP Strong Motion Records from the Santa Cruz Mountains (Loma Prieta), California Earthquake of 17 October 1989.* California Strong Motion Instrumentation Program Report No. OSMS 89-06.

Shaw, H.R. 1987. The Periodic Structure of the Natural Record and Nonlinear Dynamics. *EOS* 68-50:1651-1665.

Sheriff, R.E. 1991. *Encyclopedic Dictionary of Exploration Geophysics*. 3rd ed. Tulsa, OK. Society of Exploration Geophysicists.

Shimazaki, K., and T. Nakata. 1980. Time-predictable recurrence for large earthquakes. *Geophysical Research Letters* 7:279-282.

Sibson, R.H. 1982. Fault models in the continental crust of the U.S. *BSSA* 72: 151-163.

Sibson, R.H. 1989. Earthquake faulting as a structural process. *Journal of Structural Geology* 11:1-14.

Sibson, R.H. 1990. Rupture nucleation on unfavorably oriented faults. *BSSA* 80: 1580-1604.

Sieh, K.E. 1978. Slip along the San Andreas fault associated with the great 1857 earthquake. *BSSA* 68:1421-1448.

Sieh, K.E. 1984. Lateral offsets and revised dates of prehistoric earthquakes at Pallett Creek, Southern California. *JGR* 89B:7641-7670.

Sieh, K.E., and R.H. Jahns. 1984. Holocene activity of the San Andreas fault at Wallace Creek, California. *GSA Bulletin* 95:883-896.

Silva, W.J. 1991. *Assessment of Seismic Design Loads.* Presentation at the 38th Advisory Committee on Nuclear Waste (ACNW), December 5th, Bethesda, Maryland. Washington DC: NRC.

Silva, W.J., and R.K. Green. 1989. Magnitude and distance scaling of response spectral shapes for rock sites with applications to North American tectonic environment. *Earthquake Spectra* 5:591-702.

Silva, W.J., and K.W. Lee. 1987. *WES RASCAL Code for Synthesizing Earthquake Ground Motions*. Report 24 of the Miscellaneous Paper S-73-1 series: State-of-the-Art for Assessing Earthquake Hazards in the United States. Vicksburg, MS. U.S. Army Corps of Engineers Waterways Experiment Station.

Singh, S.K., and R.B. Herrmann. 1983. Regionalization of crustal coda Q in the continental United States. *JGR* 88B:527-538.

Singh, S.K., E. Mena, J.G. Anderson, J. Lermo, and R. Quass. 1989a. Source spectra and RMS acceleration of Mexico subduction zone earthquake. *Reducing Earthquake Hazards, Lessons Learned from the 1985 Mexico Earthquake (Abstract)*. V. Bertero, ed. Oakland, CA: EERI: 41.

Singh, S.K., A. Mori, E. Mena, F. Kruger, and R. Kind. 1989b. Evidence for anomalous body wave radiation between 0.3 and 0.7 hz from the September 19,1985, Michoacan Mexico earthquake. *Reducing Earthquake Hazards, Lessons Learned from the 1985 Mexico Earthquake (Abstract)*. V. Bertero, ed. Oakland, CA: EERI: 49.

Slemmons, D.B. 1977. *Faults and Earthquake Magnitude*. Report No. 6 in the Miscellaneous Paper S-73-1 series: State-of-the Art for Assessing Earthquake Hazards in the United States. Vicksburg, MS: U.S. Army Corps of Engineers Waterways Experiment Station.

Slemmons, D.B. 1982. Determination of design earthquake magnitudes for microzonation, *Proceedings of the International Earthquake Microzonation Conference*. Vol. 1. Seattle, WA: 119-130.

Smalley, R.F., Jr., J.L. Chatelain, D.L. Turcotte, and R. Pervot. 1987. A fractal approach to the clustering of earthquakes: Applications to the seismicity of the New Hebrides. *BSSA* 77:1368-1331.

Smith, D.E., R. Kolenkiewicz, P.J. Dunn, J.W. Robbins, M.H. Torrence, S.M. Klosko, R.G. Williamson, E.C. Pavlis, N.B. Douglas, and S.K. Fricke. 1990. Tectonic deformation from satellite laser ranging to LAGEOS. *JGR* 95B:22013-22041.

Smith, D.N., and P. Hytler, Jr. 1985. *Industrial Robots Forecasts and Trends, Delphi Study*. Ann Arbor, MI: Society of Manufacturing Engineers, University of Michigan.

Smith, W. 1976. Determination of maximum magnitude earthquakes. *Geophysical Research Letters* 3:351-354.

Snoke, J.A. 1987. Stable determination of (Brune) stress drops. *BSSA* 77:530-538.

Sommerville, P.G., and G. Nelson. 1982. The distribution of the RMS acceleration and duration around faults. *Earthquake Notes* 53:96.

Sommerville, M.R., W.A. Peppin, and J.D. VanWormer. 1980. An earthquake sequence in the Sierra Nevada-Great Basin boundary zone: Diamond Valley. *BSSA* 70:1547-1555.

Sommerville, M.R., R.C. Lee, and G.N. Owen. 1987. *Technical Basis and Parametric Study of Ground Motion and Surface Rupture Hazard Evaluations at Yucca Mountain, Nevada*. URS/John A. Blume Assoc. report to SNL. SAND86-7013. Albuquerque, NM: SNL.

Sommerville, P.G., J.P McLaren, L.V. LeFevre, R.W. Burger, and D.V. Helmberger. 1987. Comparison of source scaling relations of Eastern and Western North American earthquakes. *BSSA* 77:322-346.

Sommerville, P.G., M. Sen, and B.P. Cohee. 1991. Simulation of strong ground motions recorded during the 1985 Michoacan, Mexico, and Valparaiso, Chile earthquakes. *BSSA* 81:1-27.

Stein, R.S., G.C.P. King, and J.B. Rundle. 1988. The growth of geological structures by repeated earthquakes 2. Field examples of continental dip slip faults. *JGR* 93B: 13319-13331. (See King et al., 1988, for part 1.)

Stuart, W.D., and G.M. Mavko. 1979. Earthquake instability on a strike slip fault. *JGR* 89B: 2153-2160.

Suzuki, S., and A.S. Kiremidjian. 1988. *A Stochastic Ground Motion Forecast Model with Geophysical Considerations*. Report No. 88. Stanford, CA: The John A. Blume Earthquake Engineering Center, Stanford University.

Suzuki, S., and A.S. Kiremidjian. 1991. A random slip rate model for earthquake occurrences with Bayesian parameters. *BSSA* 81:781-795.

Swan, F.H., III, 1991. *Assessment of the Potential for Fault Displacement for High-Level Nuclear Waste Repositories*. Presentation at the 38th ACNW Meeting, December 5th, Bethesda, Maryland. Washington, DC:NRC

Swan, F.H., III, D.P. Schwartz, and L.S. Cluff. 1980. Recurrence of moderate to large magnitude earthquakes produced by surface faulting on the Wasatch fault zone. *BSSA* 70: 1431-1462.

Sykes, L.R., and S.P. Nishenko. 1984. Probabilities of occurrence of large rupturing earthquakes for the San Andreas, San Jacinto, and Imperial Faults, California, 1983-2003. *JGR* 89B 5905-5927.

Taylor, S.R., and M.D. Denny. 1991. An analysis of spectral differences between Nevada test site and Shagan River nuclear explosions. *BSSA* 96: 6237-6245.

Thatcher, W. 1984. The earthquake deformation cycle, recurrence, and the time predictable model. *JGR* 89B:5674-5680.

Thenhaus, P.C., D.M. Perkins, S.T. Algermissen, and S.L. Hanson. 1987. Earthquake hazard in the Eastern United States: Consequences of alternative seismic source zones. *Earthquake Spectra* 3:227-261.

Thenhaus, P.C., and T.P. Barnhard. 1989. Regional termination and segmentation of quaternary fault belts in the Great Basin, Nevada and Utah. *BSSA* 79:1426-1438.

Tinti, S., and Mulargia. 1985a. Application of extreme value approaches to the apparent magnitude distribution or earthquake. *Pageoph.* 123:199-20

Tinti, S., and F. Mulargia. 1985b. Application of extreme values approaches to the apparent magnitude distribution of earthquakes. *BSSA* 75:1681-1697.

Toro, G.R., and R.K. McGuire. 1987. An investigation into earthquake ground motion characteristics in Eastern North America. *BSSA* 77:468-489.

Toro, G.R., W.J. Silva, R.K. McGuire and R.B. Herrmann. 1992. Probabilistic seismic hazard mapping of the Mississippi embayment. *Seismological Research Letters*. 63:449-476.

Trifunac, M.D. 1972. Stress estimates for the San Fernando, California, earthquake of February 9, 1971: Main event and thirteen aftershocks. *BSSA* 62:62.

Tse, S.T. 1986. Crustal instability in relation to the depth variation of frictional slip properties. *JGR* 91B:9452-9472.

Turcotte, D.L. 1992. Fractals and Chaos in Geology and Geophysics. Cambridge, U.K. *Cambridge University Press*: 221.

Vanmarcke, E., and E. Rosenblueth. 1989. Space-time variation of earthquake ground motion. *Reducing Earthquake Hazards. Lessons Learned from the 1985 Mexico Earthquake*. V. Bertero, ed. El Cerrito, CA. EERI: 50-53.

VanWormer, J.D., and A.S. Ryall. 1980. Sierra Nevada-Great Basin boundary zone: Earthquake hazard related to structure, active tectonic processes, and anomalous patterns of earthquake occurrence. *BSSA* 70:1472-1557.

Vere-Jones, D. 1970. Stochastic models for earthquake occurrences. *Journal of the Royal Statistical Society* B:1-62.

Walsh, J.B., and M.A. Grosenbaugh. 1979. A new model for analyzing the effect of fractures on compressibility. *JGR* 84B:3532-3536.

Wallace, R.E. 1985. Variation in slip rates, migration, and grouping of slip events on faults in the Great Basin Province. *Proceedings of Workshop XXVIII on the Borah Peak, Idaho Earthquake*. R.S. Stein and R.A. Bucknam, eds. USGS OFR 85-290. Washington, DC: Department of the Interior: 17-26.

Wallace, R.E. 1987. Grouping and migration of surface faulting and variation in slip rates on faults in the Great Basin province. *BSSA* 77:868-876.

Wallace, R.E., and R.A. Whitney. 1984. Late quaternary history of the Stillwater Seismic Gap, Nevada. *BSSA* 74:301-314.

Wang, P., X. Liu, and E. Sanchez. 1986. Set valued statistics and its application to earthquake engineering. *International Journal of Fuzzy Sets Systems* 18:347-356.

Ward, S.N. 1990. Pacific-North America plate motions: New results from very long base line interferometry. *JGR* 95B:21965-21981.

Weertman, J. 1980. Unstable slippage across a fault that separates elastic media of different elastic constants. *JGR* 85B:1455-1461.

Weichert, D.H., R.J. Wetmiller, and P. Munro. 1986. Vertical earthquake acceleration exceeding 2g? The case of the missing peak. *BSSA* 76:1473-1478.

Weibull, W. 1949. A statistical representation of fatigue failures in solids. *Kungl. Teckniska Högskalens Handlinger* 27.

Weldon, R.J., III, and K.E. Sieh. 1985. Holocene rate of slip and tentative recurrence interval for large earthquakes on the San Andreas Fault, Cajon Pass, Southern California. *Journal of Structural Geology* 1:323-332.

Wells, D., K. Coppersmith, X. Zhang, and D.B. Slemmons. 1989. New earthquake magnitude and fault rupture parameters: Part 1. Abstract, 84th annual meeting of the Seismological Society of America, Victoria B.C., Canada. *Seismological Research Letters* 60:27.

Wells, S.G., L.D. McFadden, C.E. Renault, and B.M. Crowe. 1990. Geomorphic assessment of late quaternary volcanism in the Yucca Mountain area, Southern Nevada: Implications for the proposed high-level radioactive waste repository. *Geology* 18:549-553.

Wong, T-F., J.T. Fredrich, and G.D. Gwanmesia. 1989. Crack aperture statistics and pore space fractal geometry of Westerly granite and Rutland quartzite: Implications for an elastic contact model of rock compressibility. *JGR* 94B:10,267—10,278.

Wood, S.H., C. Wurts, C.T. Lane, N. Ballenger, M. Shaleen, and D. Totorica. 1985. The Borah Peak, Idaho Earthquake of October 27, 1983 - Hydrologic Effects. *Earthquake Spectra*. 2:127-150.

Wood, R.M. 1991. *Hydrologic Signatures of Earthquake Strain.* Abstract, 1991 Annual AGU Meeting, EOS May 14th. Washington, DC: AGU.

Woodward-Clyde Consultants. 1978. *Offshore Alaska Seismic Exposure Study.* Consulting report to the Alaska Subarctic Offshore Committee (OASES).

Working Group on California Earthquake Probabilities. 1988. *Probabilities of Large Earthquakes Occurring in California on the San Andreas Fault*. USGS OFR 88-398. Washington, DC: Department of the Interior.

Wyss, M. 1979a. *Observation and Interpretation of Tectonic Strain Release Mechanisms.* PhD Thesis. Pasadena, CA: CA Institute of Technology: 239.

Wyss, M. 1979b. Estimating maximum expectable magnitude of earthquakes from fault dimensions. *Geology* 7:336-340.

Wyss, M., and J.N. Brune. 1968. Seismic moment, stress, and source dimensions for earthquakes in the California-Nevada region. *JGR* 73:4681-4694.

Yegian, M.K. 1979. *Probabilistic Seismic Hazard Analysis*. Report No. 13 of the Miscellaneous Paper S-73-1 series: State-of-the-Art for Assessing Earthquake Hazards in the United States. Vicksburg, MS: U.S. Army Corps of Engineers Waterways Experiment Station.

Yegulalp, T.M., and J.T. Kuo. 1974. Statistical prediction of maximum magnitude earthquakes. *BSSA* 64:393-414.

Young, S.R., G.L. Stirewalt, and A.P. Morris. 1992. *Geometric modeling of faulting at Yucca Mountain*. CNWRA Report 92-008. NRC. San Antonio, Texas. Center for Nuclear Waste Regulatory Analyses.

Youngs, R.R., and K.J. Coppersmith. 1985. Implications of fault slip rates and earthquake recurrence models to probabilistic seismic hazard estimates. *BSSA* 75:939-964.

Youngs, R.R., and K.J. Coppersmith. 1989. Objective estimation of maximum magnitude using multiple assessment techniques. *(Abstract) Seismological Research Letters* 60:28.

Zhang, J., and T. Lay. 1989. A new method for determining the long-period component of the source time function of large earthquakes. *Geophysical Research Letters* 16:275-278.

Zhang, X., D.B. Slemmons, D. Wells, and K. Coppersmith. 1989. New earthquake and fault rupture parameters: Part II. Maximum and average displacement relationships. Abstract, 84th Annual Meeting of the SSA, Victoria B.C., Canada. *Seismological Research Letters* 60:27.

Zoback, M.D., M.L. Zoback, V.S. Mount, S. Suppe, J.P. Eaton, J.H. Healy, D. Oppenheimer, P. Reasonberg, L. Jones, C.B. Raleigh, I.G. Wong, O. Scotti, and C. Wentworth. 1987. New evidence on the state of stress on the San Andreas fault system. *Science* 238:1105-1111.

Zoback, M.L. 1989. State of stress and modern deformation of the Northern basin and range province. *JGR* 94:7105-7108.

Zoback, M.L., and M.D. Zoback. 1980. State of stress in the conterminous United States. *JGR* 85B:6113-6156.

Zoback, M.L., and M.D. Zoback. 1989. Tectonic stress field of the Continental United States. *Geophysical Framework of the continental United States*. L.D. Pakiser and W.D. Mooney, eds. Memoir of the Geological Society of America 172: Boulder, CO: GSA:523-539.

APPENDIX A
LIST OF ACRONYMS, SYMBOLS, AND NONSTANDARD TERMS

a	acceleration
ACRS	Advisory Committee on Reactor Safeguards
a_P	peak acceleration
aggregation	method of combining the means of several hazard calculations with estimates of the combined uncertainties inherent in each calculation
ALEAS	subroutine of the LLNL PSHA computer program
a_{rms}	root mean square acceleration
a_{max}	maximum acceleration
ASCE	American Society of Civil Engineers
ASLB	Atomic Safety and Licensing Board
b	slope term of the Gutenberg and Richter earthquake recurrence formula
b_I	slope term of the Gutenberg and Richter recurrence formula when applied to Modified Mercalli damage Intensities
Ba	billion years before present
BE	best estimate
BLWN	band limited white noise
CEUS	central and eastern United States
CFR	Code of Federal Regulation
cm	centimeter
CNWRA	Center for Nuclear Waste Regulatory Analyses
COMB	subroutine of the LLNL PSHA computer program, SEISM I
CPHC	constant percentile hazard curve
DOE	U.S. Department of Energy
EEI	Edison Electric Institute, Washington, D.C., a membership organization comprised of electric utility corporations

EERC	University of California at Berkeley Earthquake Engineering Research Center, Richmond, California
EERI	Earthquake Engineering Research Institute, Oakland, California, a membership organization which publishes the journal 'Earthquake Spectra'
EERL	Earthquake Engineering Research Laboratory, California Institute of Technology, Pasadena, CA
EPRI	Electric Power Research Institute, Palo Alto, California, a research organization supported by electric utility corporations
epicentral distance	distance from the point on the earth above an earthquake's fault rupture initiation to the point of observation (i.e. the location of a seismometer)
EST	earth science test
exceedance	(also spelled exceedence) probability of being exceeded in a given time, usually a year - sometimes as a synonym for 'being exceeded' - sometimes expressed as 1/(return period)
fault width	distance from the surface to the lowest extent of a fault as measured along its dip and perpendicular to its strike
fault surface width	the width of a fault zone including minor parallel and branching faults
f_{max}	maximum frequency before tapering of S-wave spectra
f_o	corner frequency of S-wave spectra
FST	fuzzy set theory
g	unit of gravitational attraction equal to 980 centimeters per second^2
γ	exponent which controls spectral attenuation
gouge	rock dust between fault faces with the consistency of clay when moist
Hanning	a method for reducing the effect of the window function when generating spectra from a portion of a digitized time function
HLW	high level radioactive waste
Ka	thousand years before present
km	kilometer
LANL	Los Alamos National Laboratory

LLNL	Lawrence Livermore National Laboratory
M	Richter magnitude - M_L to 6.5, M_S above 6.5
M	moment magnitude of Kanamori and Anderson (1975)
Ma	million years before present
m_b	first-P-motion body wave magnitude
m_{bLg} or m_N	lg-wave or Nuttli magnitude (similar scale to M_L and m_b)
M_L	Richter local magnitude
ML	maximum likelihood
MLH	mean log hazard
MMI	Modified Mercalli Intensity scale, based on damage
M_o	seismic moment - usually given as 10^x dyne-cm
M_S	20 second surface wave magnitude
M_W	moment magnitude of Hanks (1979)
NAS	National Academy of Sciences
near-field	defined in this report as a distance less than a fault dimension
NRC	U.S. Nuclear Regulatory Commission
NRR	NRC Office of Nuclear Reactor Regulation
NV	Nevada
ordinary structure	bridges, dams and buildings of not unusual construction or height, as opposed to nuclear power plants, HLW waste repositories, or other unique civil construction
P	compressional (primus) wave
PA	performance assessment - a complex probabilistic methodology for system performance analysis
panel	a group of experts who are individually solicited regarding particular technical aspects of a PSHA in the LLNL method. Their estimates are combined statistically to produce a final seismic hazard curve.

personalistic	describes probabilities based on judgement only (coined by Brillinger, 1985)
PFD	probabilistic fault displacement
PFD&SHA	probabilistic fault displacement and seismic hazard analysis
PG&E	Pacific Gas and Electric
PSHA	probabilistic seismic hazard analysis
Q	anelastic attenuation factor, e.g 50 for sediments, 300 for basement rock (Boatwright, 1984a). It is also called the quality factor, specific attenuation, specific absorption coefficient or specific dissipation function.
R. G.	NRC Regulatory Guide
Rhebinder effect	the breaking of molecular bonds by introducing certain ions in solution to stressed material thereby initiating failure
rms	root mean square
S	shear (secondus) wave
saturation	failure of a measure to increase as it should, e.g., magnitudes fail to be proportional to energy release above a certain value.
scenarios	hypothesized events that have a finite probability of occurring - a concept used in performance assessment
SD	standard deviation
SAR	NRC Safety Analysis Report
SH	seismic hazard
SHA	seismic hazard analysis
SHC	seismic hazards codes of LLNL
SEISM I	PSHA computer program developed by LLNL
STP	NRC Staff Technical Position
SOG	Seismic Owners Group, comprised of electric utility corporations
Subevent	the breakage of a single asperity in an earthquake that breaks several asperities
T	interoccurrence times of slips (Brown et al. 1991)

<T>	mean interoccurrence time of slips (Brown et al. 1991)
team	a group of experts who work together to provide a PSHA in the SOG/EPRI method. Several such teams are employed and their results statistically combined. Statistics concerning the spread in opinion within a team are also sometimes employed.
time function	a function in which one variable is time. In this report is means a ground motion amplitude as a function of time. It is synonymous with seismogram or strong motion record.
USGS	U.S. Geological Survey
ω	circular or angular frequency

APPENDIX B
MECHANICAL AGGREGATION OF MULTIPLE SEISMIC HAZARD RESULTS

APPENDIX B MECHANICAL AGGREGATION OF MULTIPLE SEISMIC HAZARD RESULTS

1.1 INTRODUCTION

This appendix summarizes an exercise to explore the EPRI (1988) aggregation methodology. The exercise used the computer software MATLAB and data and formulae provided in EPRI (1988). Results of the exercise are plotted on Figure 2-3. Figure 2-3a is similar to a figure in EPRI (1988) calculations were made to be sure we understood the EPRI aggregation procedure. This appendix details the calculations for that figure.

All team weights are assumed unity and a log normal distribution function of exceedance is assumed for this exercise.

1.2 AN EXPLORATION OF THE EPRI (1988) METHODOLOGY

The purpose of EPRI's aggregation procedure is to obtain an estimate of the professional consensus seismic hazard (SH) at a site. Aggregation of seismic hazard estimates and their associated uncertainties is needed because only a representative group of teams can be used to provide input on seismic hazard. The goal of the aggregation procedure is to obtain for each site and specified ground motion levels, a group consensus hazard which is defined as an estimate of the professional consensus mean log hazard (MLH), and a measure of the profession's uncertainty.

Data for seismic hazard originating from each earth science team (EST) are expressed in terms of the mean and standard deviation (SD) of the $\log_{10}$ hazard at a set of sites at specified ground motion levels. In the analysis, x_{ij} and β_{ij} represent the mean and std, respectively, of the $\log_{10}$ hazard (e.g., the annual probability of exceedance of a given ground motion level) obtained for the i^{th} site and j^{th} EST.

Due to the short historical record, the estimation of SH must depend on the interpretation of experts. Due to the uncertainties associated with the individual seismic hazard results and the differing scientific views among expert teams, multiple measures of seismic hazard for a site are necessary. The group consensus hazard is composed of two parts:

- The mean $\log_{10}$ hazard at a site, and
- The Uncertainty.

The procedure to obtain the group consensus MLH utilizes relative weights which are essential to each team. To determine the group consensus MLH, a weighted average of the individual team MLH values is used. A key step is to calculate a series of relative team weights. In this procedure team weights are based on the relative consistency (i.e., the variance) of a team's MLH values for a set of sites.

The uncertainty of the group consensus consists of two parts:

- The uncertainty attributed to the limited historical seismicity record and the current understanding of physical processes that generate earthquakes in the central and eastern United States (CEUS), and

- The difference among the team MLH values at each site.

To provide the group consensus uncertainty, the variances related to these components are summed up.

An important point of this procedure is that the specific scientific views of a team, which may cause a systematic deviation of a team's MLH from the group consensus, should not affect its measure of consistency (i.e., the variance). Therefore, a team is not to be penalized (i.e., assigned low relative weight) on the basis of its MLH which may systematically differ from the group consensus MLH. Rather, the variance of a team should be measured with respect to the deviations of a team, adjusted for their systematic deviation from the group consensus.

1.3 ALGORITHMIC PROCEDURE

1.3.1 Calculation of the Group Consensus MLH

To calculate the group consensus MLH at a specific site, a weighted average of the individual MLH values is found. The weights are established from the deviations of each team's MLH from the group consensus MLH. The term "deviation" denotes the difference between the team's systematic deviation adjusted MLH and the group consensus MLH at that given site. The reciprocal of the relative variances of each team's deviations is used as standard basis for the relative team weights. The variances of the deviations represent an estimate of the consistency that a team exhibits as an estimator of the group consensus at a site.

Assume that the relative team weights (or equivalently the covariance matrix, Σ) are known. Then, define following column vector:

$$\begin{aligned} X_i &= (x_{i1},\dots,x_{ij},\dots,x_{ip})' \\ J &= (1,\dots,1,\dots,1)' \\ G &= (\gamma_1,\dots,\gamma_j,\dots,\gamma_p)' \\ \Delta_i &= (\lambda_{i1},\dots,\lambda_{ij},\dots,\lambda_{ip})' \end{aligned} \tag{B-1}$$

where, $i = 1,2,\dots,n$ (number of sites) and $j = 1,2,\dots,p$ (number of teams). The variables will be defined later. Note that the symbol ′ denotes transpose.

The group consensus MLH, μ_i, at each site, i, is defined as

$$\mu_i = W'x_i \tag{B-2}$$

with the column vector

$$W = (w_1, w_2, \ldots, w_p)'$$

(B-3)

and w_j = relative weight of the j^{th} team and $0 \leq w_j \leq 1.0$.

In this process the weights w_j do not represent the degree to which a team's seismic hazard evaluations are correct. The weights are used to calculate the group consensus MLH, μ_i, by taking advantage of the fact that each team's seismic hazard values (adjusted for the team's systematic deviation) may exhibit different variability around μ_i.

A team's systematic deviation from the group consensus is defined to be:

$$\gamma_j = \frac{1}{n}\sum_{i=1}^{n-1}\left(xij - \frac{\sum_{k \neq j} w_k x_{ik}}{\sum_{k \neq j} w_k}\right)$$

(B-4)

The individual deviations of each team, corrected for their systematic deviation, are computed at each site as

$$\lambda_{ij} = x_{ij} - \mu_i - \gamma_j$$

(B-5)

The variance of a sampling distribution of sample means is

$$\xi_j^2 = \frac{1}{n(n-1)}\sum_{i=1}^{n}\lambda_{ij}^2$$

(B-6)

and the diagonal square matrix D_ξ^2 is formed as

$$D_\xi^2 = \begin{bmatrix} \xi_1^2 & 0 & 0 & . & . & . & 0 \\ 0 & \xi_2^2 & 0 & . & . & . & 0 \\ . & . & . & . & . & . & . \\ 0 & 0 & 0 & . & . & . & \xi_p^2 \end{bmatrix}$$

(B-7)

Then, the covariance matrix is defined as

$$\Sigma = \frac{1}{n-1}\left(\sum_{i=1}^{n}\Delta_i\Delta_i'\right) + D_\xi^2$$

(B-8)

Now, after the team covariances are calculated, the updated relative team weights are defined according to

$$W = \frac{\sum^{-1} . J}{J^{-1} . \sum^{-1} . J} \tag{B-9}$$

where the w_j are defined to always be $0 \le w_j \le 1.0$.

In rare circumstances, when the structure of Σ results in elements of W being less than zero, quadratic programming may be applicable to satisfy the above constraints. Since, generally, the off-diagonal terms of Σ are not zero, the relative weight assigned to a team is not strictly proportional to the reciprocal of the variance of the team deviations. Thus, correlations among the team deviations can also be allowed.

The process to estimate a group consensus MLH is an iterative one. Usually, it is initiated by assuming the team weights to be equal. In other words

$$W^{(1)} = \frac{1}{n}J = (\frac{1}{n},\ldots,\frac{1}{n},\ldots,\frac{1}{n})' \tag{B-10}$$

The iterative process is repeated until convergence is achieved, the criterion being

$$\sum_{j=1}^{p}\left(w_j^{(k+1)} - w_j^{(k)}\right)^2 < \varepsilon \tag{B-11}$$

where ε is a specified tolerance limit and (k) denotes, the kth iteration step.

The solution is susceptible to convergence to local solutions and slow convergence rates. To overcome these problems we can:

- Employ a doubly-controlled convergence criterion, and
- Take team weights as the average of the weights calculated in the previous iterations.

1.3.2 Calculations of the Total Uncertainty in the Seismic Hazard

The group uncertainty in the seismic hazard at a site is composed of two parts:

- Uncertainty in individual EST hazard results, and
- Variation among the EST MLH values according to the group consensus MLH.

Thus, the group consensus uncertainty in the seismic hazard at a site i is defined as

$$S^2_{Gi} = \sigma^2_{Pi} + \sigma^2_T \tag{B-12}$$

Where the symbols σ_{Pi} and σ_T are explained below.

The first term of the right hand side (RHS) corresponds to the propagated uncertainty in the seismic hazard and is a function of the site and the ground motion level. The second term corresponds to the team-to-team variance of the MLHs. This term is assumed to be site-independent.

The propagated uncertainty in the hazard at a site is determined as a simple average of the variance in the hazard estimates of each team at the specific ground motion level. Thus,

$$\sigma_{pi}^{2} = \frac{1}{p} \sum_{j=1}^{p} \beta_{ij}^{2}$$

(B-13)

The team-to-team variance of the MLH, σ_T^2, with respect to the group consensus MLH is defined as

$$\sigma_T^2 = \frac{1}{p-1} \sum_{j}^{p} \left[\left(\frac{1}{n} \sum_{i=1}^{n} xij \right) - \left(\frac{1}{n} \sum_{i=1}^{n} \mu_i \right) \right]^2$$

(B-14)

Given the group consensus MLH, [illegible] and the group consensus uncertainty, S_{Gi}^2, an aggregate description of the seismic hazard at a site i and for a ground motion level (a*) can be quantified. By assuming a distribution to describe the uncertainty in the hazard at a site, desired confidence fractiles can be calculated.

1.4 NUMERICAL IMPLEMENTATION OF THE ALGORITHM

The algorithm presented above has been implemented by the author using MATLAB, a mathematical analysis environment. In the next pages the sample data file "shmdat.m" and MATLAB file "shm.m" are presented. A test case, involving two sites and five EST seismic hazard estimates, is analyzed under the assumption of log-normal distributions. This exploration of the EPRI algorithms, as we have interpreted them, is not intended to be used as a production code.

```
%
%       data file to be used with MATLAB file "shm.m" for performing the
%       mechanical aggregation of expert opinions procedure
%
%       By Amvrossios C. Bagtzoglou
%
%       Center for Nuclear Regulatory Analyses
%       Southwest Research Institute, San Antonio, Texas
%
%       November 1991
%
clear
%
%       zero out some arrays
%
pdf=[];
er=[];
sig2_pr=[];
sig2_t=0;
sig2_tot=[];
%
```

```
%       define mean and std of log10(sh)
%       both are matrices (p x n)
%
%       where: n=number of sites
%              p=number of expert teams
%
x_m=[5.5 5
6.[illegible] 6
6 4 7
7.8 7.1
7.2 5];
x_m=-x_m;
[p n]=size(x_m);
%
x_sd=[0.9/6 0.4/6
0.9/6 0.3/6
1/6 1.3/6
1.1/6 0.9/6
1.2/6 1/6];
%
%       get some tolerances, in order to determine when to stop
%
tol=0.001;
k_max=input('enter the maximum number of iterations : ');
i_upd=input('do you wish to update the relative weights? (0--NO,1--YES) : ');

%
%       MATLAB file "shm.m" for performing the
%       mechanical aggregation of expert opinions
%       of the Seismic Hazard procedure
%
%       By Amvrossios C. Bagtzoglou
%
%       Center for Nuclear Regulatory Analyses
%       Southwest Research Institute, San Antonio, Texas
%
%       November 1991
%
%
%       load data from file "shmdat"
%
shmdat
%
%       transform to real values of sh
%
x_m=(10).^x_m;
x_sd=(10).^x_sd;
%
%       initialize the relative weights
%
w=1/n*ones(p,1);
wnew=zeros(p,1);
%
%       loop over the maximum number of iterations
%
                for k=1:k_max
%
%       zero out some arrays
%
g=zeros(p,1);
```

```
m=zeros(1,n);
xi2=zeros(p,1);
dxi2=eye(p);
delt=zeros(p,n);
sig=zeros(p,p);
%
%       get means according to equation (2)
%
m=w'*x_m;
%
%       loop over the number of teams (p) and sites (n)
%       and get gammas according to equation (4)
%
for i_p=1:p
        for i_n=1:n
g(i_p)=g(i_p)+x_m(i_p,i_n);
g(i_p)=g(i_p)-(sum(w.*x_m(:,i_n))-w(i_p)*x_m(i_p,i_n))/(sum(w)-w(i_p));
        end
end
g=g/n;
%
%       loop over the number of teams (p) and sites (n)
%       and get lamdas according to equation (5)
%
for i_p=1:p
        for i_n=1:n
delt(i_p,i_n)=x_m(i_p,i_n)-m(i_n)-g(i_p);
        end
end
%
%       loop over the number of teams (p) and sites (n)
%       and get xi squares according to equation (6)
%
for i_p=1:p
        xi2(i_p)=sum(delt(i_p,:).^2);
end
%
%       check for the case n=1 (i.e., only one site)
%
if n==1
        xi2=zeros(p,1);
else
        xi2=xi2/(n*(n-1));
end
%
%       get matrix D xi square according to equation (7)
%
dxi2=diag(dxi2*xi2);
%
%       loop over the number of teams (p) and sites (n)
%       and get the covariance matrix Sigma according to equation (8)
%
for i_n=1:n
        sig=sig+delt(:,i_n)*delt(:,i_n)';
end
%
%       check for the case n=1 (i.e., only one site)
%
if n==1
        sig=zeros(p,p);
else
        sig=sig/(n-1)+dxi2;
end
```

```
%
%       update relative weights according to equation (9)
%
if i_upd==1
        numer=inv(sig)*ones(p,1);
        denom=ones(1,p)*inv(sig)*ones(p,1);
        wnew=numer/denom;
        er=[er sum((wnew-w).^2)];
        w=wnew;
else
        k=k_max;
        er=0;
end
                end
%
%       plot the convergence measure versus number of iterations
%
plot([1:k_max],er)
grid
title('Globar Error Measure for Relative Weights vs. Number of Iterations')
xlabel('Number of Iterations')
ylabel('Global Error Measure')
pause
print
%
%       now calculate the uncertainties
%
%
%       loop over the number of sites (n) and get the
%       propagated uncertainty according to equation (13)
%
for i_n=1:n
        sig2_pr(i_n)=sum(x_sd(:,i_n).^2);
end
sig2_pr=sig2_pr/p;
%
%       loop over the number of teams (p) and get the
%       team-to-team uncertainty according to equation (14)
%
for i_p=1:p
        sig2_t=sig2_t+((sum(x_m(i_p,:))-sum(m))/n)^2;
end
sig2_t=sig2_t/(p-1);
%
%       get the total uncertainty according to equation (12)
%
sig2_tot=sig2_pr+sig2_t;
%
%       do some more ploting
%
x_m=[x_m
m];
x_sd=[x_sd
sig2_tot];
%
```

```
x_m=log10(x_m);
x_sd=log10(x_sd);
dx=0.01;
x=[-3:-dx:-9];
for i_n=1:n
for i_p=1:p+1
        pdf=[pdf
exp(-0.5*((x-x_m(i_p,i_n))/x_sd(i_p,i_n)).^2)/(sqrt(2*pi)*x_sd(i_p,i_n))];
end
plot(x,pdf)
grid
title('Site-Specific MLH for a Group of Experts and its Aggregated Group Consens
xlabel('Probability of Exceedance for a Specific Ground Motion Level (a*)')
ylabel('Probability Density Function')
pause
print
pdf=[];
end
```