From: "Jeffrey Kimball" <JeffreyK@DNFSB.GOV>
To: "Sarah Gonzalez" <SHG1@nrc.gov>
Date: 11/1/2007 9:27:39 AM
Subject: Re: thanks

Sarah here is the NRC SER on the EPRI SOG work. Jeff

>>> "Sarah Gonzalez" <SHG1@nrc.gov> 10/30/2007 11:48 AM >>>
Jeff,
I was wondering if you knew where I might be able to obtain the USGS
hazard study for the SRS. I'm particularly interested in the
contribution from the Eastern Tennessee seismic zone.
Thanks so much.
--Sarah
P.S I wasn't able to find the EPRI report with the NRC review in it.

>>> "Jeffrey Kimball" <JeffreyK@DNFSB.GOV> 10/29/2007 9:31 AM >>>
Sarah - Is the NRC review of the EPRI report published as Vol. 11 of
the EPRI Report? I
do not have a copy but if you do it may also be good to read what the
NRC Safety
Evaluation says? Jeff

>>> "Sarah Gonzalez" <SHG1@nrc.gov> 10/29/2007 8:56 AM >>>
Hi Jeff,
Thanks so much for taking the time to talk to us this morning! We
really appreciate it.
--Sarah

Hearing Identifier: Vogtle_Non_Public
Email Number: 8076

Mail Envelope Properties (475E563A.HQGWDO01.TWGWPO04.200.200000C.1.12D9FA.1)

Subject: Re: thanks
Creation Date: 11/1/2007 9:27:39 AM
From: "Jeffrey Kimball" <JeffreyK@DNFSB.GOV>

Created By: JeffreyK@DNFSB.GOV

Recipients
"Sarah Gonzalez" <SHG1@nrc.gov>

Post Office	**Route**
TWGWPO04.HQGWDO01	nrc.gov

Files	**Size**	**Date & Time**
MESSAGE	848	11/1/2007 9:27:39 AM
NRC EPRI SOG SER.pdf	1908248	12/11/2007 9:19:54 AM
Mime.822	2613728	12/11/2007 9:19:54 AM

Options
Priority: Standard
Reply Requested: No
Return Notification: None
None

Concealed Subject: No
Security: Standard

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

SEP 2 0 198$

Mr. Ruble A. Thomas, Chairman
Licensing Steering Panel
Seismicity Owners Group
Southern Company Services, Inc.
P.O. Box 2625
Birmingham, Alabama, 35202

SUBJECT: SAFETY EVALUATION REVIEW OF THE SOG/EPRI TOPICAL REPORT TITLED "SEISMIC HAZARD METHODOLOGY FOR THE CENTRAL AND EASTERN UNITED STATES", EPRI NP 4726

We have completed our review of the subject topical report submitted by the Seismicity Owners Group by letter dated July 14, 1986. Enclosure 1 constitutes our Safety Evaluation Report (SER) which was prepared after reviewing the Technical Evaluation Report (TER), Enclosure 2, developed under contract by the United States Geological Survey. We concur with the findings contained in the TER.

We find that the EPRI NP-4726 topical report and associated submittals to be an acceptable methodology to be used in calculating seismic hazard in the central *and* eastern United States, provided that certain precautions outlined in the safety review are adhered to. Although it is generally understood that the SOG/EPRI topical report will be used in assessing seismic issues at nuclear power plants, acceptance of the topical report involves only acceptance of the methodology. Any application to regulatory issues is not part of this approval and.will require a separate review. In regulatory application it is the staff's intention to compare seismic hazard calculations resulting from the application of the SOG/EPRI methodology to results available from similar studies.

In accordance with procedures established in NUREG-0390, it is requested that the Seismicity Owners Group publish accepted versions of this report, proprietary and non-proprietary, within three oaths of receipt of this letter. The accepted 4ersions shall incorporate this letter and the enclosed evaluation between the title cage end the abstract. The accepted versions shall include an -A (designating accepted) following the report identification symbol.

Should our criteria or regulations change such that our conclusions as to the acceptability of the report are invalidated, licensees referencing the topical report will be expected to revise and resubmit their respective documentation, or submit justification for the continued effective applicability of the topical report without revision of their respective documentation.

Sincerely,

James E. Richardson, Assistant Director
for Engineering
Division of Engineering and Systems
Technology
Office of Nuclear Reactor Regulation

Enclosures: 1. Safety Evaluation Report
2. USGS Review Report

cc: J. C. Stepp
R. L. Wesson
S. T. Algermi.ssen
D. M. Perkins
B. K. Bender
P. C. Thenhans

Southern Ccmpanv Services. Inc.
800 Shades Creek Parkwl:
Post Office Box 2625
Birmmgnam, Alabama 35202
7eleorione 205 870-6011

Ruble A. Thomas

the southern electric *system*

October 26, 1988

Mr. James E. Richardson
Assistant Director for Engineering
Division of Engineering and Systems Technology
Office of Nuclear Regulatory Research
U. S. Nuclear Regulatory Commission
Washington D. C. 20555

Subject: Safety Evaluation Review: SOG Topical Report, "Seismic Hazard Methodology for the Central and Eastern United States."

Dear Mr. Richardson:

We are pleased to have the NRC Staff's Safety Evaluation Review (SER) of SOG's topical report, "Seismic Hazard Methodology for the Central and Eastern United States" and the Technical Evaluation Report (TER) prepared by the U. S. Geological Survey. We appreciate the serious, thorough review effort that was expended and we are delighted that the NRC has found the SOG's seismic hazard methodology and seismic source interpretations acceptable to be used in calculating seismic hazard in the central and eastern United States. We note that the staff conditioned its approval by noting four areas in which problems may arise if precautions are not observed, as follows:

1) ",Future users . of the methodology should verify that the earthquake-magnitude recurrence relationships resulting from the assumed smoothing parameters are consulted at the magnitude 5 level to avoid unrealistic fluctuations between cells. Parameter choices which may cause undesirable results are low or no smoothing on b values and weak or no prior estimates on b values.

2) The methodology should not be applied to sites in the near field of large known causative faults where the point source approximation breaks down and the finite nature of the rupture fault must be taken into acccunt. An example of such an areas is the New Madrid area.

3) For seismic hazard calculations in areas of the CEUS where new discoveries (e.g., Meers fault) may significantly //S//

affect the seismic hazard, the input parameters should be reassessed to ascertain their validity with respect to these discoveries.

4) Because of unresolved questions concerning the group consensus seismic hazard estimate scheme, the staff will place primary emphasis on those hazard calculations that utilize equal weights for combining the data collected b y each earth science team.

With respect to item one: The six interpretations included in SOG's Topical Report (EPRI NP-4726, Vols 5 through 10) were reviewed during the staff's topical review and found to satisfy this caution. The SER has been appended to the Topical Report for reference by future users.

With respect to item two: **None** of the SOG member's sites (attachment) fall within the near field of a large, known causative fault; thus this caution does not apply for the set of sites. The SER is appended to SOG's Topical Report for reference by future users.

With respect to item three: The SER is appended to SOG's Topical Report for reference by future users.

With respect to item four: The SOG continues to support the group consensus input weighting approach as state-of-the-art. However, we recognize the concerns raised by the TER and in the SER. Accordingly, final aggregation for site specific computations now underway will utilize only equal weights on team inputs.

In addition to the above four cautions, the SOG in its July 8, 1988 response to staff questions committed to include all seismic sources within 200 km in the seismic hazard computations for members sites. Accordingly, seismic hazard computations will be made for all sources within 200 km of each site. Because of the volume of computational time required to aggregate the results from such a large number of sites, a large portion of which will not contribute to the final aggregated site hazard, the following approach is being used to identify contributing sources.

1. Seismic hazard will be computed for all sources within 200 km of each si*.e using a single, most conservative, ground motion attenuation relation (Nuttli-Herrmann). Computations will be made for two ground motion levels - one Hz and pga.

2. Sources will be ordered on decreasing hazard contribution and a running sum of the site's total hazard will be computed for each of the two ground motion levels. Sources that contribute one percent or more to the site's hazard at either ground motion level will be included in the aggregated computations.

This approach insures that all sources within 200 km of each site will be included in the site's hazard computation and that all contributing sources will be included in the aggregated results for each site.

Seismic hazard will be computed for those nuclear plant sites where owners are currently contributors to the Seismicity Owners Group. A listing of current contributors and sites is attached to this letter.

Computations have been initiated. Our final report containing hazard results and supporting resolution of the "Charleston Earthquake issue" is scheduled to be submitted to the NRC on April 14, 1989.

Please contact me if you have any questions.

Sincerely,

Ruble A. Thomas
Chairman
SOG Licensing Steering Panel

JCS:dh

Enclosure - SOG Members and Nuclear Plant Sites

cc: S. Burstein
J. Taylor
A. Rubio
C. Stepp
W. Lindblad (NUMARC)
J. Whitcraft (NUMARC)
R. Whorton
SOG Company Contacts
SOG Oversight Committee

SEISMICITY OWNERS GROUP MEMBER AND PLANT LISTING

Alabama Power Company
  Joseph M. Farley 1 & 2

Arkansas Power & Light.Co.
  Arkansas Nuclear 1 & 2

Baltimore Gas & Electric
  Calvert Cliffs 1 & 2

Boston Edison Company
  Pilgrim 1

Carolina Power & Light Co.
  Robinson 2
  Brunswick 1 **& 2**
  Shearon Harris 1

The Cleveland Electric Illuminating Co.
  Perry 1

Commonwealth Edison Company
  Dresden 2 & 3
  LaSalle County 1 & 2
  Zion 1 & 2
  Byron 1 & 2
  Braidwood 1 & 2
  Quad-Cities 1 & 2

Connecticut Yankee Atomic Power Company
  Haddam Neck

Consolidated Edison Company
  Indian Point 2

Detroit Edison Co.
  Fermi 2

Duke Power Co.
  Oconee 1, 2 & 3
  McGuire 1 & 2
  Catawba 1 & 2

Duquesne Light Co.
  Beaver Valley 1 & 2

Florida Power & Light Co.
Turkey Point 3 & 4
St. Lucie 1 & 2
(Performing computations independently of the Seismicity Owners Group and will not be included in SOG future submittal to the NRC)

Florida Power Corporation
Crystal River 3

Georgia Power Co.-
Edwin I Hatch I & 2
Vogtle 1 & 2

GPU Nuclear Corporation
Oyster Creek 1
Three Mile Island 1 & 2

Gulf states utilities Co.
River Bend 1

Houston Lighting & Power Company
South Texas Project 1 & 2

Illinois Power Co.
Clinton 1

Kansas Gas & Electric Co.
Wolf Creek

Louisiana Power & Light Co.
Waterford 3

Maine Yankee Atomic Power Co.
Maine Yankee

New Hampshire Yankee, Inc.
Seabrook 1

New York Power Authority
James A. Fitzpatrick
Indian Point 3

Niagara Mohawk Power Corp.
Nine Mile Point 1 & 2

Northeast Utilities
Millstone 1, 2 & 3

Northern States Power Co.
Monticello
Prairie Island 1 & 2

Pennsylvania Power & Light Co.
    Susquehanna 1 & 2

Philadelphia Electric Co.
    Peach Bottom 2 & 3
    Limerick 1 & 2

Public Service Electric & Gas Co.
    Salem 1 & 2
    Hope Creek 1

Rochester Gas & Electric Corp
    Robert E. Ginna

South Carolina Electric & Gas Co.
    Virgil C. Summer 1

Tennessee Valley Authority
    Browns Ferry 1, 2 & 3
    Sequoyah 1 & 2
    Watts Bar 1 & 2
    Bellefonte 1 & 2

Texas Utilities Generating Company
    Comanche Peak 1 & 2

Toledo Edison Co.
    Davis-Besse 1

Vermont Yankee Nuclear Power Co.
    Vermont Yankee

Virginia Power
    Surry 1 & 2
    North Anna 1 & 2

Wisconsin Electric Power Co.
    Point Beach 1 & 2

Wisconsin Public Service Corporation
    Kewa unee

Yankee Atomic Electric Co.
    Yankee Rowe

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, O. C. 2064

DEC 121988

fir. Ruble A. Thomas, Chairman
Licensing Steering Panel
Seismicity Company Services, Inc.
P.O. Box 2625
Birmingham, Alabama, 35202

Subject: Safety Evaluation Review: Seismic Owners Group (SOG) Topical Report, "Seismic Hazard Methodology for the Central and Eastern United States."

Dear Mr. Thomas:

Thank you for your letter dated October 26, 1988 in which you outlined SOG's plan to undertake the site-hazard calculation phase of the SOG/EPRI seismic hazard methodology (SHM).

We agree that the method outlined to include any significant contribution from seismic sources within a 200km radius of each site is reasonable and acceptable. However, contributions from such sources as hew Madrid, LaMalbaie and Charleston should still be included if they are within a 500km radius from the site in question.

We noted that **some** eight utilities chose not to participate in the program. If any of those utilities, or Florida Power and Light which is performing **calculations independently,** wish to submit seismic hazard calculations which refer to the EPRI-SHM Safety Evaluation Review (SER), the staff will require the utility in question to demonstrate that all limitations discussed in the SER have been adhered to and that the results would be identical to those that would have been obtained, had the site been included in the SOG/EPRI calculations. Any deviations from this approach will require a separate review. Similarly, ground motion models used shall be consistent with those recommended In the Reiter to Thomas letter of August 3, 1988.

In addition **we** wish to make some recommendations with respect to the format of the results as Indicated in a letter from Stepp to Reiter dated October 27, 1988:

1. **We** recommend that the seismic hazard results be displayed both in graphical and numerical form.

2. **We** recommend that, if feasible, the 5th and 95th percentiles be calculated in addition to the 15tn, 50th and 85th as proposed.

3. We recommend that sensitivity analyses be performed to identify significant contributors to the hazard calculated such as magnitude ranges (5<m <5.25, 5.254m < 6.5, 6.5 < m), distance ranges (0-15km, 15-9Okm, 50-150km, Ad those greater ~han 150km), and source zones

We are looking forward to the completion of this very worthwhile project. Should you have any question concerning our comments and recommendations, please contact Leon Reiter at (301) 492-0841.

Your letter of October 26, 1988 and this response should be attached to the Safety Evaluation Review and the topical report since it does modify statements made in those documents.

Sincerely,

AOOVI

s E. Richardson, Assistant Director
for Engineering
Division of Engineering and Systems
Technology
Office of Nuclear Reactor Regulation

cc: J. C. Stepp
L. Shao

ABSTRACT

Aided by its consultant, the U.S. Geological Survey (USGS), the Nuclear Regulatory Commission (NRC) reviewed "Seismic Hazard Methodology for the Central and Eastern United States."* This topical report was submitted jointly by the Seismicity Owners Group (SOG) and the Electric Power Research Institute (EPRI) in July 1986 and was revised in February 1987.

The topical report consists of the following volumes and ancillary documents:

- Volume 1: "Methodology and Theory"
- Volume 2: "Programmer's Manual"
- Volume 3: "User's Manual"
- Volume 4: "Applications"
- Volumes 5 through 10: Tectonic interpretations by the six EPRI earth science teams
- Volume 11: Responses to NRC's first round of questions and scientific Peer Review Panel Report
- Volume 11, Supplement 1: Responses to NRC questions
- Volume 11, Supplement 2: Responses to NRC's second round of questions
- Volume 11, Supplement 3: Additional responses to NRC's questions
- Letter report, June 3, 1988: Response to USGS comments of May 26, 1988, on EPRI's seismic hazard methodology
- Transmittals, July 8 and 19, 1988: Responses to NRC questions

The NRC staff concludes that SOG/EPRI Seismic Hazard Methodology as documented in the topical report and associated submittals, is an acceptable methodology for use in calculating seismic hazard in the Central and Eastern United States (CEUS). These calculations will be based upon the data and information documented in the material that was submitted as the SOG/EPRI topical report and ancillary submittals. However, as part of the review process the staff conditions its approval by noting areas in which problems may arise unless precautions detailed in the report are observed.

*EPRI NP-4726

CONTENTS

APPENDICES

SAFETY EVALUATION REVIEW OF SOG/EPRI REPORT, "SEISMIC HAZARD METHODOLOGY FOR THE CENTRAL AND EASTERN UNITED STATES" (EPRI NP-4726)

1 BACKGROUND

During the past ten years, many groups have studied the seismotectonics of the Central and Eastern United States (CEUS). Although these studies have contributed significantly to the understanding of the seismotectonic regimes in the CEUS, a direct correlation between seismic activity and identifiable tectonic structures remains hypothetical to a large degree. However, concerns have arisen with respect to the possibility that large, damaging earthquakes could occur at locations not normally considered. Most importantly, in a letter dated November 18, 1982 (Reference 1), the U.S. Geological Survey (USGS) informed the U.S. Nuclear Regulatory Commission (NRC) that:

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

This letter represents not so much a new understanding but rather a clearer recognition of existing uncertainties with respect to the causative structure and mechanism of the 1886 Charleston earthquake. Many hypotheses have been proposed about where on the eastern seaboard Charleston-size earthquakes are likely to occur. Some of these hypotheses are very restrictive in location; others would allow these earthquakes to recur over very large areas. Presently, none of these hypotheses are definitive and all contain a strong element of speculation. However, traditional deterministic approaches such as that outlined in Section 2.5.2 of the NRC Standard Review Plan (Reference 2) were not designed to deal with this situation. Probabilistic methods that allow for the consideration of many hypotheses, their associated credibilities, and the explicit incorporation of uncertainty are much better equipped to provide rational frameworks for decisionmaking.

One way of addressing uncertainty in seismic issues is by using probabilistic assessments of seismic hazard. NRC has contracted with its consultants at the Lawrence Livermore National Laboratory to expand on its Uniform Hazard Methodology Program which was developed for the Systematic Evaluation Program. This methodology relies upon the incorporation of diverse expert opinion with regard to the input parameters needed to make probabilistic estimates. In addition, the methodology attempts to incorporate the uncertainties associated with the hypotheses suggested by the experts as well as uncertainties arising from computational methods. With the understanding that'different methodologies and different groups of experts could arrive at different estimates of seismic hazard, the staff suggested that the nuclear power utility industry conduct an independent assessment parallel to the probabilistic assessment to be undertaken by LLNL, which would facilitate the decisionmaking process for the NRC (Reference 3). As a result, a number of nuclear power utilities in the Central and Eastern United States formed the Seismicity Owners Group (SOG) which in a joint effort with the Electric Power Research Institute (EPRI) planned and developed a methodology to address the so-called "Charleston earthquake issue" using a probabilistic approach. The SOG/EPRI effort has culminated in an 11-volume topical report titled "Seismic Hazard Methodology (SHM) for the Central and Eastern United States."

The topical report consists of the following volumes and ancillary documents:

- Volume 1: "Methodology and Theory"
- Volume 2: "Programmer's Manual"
- Volume 3: "User's Manual"
- Volume 4: "Applications"
- Volumes 5 through 10: Tectonic interpretation by the six EPRI earth science teams
- Volume 11: Responses to NRC's first round of questions and scientific Peer Review Panel Report
- Volume 11, Supplement 1: Responses to NRC questions
- Volume 11, Supplement 2: Responses to NRC's second round of questions
- Volume 11, Supplement 3: Additional responses to NRC's questions
- Letter report, June 3, 1988: Response to USGS comments of May 26, 1988 on EPRI's seismic hazard methodology
- Transmittals, July 8 and 19, 1988: Responses to NRC questions

The staff engaged the USGS as its consultant for the review of this topical report. NRC and its consultant have worked with EPRI. during the development stage by attending the workshops organized by EPRI for the purpose of facilitating interaction between the earth science teams (ESTs) formed to provide scientific input into the SHM. On July 14, 1986, SOG submitted the topical report to NRC for review as outlined in the NRC Topical Report Program. The staff's evaluation of the topical report follows. Also, appended to this evaluation is the report to the NRC by its consultant, the USGS (see Appendix H).

2 INTRODUCTION

Probabilistic seismic hazard analysis provides a basis for informed decision-making about earthquakes and their associated vibratory motions. Probabilistic analysis can be a powerful tool for obtaining information about a specific process, although it is subject to a degree of uncertainty accompanying the parameters specified as input. In the probabilistic seismic hazard analysis for the CEUS, three major factors contribute to uncertainty, namely: (1) the short record (in time) of seismic activity in the United States, (2) the general absence of surface expressions of active faults (the Meers fault appears to be the only exception), and (3) a lack of understanding of the causative association between geologic features and mid-plate earthquakes.

To deal with these uncertainties and to make use of the state-of-the-art earth science practices, EPRI convened six teams of experts in the fields of geology, seismology, and geophysics to prepare and interpret input to the seismic hazard analysis, hereafter called the SOG/EPRI Seismic Hazard Methodology (SHM). These teams were first called technical evaluation teams (TEC's) (the appended review by the USGS refers to the teams as TEC's), and were later renamed earth science teams (EST's) (both the /EPRI topical report and the NRC review refer to the teams as EST's). The team approach was used to achieve the interdisciplinary expertise needed to evaluate various data sets and tectonic processes. Team personnel were selected for their academic and applied experience as well as for their regional expertise.

The aim of the SOG/EPRI SHM was to compile and present up-to-date and uniform sets of seismological, geological, and geophysical data to a group of prominent scientists in the fields of geology, seismology, and geophysics for interpretation in a manner that would (1) reflect a systematic understanding of both the input data and the interpretative procedure, (2) allow integration of available scientific knowledge, and (3) accept a quantified expression of uncertainty. In addition, the methodology provided for elaborate documentation of structured interpretations leading to seismic source interpretations that are fully trackable and amenable to scientific peer review.

3 THE SOG/EPRI SEISMIC HAZARD METHODOLOGY

3.1 Overview

In this topical report, SOG and EPRI offer a means of estimating earthquake hazard at a site in the CEUS in terms of probabilities of exceedance for specified levels of a chosen ground motion parameter. The methodology provides for a specification of the locations of future earthquake sources and for a characterization of future seismicity for each of the sources. (The attenuation functions for the ground motion parameters needed for determining the final ground motion exceedance calculation have been treated by SOG/EPRI separately. Thus, the staff's review of the ground motion issue is the subject of an independent evaluation, not reported here.)

The methodology provides procedures for specifying seismic sources and the accompanying rate of activity which are probably the most ambitious, extensive, and comprehensive ever undertaken for the Eastern United States. The source specification part of the methodology allows the use of either conventional source zones (bounding tectonic features or areas of historical seismicity) which can be subdivided into smaller "cells" to allow for local variation. Important technical steps taken by EPRI are the explicit representation of the subjective probability that a candidate tectonic feature is seismically "active" and the provision for various scenarios in which different combinations of features are judged to be active. The probability that a given feature is active is determined by the interaction of a generic characteristic matrix and a feature assessment form. The.characteristic matrix for each possible combination of"the characteristics specifies the probability that any hypothetical feature is active, given the presence of the particular combination of characteristics. The feature assessment form, for each real candidate feature, gives the team's estimate of the likelihood that each of the characteristics is present. This matrix description is intended to explicitly (1) specify the analyst's professional opinion as to the significance of a given tectonic characteristic, (2) document the analyst's assessment of the likelihood of the presence of the characteristic at each feature, and (3) provide some consistency in the assessment of probability of activity (p^A), across all features.

The characterization of the seismicity part of the methodology makes the usual assumptions of Poisson occurrences and Gutenberg-Richter magnitude distribution. The EPRI methodology provides for the description of seismic parameters (rate, b values, and maximum magnitudes) for each of the cells in a latitude-longitude grid, that is, cell-by-cell spatial variation of seismicity within a source zone is allowed. The use of the conventional "homogeneous" seismic rate throughout any source zone is also possible. This "seismic parameter methodology" includes the novel use of a penalized maximum likelihood technique to simultaneously estimate, for each cell, a values and b values and the probability of having detected a random earthquake of a given size in a given historical time window. Ancillary to the seismicity parameter methodology is the determination of a "uniform" magnitude, m_b*, used to obtain equivalent rates for magnitudes converted from various magnitude scales and intensities.

As stated in the report: "The fundamental goal of the study was to develop a methodology that would incorporate state-of-the-art scientific and engineering approaches and include uncertainty estimates that reflect the current state of scientific understanding of earthquake causes and processes." The state-of-the-art features were largely incorporated in the source specification and seismicity characterization methodologies. "Current scientific understanding" was provided through a series of workshops bringing together specialists in tectonics, seismicity, etc. "Uncertainty estimates" were provided by using multiple assessments of parameters and multiple specification of inputs.

The methodology was realized by assembling six teams of scientists, incorporating in each team the viewpoints of academic and consultant specialists. These teams were asked to develop the tectonic interpretations, source specifications, and seismicity parameter inputs for the hazard analysis. The review by NRC and USGS staffs considered the methodology itself and its implementation. The NRC staff agrees with the comment in the USGS review which states that:

> The EPRI methodology is a major step forward in documenting and integrating all the aspects involved in conducting a seismic hazard analysis. Particularly to be commended are the-flexibility afforded by the seismicity characterization part of the methodology, the documentation provided by the source characterization part of the methodology, and the general aim (and achievement) of rendering explicit and detailed the many aspects of hazard estimation procedures that were previously considered only implicitly or vaguely. In this latter category, we call attention to the determination of completeness of the seismic record in various magnitude ranges, over various lengths of time, in various geographic regions. We also believe that the documentation provided by the feature assessment methodology is a very desirable feature of the methodology.

However, USGS staff recognizes that certain aspects of the methodology and its associated input parameters could lead to unrealistic estimates of seismic hazard. The areas of concern are listed below and discussed individually in Sections 3.2 through 3.7 of this Safety Evaluation Review.

- Feature Matrix Methodology
- Seismicity Parameter Method
- Magnitude Conversion Approach
- Maximum Magnitude Assumptions
- Zone Exclusion Distance Approach
- Group Consensus Seismic Hazard Estimate Scheme

3.2 Feature Matrix Methodology

The feature matrix methodology (FMM) was developed as a consequence of EPRI's *interpretation of the 1982 clarification (Reference 1) of the USGS position* on the implications of the Charleston, South Carolina, earthquake of 1886. The FMM attempted to address the problem of assessing seismic hazard by adhering to two basic premises:

(1) The state-of-the-art knowledge of geological and geophysical features of the contiguous 48 States and the dominant mechanics generating moderate-scale or large-scale earthquakes should be sufficiently clear to serve as a basis for seismic hazard interpretations.-

(2) The approach to identifying seismic sources and their associated activity characteristics should rely on a format that would facilitate both the assignment of probability of activity (expressing a measure of uncertainty) and the aggregation of these probabilities. In addition, this format should be structured in such a way that the input data can be simply and unambiguously tracked.

The USGS commented that the EPRI seismic hazard methodology provides procedures for source specification and seismicity characterization which are probably the most ambitious, extensive, and comprehensive ever undertaken for the Eastern United States. In this methodology, the probability that a candidate feature is "active" (i.e., that it can generate an earthquake) is determined by the interaction of a generic characteristic matrix and a feature assessment form. The characteristic matrix specifies the probability that any hypothetical feature is active given the presence of the particular combination of characteristics. The feature assessment form gives the likelihood that each characteristic is present. This method (matrix description) is intended to (1) explicitly specify the analyst's professional opinion as to the significance of a given tectonic characteristic (with respect to seismic hazard), (2) document the analyst's assessment of the likelihood of the presence of the characteristic at each feature, and (3) provide some consistency in the assessment of the probability of activity (p^A) across all features.

The USGS noted that the FIN data presented by the different earth science teams were biased toward recorded (historic) seismicity. All other characteristics being the same, the probability of activity assigned to a feature was generally larger if it had a favorable association with seismicity than if it had a favorable association with another characteristic, such as a particular tectonic feature.

The USGS indicated that a consequence of using "spatial correlation with historical seismicity" as the most important factor in assessing-the probability of feature activity p^A would be that low values of p^A will predominate if the historic earthquake record is not a true picture of the prevailing tectonic stress regime. Furthermore, the USGS stated that in the Eastern United States the historic earthquake record is generally considered inadequate because the seismic activity rate is relatively low and thus only a small fraction of the features identified would have spatial correlation with historic seismicity, especia fly when moderate to large earthquakes are considered.

The USGS finds that this feature characteristic methodology may result in highly seismic areas having their historical seismicity rate lowered, since most of the tectonic features that might contain that seismicity will not have p^A values near 1.0 and the seismicity tends to be "spread out" in scenarios in which the feature is not active. However, the USGS also stated that any methodology that utilizes alternative source zones would also result in lowering of the activity rate in historically active areas. Thus, local seismicity values assigned under the EPRI methodology may, in fact, be roughly comparable to those that would be obtained under other methodologies in which one models alternative sources and background source zones.

An example of this problem is the Meers fault which is considered to be an active fault but has no association with historic seismicity. On the other hand, the Meers fault as of today is unique in the CEUS and there appears to be a reasonable justification for emphasizing historic seismicity. As one earth science team noted: "Seismicity is often the best guide for identifying general areas of crust that are treated as features." The very basis of this project was to address the problem of having a historic record of a large event (the 1886 Charleston, South Carolina, earthquake) for which no tectonic feature could be identified. This fact leads-the staff to believe the EST's were well aware of the dilemma. Also, the clear recordkeeping of the assigned. probabilities and the kind of feedback that this recordkeeping provided to the EST's leads the staff to believe that the FMM is a viable approach to assessing seismic hazard and that the choices made by the various teams are **conscious "expert opinions." By convening a series of workshops, EPRI acted** commendably to incorporate geological and geophysical information and alternative tectonic hypotheses into the definition of seismic zones. These workshops served a multiple purpose of arriving at a consensus concerning (1) the **mode of compilation, analysis, and presentation of the necessary data and** (2) method and format for interpreting the data.

In the light of these efforts, the staff notes that the apparent emphasis placed by the earth science teams on historic seismicity as an indicator of future probable activity indicates that the basic knowledge needed to place greater reliance on alternative hypotheses aboyt the causes of earthquakes is simply not yet available. However, for areas in which significant new information (e.g., actual discoveries of active faults) is developing as a result of ongoing studies (e.g., the **Meers** fault), the input provided by the experts in this topical report should **be reexamined** to ascertain whether or not this (new) information has any significant impact upon the seismic hazard presented by sites affected.

3.3 Seismicity Parameter Method

The record of historic earthquakes in the CEUS is not long enough and not **accurate enough** to accurately predict the frequency and size of earthquakes. To compensate for this deficiency, EPRI devised a method based on the Gutenberg-Richter (empirical) magnitude- recurrence relationship together with a penalized maximum likelihood technique and applied it to-the (incomplete) historic record to estimate the distribution of earthquake magnitudes and to predict when and where earthquakes could occur. The EPRI algorithm allows for spatial smoothing of estimated a and b values (where the a value defines the rate of earthquake occurrence and the b value is the slope of that recurrence rate), smoothing of the probability of having detected random **earthquakes** of given magnitudes at given times in given areas, which may be as small as 1/2 degree in latitude and longitude (these areas are called cells). In addition, the EPRI method allows specification of a prior distribution on b values.

The USGS review notes that smoothing options in the EPRI met')odology range from reproducing historic cell-by-cell seismicity exactly to, in effect, "spreading" the observed historical seismicity uniformly over a large area. The methodology allows the analyst to formulate -a more detailed representation of the selected seismicity model than is permitted by the usual techniques. It is intended also to allow the analyst to evaluate uncertainty by providing several options for estimating and smoothing parameters.

The USGS review comments that the seismicity parameter method is a powerful tool, and is perhaps the most significant of the EPRI innovations because it advances the difficult process of estimating earthquake recurrence rates from incomplete data. However, the USGS expressed concern about the applicability of the method because the particular formulation used by EPRI results in an interdependence of the estimated rate of occurrence (value a) and the distribution (value b) of earthquakes, i.e., the estimated a and b values are interdependent. According to the USGS, the effect of the EPRI formulation is such that, under certain conditions (low or no smoothing on b values and weak or no prior estimates on b values), the results lead to excessive variability. For instance, some choices of smoothing in the EPRI algorithm produce greater variability in the rates of earthquakes with magnitudes greater than 5 than can be justified by the actual data. In the SOG/EPRI methodology submittal which documents the choices on prior estimates and smoothing, parameters were generally selected which should avoid this behavior. Thus, although it is possible that some combinations of smoothing options and choices of prior estimates may give rise to excessive variability, these choices were rare and neither the NRC staff nor the USGS staff expect that this problem will significantly affect the overall site hazard estimates resulting from the application of parameter choices documented in the"SOG/EPRI topical report.

EPRI examined an alternate method suggested by the USGS and discussed its findings with the NRC staff. EPRI concluded that the USGS method did not produce superior results when the earthquake record is incomplete (as is the case for the CEUS).

The NRC staff recommends that future users of the SOG/EPRI methodology adequately address the above problems. In particular, the staff recommends that the earthquake-magnitude recurrence relationships (Reference 4, Volume IV, Figures 4-3 to 4-5) resulting from the assumed smoothing parameters be examined to ascertain that the cell-to-cell recurrence rates show no excessive variability above the magnitude 5 level. Parameter choices that may cause undesirable results are low or no smoothing on b values and/or weak or no prior estimates on b values.

3.4 Magnitude Conversion Approach

Because earthquake sizes have been recorded in various terms (m_{bLg}, m_b, M_L, M_s, I_O, etc.), EPRI converted all available data from earthquake catalogs to a common m_b* value which was assumed to exhibit the same exceedance rate as the true m_b value (i.e., the instrumentally derived m_b value had the earthquake been recorded with the proper instrument).

The USGS expressed concern that because of the variability in the conversion of different measures of magnitude to one common scale (m_b*), relative weights should have been assigned to the converted data depending upon how the original magnitude had been measured. This could affect the estimation of recurrence rates (b values). EPRI disagrees strongly with the USGS (Reference 5). In any case, because of the input assumptions on smoothing and prior estimates (of the a and b values) used by EPRI, the USGS does not consider this to have a significant impact; consequently, the staff does not consider this an important issue.

3.5 Maximum Magnitude Assumptions

One of the constituent operations of the SOG/EPRI SHM is the assignment of maximum earthquake magnitudes to each source zone identified. Several earth science teams used the observed (historic) maximum magnitude (within a designated error band) as a basis for establishing an upper bound maximum magnitude for most source zones. Because of the low rate of seismicity in most eastern areas, relatively few zones exhibit maximum magnitudes equal to or greater than the magnitude of the Charleston 1886 earthquake. The USGS indicated that this approach, if used, tends to diminish the probability that a large 1886 Charleston-type earthquake will occur anywhere but in specifically designated zones. However, both the USGS and the NRC staffs find that the EST's were aware of problems associated with truncating the earthquake-recurrence relationships used. This is exemplified by at least one EST choosing extrapolated low-recurrence-rate magnitudes equal to or larger than magnitude 6.6 (the estimated magnitude of the 1886 Charleston earthquake) for a large number of zones outside the Charleston, South Carolina, seismic zone, and other EST's making broad use of an upper magnitude of 6.6 (with or without an error band) for specific features. Therefore, the staff finds that the EST's recognized the **issues** involved and that the choices made should be considered as "expert opinions."

Another concern expressed by the USGS is related to the choice of maximum magnitude in its (relative) relationship to the minimum magnitude that was set at 5.0 for all calculations. The use of a magnitude of 5 for the minimum magnitude makes the **calculated exceedance** rates of some ground motion levels more sensitive **to** the choice of maximum magnitude than would be the case if the lower bound magnitude were 4. The staff as well as EPRI are aware of this effect which was examined by LLNL (Reference 5) upon request from NRC. However, the staff finds that the choice of a lower bound of 5 for the minimum magnitude is an appropriate choice in the context of probabilistic estimates of seismic hazard. It should be noted also that LLNL, upon request from the NRC, is using a magnitude of 5 as the lower bound magnitude for its hazard calculations.

3.6 Zone Exclusion Distance Approach

Originally, EPRI included into its calculations of seismic hazard only those sources whose locations were within 100 km (62 miles) of the site under consideration. Exceptions were made with respect to sources of high seismicity and sources of very large earthquakes such as New Madrid, LaMalbaie, and Charleston sources.

USGS indicated concern that the basic 100-km inclusion distance may not be adequately conservative, particularly if several newly suggested ground motion models are used which show that significant ground motions could originate from earthquakes as far as 200 km away. Although this concern may be academic since EPRI is not planning to use those models, EPRI has since indicated to the NRC that it will extend the basic inclusion distance to 200 km. The staff considers this an appropriate action.

3.7 Group Consensus Seismic Hazard Estimate Scheme

Test results calculated by using the EPRI methodology (Reference 4) show two ways of aggregating the input from the individual earth science teams. One assumes equal weights to each EST and another assigns weights to each EST obtained from the group consensus seismic hazard estimate relation which is based on a measure of consistency of each EST.

The USGS finds that the EPRI methodology for determining group consensus seismic hazard estimates would tend to decrease the apparent hazard at a site if point estimates using mean log hazards are used rather than mean estimates. In addition, the USGS indicated that the weighting scheme used by EPRI to arrive at a "preferred consensus estimate" produced unrealistic results because teams that are "consistent" in their evaluation receive more weight than those whose estimates show wide variations.

The staff agrees with the USGS finding that the considerations by the teams, which should be considered "expert opinions," cannot be evaluated according to a measure of consistency when no standard of what is consistent in the deliberations of the teams can be reasonably estimated.' A problematic result of the group consensus seismic hazard estimate method is that in certain cases the estimates of some teams were effectively omitted because of the team's "inconsistency."

The staff, therefore, will place primary emphasis on those results from the hazard calculations in which all teams are given equal weights.

4 SUMMARY AND CONCLUSIONS

The NRC staff finds that the SOG/EPRI Seismic Hazard Methodology as documented in the topical report and identified as EPRI NP-4726, Volumes 1 through 11 and associated submittals (Reference 4), is an acceptable methodology for use in calculating seismic hazard in the Central and Eastern United States (CEUS). These calculations will be based upon the data and information documented in the material that was submitted as the SOG/EPRI topical report and ancillary submittals. However, as part of the review process, the staff conditions its approval by noting areas in which problems may arise if the following precautions are not observed:

(1) Future users of the methodology should verify that the earthquake-magnitude recurrence relationships resulting from the assumed smoothing parameters are consulted at the magnitude 5 level to avoid unrealistic fluctuations between cells. Parameter choices which may cause undesirable results are low or no smoothing on b values and weak or no prior estimates on b values.

(2) The methodology should not be applied to sites in the near field of large known causative faults where the point source approximation breaks down and the finite nature of the rupture fault must be taken into account. An example of such an area is the New Madrid area.

(3) For seismic hazard calculations in areas of the CEUS where new discoveries (e.g., Meers fault) may significantly affect the seismic hazard, the input parameters should be reassessed to ascertain. their validity with respect to these discoveries.

(4) Because of unresolved questions concerning the group consensus seismic hazard estimate scheme, the staff will place primary emphasis on those hazard calculations that utilize equal weights for combining the data collected by each earth science team.

It should be noted that the ground motion models needed to calculate seismic hazard are not included in this topical report. EPRI's submittal of ground motion models (Reference 7) will be reviewed separately by the staff.

EPRI has indicated that it considers the interpretations provided in the topical report (Reference 4) suitable for application for the SOG/EPRI methodology during the next five to tan years. Although NRC recognizes the need for stability and does not expect significant changes during the next few years, the staff cannot predict precisely when new generalized interpretations would be suitable.

Because such a wide range of uncertainties exists within the earth science community regarding seismic hazard in the CEUS in general and differences in estimating seismic hazard in particular, the staff intends to use seismic hazard calculations resulting from the application of the SOG/EPRI methodology in conjunction with similar results obtained from LLNL Seismic Hazard Characterization

Program (SHCP). If significant differences are observed that cannot be resolved, the NRC staff will use the two sets of calculations to define the range of seismic hazard to be used in the decisionmaking process. In any case, these uncertainties are such that the specific calculation of seismic hazard, be it that obtained by EPRI or LLNL, should be viewed with some caution. The staff finds that seismic hazard calculations are better used for making relative comparisons than for placing reliance upon the specific numerical estimates.

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APPENDIX A

ABBREVIATIONS

CEUS	Central and Eastern United States
EPRI	Electric Power Research Institute
EST	earth science team
LLNL	Lawrence Livermore National Laboratory
NRC	U.S. Nuclear Regulatory Commission
SHCP	Seismic Hazard Characterization Program
SHM	Seismic Hazard Methodology
SOG	Seismicity Owners Group
TEC	Technical Evaluation Team
USGS	U.S. Geological Survey

APPENDIX B

U.S. GEOLOGICAL SURVEY'S REVIEW OF SEISMICITY OWNERS GROUP/ELECTRIC POWER RESEARCH INSTITUTE SEISMIC HAZARD METHODOLOGY

Report to

the

U.S. Nuclear Regulatory Commission

REVIEW OF

SEISMICITY OWNERS GROUP-ELECTRIC POWER RESEARCH I STITUTE

SEISMIC HAZARD METHODOLOGY

by

U.S. Geological Survey

David M. Perkins
Bernice K. Bender
Paul C. Thenhaus

July 25, 1988

Review of
Seismicity Owners Group-Electric Power Research Institute
Seismic Hazard Methodology

I. Summary

I.A. Introduction

The U.S. Geological Survey (USGS) **was** asked by the Nuclear Regulatory Commission (NRC) to prepare a technical review of the Seismicity Owners Group-Electric Power Research Institute **(EPRI/SOG)** program to develop a probabilistic seismic hazard methodology for seismic hazard assessment in the eastern United States (EUS). The EPRI/SOG methodology is limited to the probabilistic assessment of earthquake ground motion and does not include the assessment of geological hazards such as landsliding and liquefaction that might be earthquake induced.

The aim of probabilistic ground motion analysis is to provide a description of the earthquake hazard at a site in terms of probabilities of exceeding specified levels of a chosen ground motion parameter. For input, the analysis requires a specification of the locations of future earthquake sources, characterization of the future seismicity for each of the sources, and an attenuation function for the ground motion parameter, in terms of magnitude and distance from the site to the source. The EPRI/SOG methodology considers all these features of a hazard analysis. (The attenuation functions used by EPRI/SOG in the submittal are intended to be exemplary rather than part of either the methodology or implementation submitted and, therefore, are not currently under review.)

EPRI/SOG stated that the fundamental goal of the study **was** to develop a methodology that would incorporate state-of-the-art scientific and engineering approaches and include uncertainty estimates that reflect the current state of scientific understanding of earthquake causes and procraees. The "state of the a W features were largely incorporated in the source specification and seismicity characterization methodologies. "Current scientific understanding" **was** provided through a series of topical meetings bringing together specialists in tectonics, seismicity, attenuation, etc. "Uncertainty estimates" were provided by using multiple assessments of parameters and multiple specifications of inputs.

Implementation of the methodology was aclLiewtd by assembling six teams of scientists, incorporating **in each team** the viewpoint of **academic** and consultant specialists. These teams were asked to **develop the tectonic** interpretations, source specifications, and seismicity parameter inputs for the hazard **analysis.** Throughout the project these teams **were** referred to as Tectonic **Evaluation Committees, or** TEC's, and bore contractor titles-Bechtel, Dames and lire, Law Engineering, Rondout, Wanton Geophysical and Woodward-G d*. The team members participated is a ammber of workshops at which they learned the ground rules, discussed proble=, and exchanged technical ideas and information. Within the specified **framework,** each TEC was encouraged to work independently, to develop its own interpretations, and to arrive at its own conclusions, in order to "encompass the diversity of scientific opinion." Different members of each team represented different disciplines and brought expertise in a variety of areas.

This USGS review of the EPRI/SOG submittal considers the methodology itself, the interaction of the methodology with the teams, and the teams' implementations of the methodology. The USGS objective is to assess the correctness of the EPRI/SOG methodology and the desirability of the properties and options designed into it, the support and guidance which the methodology affords the user in making choices among options or values of input parameters, and finally the correctness or prudence of the teams' implementations.

The EPRI/SOG seismic hazard methodology (EPRTI/SOG, v.1-11, 1986, 1987) provides procedures for source *specification* and seismicity characterization which are probably the most ambitious, extensive, and comprehensive ever undertaken for the eastern United States. The *source specification* part of the methodology allows the use of either conventional source zones (bounding tectonic features or areas of historical seismicity) or cells defined by a latitude-longitude grid. Important technical steps taken by EPRI/SOG are the **explicit representation of the subjective probability that a candidate** tectonic feature is seismically "active" and the provision for various scenarios in which different combinations of features are judged to be active. The determination of the probability that a given feature is active is accomplished by the ***interaction* of** a generic *characteristic-* matrix and *a feature* assessment form. **The characteristic** matrix, for each possible combination of the characteristics, specifies the probability that any *hypothetical* feature is active, given the presence **of the particular *combination* of characteristics.** The feature assessment form, for each real candidate feature, gives the team's estimate of the likelihood that each of the characteristics is present. This matrix description is intended to provide explicit **specification of the analyst's professional *opinion* as to the significance of a given tectonic** characteristic, to document the analyst's assessment of the likelihood of the presence of the characteristic- at each feature, and to assure some consistency in the assessment of probability of activity, pA, across all features.

The *characterization* of seismicity part of the methodology makes the usual assumptions of Poisson occurrences and Gutenberg-Richter magnitude-frequency relationship. The EPRI/SOG methodology provides for the description of seismic parameters (rates, b-values, and maximum magnitudes) for each of the cells in a latitude-longitude grid, that is, cell-by-cell spatial variation of seismicity within a source zone is allowed. The use of the conventional "homogeneous" seismic rate throughout any source zone is also possible. This "seismic parameter methodology" includes the novel use of a penalized maximum likelihood technique to simultaneously estimate, for each cell, a- and b-values and the probability of having **detected** a random earthquake of a given size at a given time in a given area. Ancillary to the seismicity parameter methodology is the determination of a "uniform" magnitude, mb, used to obtain equivalent rates for magnitudes converted from various magnitude scales and intensities.

In the following subsection, we present a summary view of individual aspects of the EPRI/SOG methodology, followed, in later sections, by more detailed analyses. The summary focuses on USGS concerns and on the "resolution" of those concerns. A concern, for example, might be that the'use of the methodology can lead to undesirable consequences if particular choices of parameters are used. The resolution might be that the TEC's were aware of the possible problems, and that in the submittal the particular choices were not made, or that they were made so infrequently that. the overall results would not be significantly affected.

LB. Overview

It is clear that overall the EPRI/SOG methodology is a major step forward in documenting and integrating all the aspects involved in conducting a seismic hazard analysis. We particularly commend the flexibility afforded by the seismicity characterization part of the methodology, the documentation provided by the source characterization part of the methodology, and the general aim (and achievement) of rendering explicit and detailed the many aspects of seismic hazard estimation procedures that were previously considered only implicitly or vaguely. In this latter category, we call attention to the determination of completeness of the seismic record in various magnitude ranges, over various lengths of time, in various geographic regions. We also believe that the documentation provided by the feature assessment methodology is a very desirable aspect of the methodology.

We believe that the methodology can be a powerful tool to use in obtaining probabilistic hazard estimates. EPRI/SOG **deserves** considerable credit for undertaking such a complex project and for the advances made through the development of this methodology. We do, however, in some instances, question aspects of the methodology and some of the TEC's implementations. Therefore, we suggest that the discussions contained in this **review be** considered when using the methodology in the future, and when evaluating the results from the submittal implementation.

In broad **overview, we** think it is **possible to characterize** the methodology as flexible to a fault. In order to permit the user all the choices he may wish to exercise, the EPRI/SOG methodology designers have sought to provide the user with the maximum amount of flexibility in implementation. This flexibility means that the user is presented with a large menu of choices. In our view, in some instances, the user may not be aware or forewarned of the consequences of particular choices. We are particularly concerned with some teams' choices of maximum magnitudes and pA-values, which may be strongly biased by the sparsity of the historical seismicity in the EUS. In keeping with other advances in the EPRI/SOG methodology, **we** would have preferred that the EPRI/SOG methodology provide the analyst more guidance in some instances.

Furthermore, due to what we consider an unfortunate formulation in the seismicity methodology, estimates of b-values are altered when a-values are spatially smoothed, and unless sufficient spatial smoothing in b values is requested (or sufficiently strong b-value priors are used), estimated **b-values** may **vary excessively** from cell-to-cell. In other words, **we believe user** flexibility in the choice of smoothing parameters needs to be limited. (We have suggested a revision to the equations which would remove the dependence of the estimated b-values on the estimated a-values, and which **we** believe, would also render the results more stable, and the algorithm faster in operation.)

In contrast to the flexibility provided by the methodology algorithms, the EP RI/SOG project sought to provide the teams with a common data base and a systematic procedure for evaluating the probability that a feature is active. The result **was** that the teams ended up with **less variation in approach to identification of** feature characteristics than we might have expected in a region where earthquake causes are unknown.

The following discussion provides somewhat more detail of various aspects of the methodology and implementation, particularly of those aspects that we questioned.

I.C. The Seismicity Parameter Methodology

Central to the EPRI/SOG characterization of seismicity is the use of a seismicity parameter methodology in which a penalized maximum likelihood technique is used to simultaneously estimate a and *b* values for earthquakes in each cell of a set of cells in a latitude-longitude grid. The EPRI/SOG algorithm thus permits estimated a- and *b* values to vary from cell-to-cell within a source, permits spatial smoothing of estimated *a* and *b* values, permits estimation and smoothing of the probabilities of having detected random earthquakes of given magnitudes at given times in given areas, and allows specification of a prior estimate of *b* together with the "strength" of that prior.

The EPRI/SOG methodology smoothing options range from reproducing historic cell-by-cell seismicity exactly to, in effect, "spreading" the observed historical seismicity uniformly over a large area. The methodology is intended to be less restrictive and allow the analyst a more detailed representation of the selected seismicity model than is permitted by the usual techniques. It also is intended to allow the analyst to reflect his/her uncertainty by permitting him/her to select several alternative options for estimating and smoothing parameters.

The EPRI/SOG goals are useful and desirable, and, to the extent that they have been achieved, they are a clear step forward. **However, we** are not convinced of the appropriateness of the specific equations that are used in the algorithm when a and b estimates are spatially smoothed. One demonstrable problem is that estimates of b values are altered when estimates of a values are spatially smoothed. For example, if 9, 3 and 1 earthquakes are observed in successive magnitude intervals (e.g., $3.3 < m < 3.9$, $3.9 \le m < 4.5$ and $4.5 \le m < 5.1$) in one cell (1° in latitude by 1° in longitude), and 18, 6 and 2 earthquakes are observed in the same intervals in a second cell, we would estimate the same b value for earthquakes in both cells when the b values are estimated for each cell individually. We would also obtain the same b **value** if all the earthquakes from the two cells are combined (yielding 27, 9 and 3 earthquakes in the three magnitude intervals), and a single b value is estimated **for the** combined data. However, in the EPRI/SOG procedure if the a values are spatially smoothed, the estimated b values for each cell are also altered, and are no longer the same for the two cells. Changing the estimate of *b* in this case to compensate for smoothing of a does not **seem** reasonable to us. In standard Bayesian techniques (e.g., see Cornell, *1972;* Mortgat and Shah, 1979; and Campbell, 1982) the estimate of the rate of earthquakes depends on the number of earthquakes observed and the estimate of b depends on the mean magnitude; estimates of rates and b-values do not covary.

We view the dependence of b-value estimates on a-value estimates under smoothing as undesirable. This covariance can result, for example, in cell-to-cell contrasts in seismicity rates in magnitude intervals above magnitude 5.0 that are significantly greater than the cell-to-cell contrasts in total numbers **of observed earthquakes** (magnitudes $M_b \ge 3.3$). Thus, some choices of smoothing parameters may put more variability into the smoothed fitted rates for $M_b > 5.0$ than is present in the observed data. (This variability appears to be controlled by using sufficiently strong smoothing on estimated b values or sufficiently strong priors on *b* values. In the EPRI/SOG submittal, most teams generally used strong smoothing on b values or strong priors on b values.)

The **consequences of selecting various *combinations* of** strengths of smoothing for a and for b estimates, and various strengths of the prior estimate of *b* are not always predictable. We noted some counterintuitive results in several examples provided by EPRI/SOG. In one case, the estimated b value obtained for a cell using moderate spatial smoothing of a and b values did not lie between the estimate obtained for lower smoothing and that obtained for higher smoothing. In another case, estimates of the probability of detection obtained for "moderate" smoothing on probability of detection did not lie between those obtained for "low" smoothing and those obtained for "high smoothing". EPRI/SOG responded that in the first case, the difference **was** not significant, and in the second case, the data cells considered did not provide sufficient ***"anchoring."*** We accept these responses, but believe the effects cited are clues to possible unstable behavior in the algorithm in other situations.

We derived the EPRI/SOG equations (in which estimates of a and *b* values covary), and an "alternate formulation" (in which the estimate of *b* does not depend on the estimate of a) for the case when the catalog is complete. We showed that the EPRI/SOG equations produce dependencies between estimated a and *b* values under smoothing due, in part, to ***conditioning* on fitted rates rather than observed numbers of earthquakes, and,** in part, to smoothing on (log) interval rates rather than on total rates.

We communicated the above formulation to **EPRI/SOG** (through NRC). SOG/ EPRI responded that necessarily a and *b* **values** will **covary** when one smooths over cells with different levels of completeness and detectibility, and that "the parametrization suggested by the USGS is not advantageous when one considers incompleteness, as one must do." We **believe** that algorithms should behave properly in **various cases,** including the case "data complete for all time intervals.' **We have** shown why the EPRI/SOG algorithm does not always behave properly when the data are complete, and, by inference, **we** do not. know whether the algorithm behaves correctly in other situations.

In smoothing a and b **values,, the methodology may** produce greater variability in the rates of earthquakes with magnitudes mb > 5.0 than is present in the data. In the submittal, teams generally selected smoothing parameter values which should avoid this behavior. While it is possible that some combinations of smoothing options may give this **excessive** variability in individnsl scenarios,. such choices were rare, and **we** do not expect that this problem will significantly affect **overall** site hazard estimates.

LD. The Feature Matrix Methodology

In order to select feature characteristics, the teams evaluated assorted hypotheses for earthquake causes, and exchanged technical **ideas** and information at a. **swim** of workshops. **However,** the relationship to earthquakes of the **various** physical characteristics considered remained somewhat ambiguous. All teams, **eventually,** selected the presence or absence of 'spatial association with seismicity' by a feature as the most important characteristic **to use** in estimating the probability that a feature is active. Using the consensus that earthquake sources are featus s responding to region-wide compression, all teams selected geometry relative to the stress field (orientation and/or **sense** of slip) being `favorable" or "unfavorable" as **a** second characteristic. Five of the six teams chose deep crustal expression being present near intersections (or with a barrier), present but not near intersections (or without a barrier), or not present, as the third characteristic.

All teams allowed the seismicity characteristic to dominate the tectonic characteristics. For example, each team assigned a higher probability of activity to a feature that has had spatial association with seismicity but has unfavorable geometry, than to a feature that has had no spatial association with seismicity but does have favorable geometry. One consequence of this dominance is that a feature that has no spatial association with seismicity is assigned a low probability of being active, regardless of the presence or absence of other "characteristics." The selection of "spatial association with seismicity" as a criterion means that historic earthquakes rather than physical criteria become the basis for estimating the probability of feature activity. This suggests that a tectonic basis for "generalizing" seismicity from features that have had earthquakes to "tectonically similar" features that have not had earthquakes was, in fact, not established.

The teams expended considerable effort to conscientiously evaluate the probability that each feature considered had each of the characteristics listed in the feature characteristic matrices, and then to document their findings in detail in the ten volume Final Report. We are impressed by the careful and **extensive** investigation and documentation of estimated probabilities that individual features have each of the specified characteristics.

In our opinion, using "spatial correlation with historical seismicity" as the most important factor in assessing the probability of feature activity, p^A, **has** its weaknesses. The seismic activity rate in the EUS is generally so low that only a small fraction of the features will have experienced "high spatial correlation with historical seismicity," much less association with moderate-to-high magnitude events. Consequently, when large numbers of features are candidates for assessment of probability of activity, the random nature of seismicity observed over the historical time span dominates the assigned values of pA, and low $_{pw}$ values will predominate. It seems likely to us that many features'will have a lower ^{pw} value than if only tectonic considerations governed assignment of $_{pw}$ values.

We believe that the feature **characteristic methodology will usually** result in highly seismic areas having predicted earthquake rates that are lower than the observed historic rates, since most of the tectonic features which might contain that seismicity will not have pA values near 1.0, and the seismicity tends to be "spread out" in scenarios in which the feature is not active. However, any other methodology which utilizes alternative source zones would probably also result in a lowering of the predicted activity rate in historically active areas. Thus, local seismicity values assigned under the methodology may, in fact, be roughly comparable to those that would be obtained under other methodologies in which one models alternative source structures and background source zones.

The **"effective"** seismic rate of a feature is the product of the p^A value assigned and the seismic rate attributed to the feature when it is active. Because the rate assigned to a feature when it active is also obtained from the historic seismicity, the sparseness of historic seismicity has a double effect for those features that do not **have a** clear spatial correlation with seismicity. This issue is of particular interest for sites in the vicinity of features which belong to an identifiable category (e.g., "basement arches" or "plutons") and for which there is seismicity present in the vicinity of all or most of such features, although there is no clear spatial correlation of seismicity at any individual feature. This correspondence of seismicity and feature should lead to the assignment of a high p" value.

Failure to assign such high values could result *in* local rates one-third to one-fifth (about the size of average p^A '3) those assigned under other methodologies, unless the background zone seismicity is sufficiently high. Inasmuch as two teams sought to counter such an effect-one by assigning a high p^A and a large percentage of regional seismicity to such features; another by grouping low-p^A features into high-p^A source zones, we assume that this effect **was** known to participants, some of whom may have chosen to ignore it for philosophical reasons.

The feature matrix methodology is a natural response to the need to make site specific estimates for ***which*** **the question of seismic potential of nearby** features is a prime issue. The emphasis on individual features in this methodology produces two effects which are likely to lead to differences in results from those which might be obtained using other methodologies, unless TEC's make a special effort to overcome these effects. 1. Geological themes which are not feature-oriented may not be represented as source zones. 2. Features which individually do not have strong spatial correlation with seismicity, but collectively do, may have p^A values which are too low.

The implementations of the methodology *in* the EPRI/SOG submittal have what we consider to be an overemphasis on the characteristic, "spatial correlation with seismicity." We believe this emphasis results in predominately low p^A values. For many sites, hazard estimates will be comparable to those obtained from other methodologies using alternative source zones. However sites in the vicinity of features having sparse seismicity are more likely to have hazard estimates that are driven by the seismicity of the background zones rather than that of the local features, compared with what might be expected from alternative methodologies.

I.E. Maximum Magnitudes

Several teams used observed maximum magnitude (plus or minus an increment) as a basis for ***establishing*** an upperbound maximum magnitude for some source zones. Because of the low rate of seismicity in most eastern areas, very few zones **are** likely to have observed magnitudes **even** half a unit below the Charleston 1886 magnitude. Probabilistic ground motion is very sensitive to changes in maximum magnitudes below 6.5 to 7.0. The use of relatively high **minimum** <u>magnitudes</u> in this submittal increases this sensitivity. Use of maximum observed magnitude **will *probably* account for some relatively low** site estimates *for* a teams.

Teams also chose maximum magnitudes on the basis of structural characteristics of the features, but since the Charleston area has no specific characteristics which can be shown to be associated with a magnitude as large as that of the 1886 earthquake, some choices of maximum magnitude may, in our opinion, be too low.

At least one team apparently compensated for each of these two problems, choosing extrapolated long-recurrence magnitudes in the one case, and making broad use of Charleston-value magnitudes in the other, and we believe that in general the TEC teams recognized the issues involved.

Finally, if background or default sources have lower maximum magnitudes than do the features contained in them, there may be diminution of the allowed recurrence of large-magnitude, Charleston-sized events *in* the scenarios *in* which not all features are active.

I.F. Magnitude Conversion

The USGS and EPRI/SOG differ over the manner in which to account for variability in the *conversion* of various measures of magnitude to a common magnitude scale, my. USGS reviewers also believe that different relative weights should be used when combining mb's from different scales, e.g., *combining* rn values from directly recorded m_b values with mb values obtained from converted intensity data, to estimate b values. The effects of incorrect conversion or lack of weighting could be substantial in the estimation of b values from large groups of data, as, for instance, when the data from all the cells are combined to obtain a "best overall value of b." In the EPRI/SOG implementation, the fitting of b values is generally strongly driven by smoothing and priors, and the data are sufficiently sparse in most cells, that even with conversion errors data are unlikely to drive fits for individual cells far from the priors. Also of concern is the possibility that the difference between a correct and an incorrect conversion places an *mb* value above or below some threshold value for consideration *in* assessing the probability of activity of a feature. The change in definition of activity from p' to p^A, in the latter part of the development of the methodology (which lowers the threshold magnitude), probably renders this latter concern relatively unimportant.

I.G. Zone Exclusion Distance

EPRI/SOG generally included in calculations of ground motion hazard only earthquakes in sources within 100 km of the site, with the exception of highly seismic sources (200 km) and the New Madrid and La Malbaie sources (500 km). We believe that 100 km is too small a distance for computing ground motion exceedances at the lower ground motion levels. However, the errors in the exceedances are probably not larger than a factor of two, and for higher ground motions the errors will be smaller.

These conclusions are based on studies using conventional attenuation functions. EPRI/SOG has recently funded work i**nvestigating** "real *attenuations,"* in which crustal properties, earthquake depths, mechanisms, and dominating phases are taken into account (Barker and others, 1988). Many of these "real attenuations" show significant ground motions coming from between 50 to 200 km. If **these attenuations** were to be used, the exclusion distance should be increased, unless it can be shown that using an increased distance has no significant impact on site hazard results.

I.H. EPRI/SOG Sources

In conventional methodologies, sources are either areal *source zones,* in which earthquakes are modeled as point ruptures, or *source faults,* on which earthquakes are modeled as linear ruptures, with rupture-length dependent upon magnitude. In the EPRI/SOG submittal, earth akes are modeled only as points in areal source zones. Treating earthquakes as infinitesimal point ruptures can substantially underestimate the calculated ground motion exceedances at sites near real faults. This is because the near-fault loci of constant ground motion, instead of being circular, become extended parallel to the rupture. It is not possible to adjust an attenuation function based on epicentral or hypocentral distance to give the same results at all sites as an attenuation function based on closest site-to-source distance in the *case* of finite ruptures (Bender, 1984).

We believe that a point-source model may be adequate for most areas of the eastern U.S., for the magnitudes assumed in those areas. However, in the New Madrid area we might expect large-magnitude earthquakes to have rupture lengths of tens of kilometers. Ground motions of 0.6 g or greater are likely to be experienced in the near field of such large, rupturing earthquakes, and one might seriously underestimate the recurrence of such large ground motions when point sources are assumed. It is unlikely that the SOS/EPRI submittal will be used to assess sites close enough to the New Madrid area (or other high-seismicity sources having potential for large magnitude events) for the point-source approximation to be inappropriate.

I.I. Consensus Best Hazard Estimate

The EPRI/SOG methodology for determining consensus best hazard estimates uses mean log hazard to provide a single-parameter team best estimate at a site. The use of mean-log estimates rather than mean estimates of hazard tends to decrease the apparent site hazard. The team mean log hazard is sensitive to the lowest alternative estimate. As an extreme example, let us imagine **we toss a** coin and receive one dollar if a "heads" comes up and nothing if a "tails" results. The expected value or mean is M = 1/2(1.00 + 0.) = 0.50 but an estimate based on the mean log value M_{ML} = ***101/2(1041.00+1040)*** is undefined (log(0) = -oo).

Analogously, if a single feature is near a **site,** the calculated ground motion levels may be considerably higher for' scenarios in which the feature is **active** than for scenarios in *which* the feature is inactive, and the seismicity dispersed to the background. A single scenario in which there is no (or low) seismicity near the site, could, in fact, result in no (or low) predicted exceedances of a ground motion **level. A** single low estimate could unduly reduce the apparent hazard when log-values are used in the estimation. There are several low outliers among the team mean log hazard estimates. We question whether possibly a single low estimate for a single scenario resulted one or more of the outliers.

In those aspects of the EPRI/SOG work in which point estimates are combined, we believe it is more desirab2e that means rather than log means or medians be used, in order to prevent under-representation of site hazard. Our opinion is that a team mean hazard estimate is more consistent with **an expected-value** interpretation of "best team estimate." A further argument for using mean values is that, because the contribution of a source to the mean or expected hazard at a site is the contribution of the source to the hazard when the source is active, multiplied by the probability that the source is active, we can sum the contribution to the mean hazard on **a source-by-source** basis. By contrast, in evaluating the mean-log **value, we** need to evaluate the hazard for each scenario or combination of active sources and multiply by the probability of that scenario. This requires considering many combinations of active features and background sources in order to calculate the log exceedance rate for each scenario.

EPRI/SOG's preferred methodology for combining team mean log hazard site hazard estimates to obtain a best consensus site estimate removes each team's systematic deviation

(TSD), a constant determined from the average difference between the team's own estimate and the consensus estimate at each site. After the TSD's have been removed, weights are determined in accordance with the remaining team variances and inter-team covariances. The method used by EPRI/SOG is analogous to one appropriate for instruments of measurement, for *which* there can be both a measuring standard and identifiable sources of variability. The method does not appear appropriate for site hazard estimates, in which there is no standard, and for which the source of variability changes from site to site. For instance, the assumptions used by EPRI/SOG do not consider that it is likely that **team *zoning* practices (such** as use of broad zones instead of narrow zones) will produce different systematic **deviations at *high-seismicity* sites** than at low-seismicity sites. When the source of site-to-site variability for a team is not known, we suggest it might be better to estimate **a *consensus* on a site-to-site basis, for instance** by combining team estimates after removing outliers, etc. This means that a site-specific bias only penalizes a team at one site rather than all sites. We note that in the mean log hazard results for the six. teams at nine sites presented by EPRI/SOG (Vol.11, **supp.3, 1988, p.41)** each of the two lowest-weighted teams produce a greater number of near-median site estimates *than* do each of the three moderate-weighted teams.

We found that this EPRI/SOG methodology had puzzling behavior when we tested it on random and simulated data with known properties. For instance, if we shift one team's estimates by a constant amount-only the team's systematic deviation changes-the ***consensus*** estimates changes the other teams' TSD's change; their relative variances change; and the weights change. The EPRI/SOG procedure intends to make team weights insensitive to systematic bias. That all team weights change under a constant change of bias for one team seems counter to the intent of the EPRI/SOG preferred methodology. Furthermore, if we arrange for two hypothetical teams to have very similar estimates, the, two may monopolize the total weight between them. It is not obvious to us why this should be desirable behavior. In the EPRI/SOG submittal, one team monopolizes the weight, and two teams have very little weight. **We** think this drastic contrast in weight is ***inconsistent*** with the likely relative goodness of team estimates. A substantial amount of this monopolization and contrast appears to result from the adjustment of the consensus means using initial team weightings and recycling. (Less contrastive weights are obtained under inverse-variance weighting based on the initial variance matrix, without further adjustment.)

EPRI/SOG acknowledged that in tests it performed in which there **was** no systematic bias and all **team** had **the same variances** about the **average value,** the weightings assigned to the teams were not accurate, but stated that the final estimates were nevertheless good. We believe that in a no-bias, equal-variance case, almost any weighting would give good results, and the fact that the weightings were not reliable even in this **case** strongly suggests a problem in those cases in which the weightings do make a difference, i.e., when variances are not equal and biases are present.

The results under **EPRI/SOG's preferred methodology do not appear *significantly*** different from results obtained by taking simple means, when obvious outliers sic removed, but the EPRI/SOG methodology **provides** weights which effectively remove the teams with the greatest variance or with outliers at a single site. The EPRI/SOG weights seem to us to provide an excessive penalty on some teams without achieving better consensus hazard **estimates.**

I.J. *Conclusions* and Recommendations

We believe that the methodology can be a powerful tool to use in obtaining probabilistic hazard estimates. Particularly to be commended are the flexibility afforded by the seismicity parameter methodology, the documentation provided by the feature assessment methodology, and the general aim (and achievement) of rendering explicit and detailed the many aspects of hazard estimation procedures that were previously considered only implicitly or vaguely. The implementation of the methodology submitted to NRC can be used to estimate probabilistic ground motions in most of the eastern U.S. (where finite rupture models are not necessary).

We recommend that users of the methodology carefully consider the detailed comments provided in this review. We believe that these comments should provide additional insight in the understanding and application of the methodology. For example, new users of the methodology should assure that sufficient spatial smoothing or sufficiently strong priors on b **values be** applied in order to control excessive cell-to-cell variability in recurrence rates. Additionally, interpreters of the results need to bear in mind that some teams' choices of pI values and maximum magnitudes may be strongly influenced by the sparsity of the historical seismicity in the eastern U.S., resulting in relatively low hazard estimates at some sites.

The EPRI/SOG submittal represents a major scientific and engineering effort to resolve problems in earthquake ground motion hazard assessment. It has provided much needed insight 'into a number of problems in this field. As in all such techniques,. it represents a particular scientific approach and point of **view.** With careful application, the technique should provide important insight into the assessment of earthquake hazard in the eastern U.S.

II. Background

II.A. The Charleston Issue

The U.S. Geological Survey has long acted as a consultant for the Nuclear Regulatory Commission in matters pertaining to the earthquake hazard at sites of nuclear power plants. The USGS has also been very active in the quantification of the earthquake ground motion hazard for the United States. Versions of the USGS hazard maps are now reflected in virtually every national building code. National earthquake hazard mapping has evolved into the representation of probabilistic ground motion for various levels of probability. The NRC is now seeking to evaluate the ground motion at nuclear power plants using probabilistic as well as deterministic analysis techniques. To some extent, increasing interest in probabilistic methods of ground motion assessment has occurred because of a USGS communication with NRC in *1982* which states, in part,

> "Because the geologic and tectonic features of the Charleston region are similar to those in other regions of the eastern seaboard, we conclude that although there is no recent or historical evidence that other regions have experienced strong earthquakes, the historical record is not, of itself, sufficient grounds for ruling out the occurrence in these other regions of strong seismic ground motions similar to those experienced near ***Charleston*** in *1886.* Although the probability of strong ground motion due to an earthquake in any given year at a particular location in the eastern seaboard may be very low, deterministic and probabilistic evaluations of the seismic hazard should be made for individual sites in the eastern seaboard to establish the seismic engineering parameters for critical facilities." (USGS letter to NRC, **Nov *18, 1982.)***

In response to the USGS statement, the NRC began a program to investigate the issue, stated in the following manner:

> "Taking uncertainties into account, have licensing decisions for plants in the eastern seaboard (i.e., in the region affected by the USGS clarified position on the Charleston Earthquake) resulted in acceptable levels of assumed seismic hazard (exposure to earthquake ground motion) at the individual sites?" (USNRC memorandum, Mar ***02 1983,*** from R.H. Vollmer to H.R. Denton, Division of Engineering Geoscience plan to address USGS clarification relating to seismic design earthquakes in the eastern seaboard of the United States, enclosure 1, page 3.)

As part of its plan to investigate this issue, the NRC has not only funded both deterministic and probabilistic research among its own ***consultants,*** but also has encouraged the various utilities to perform their own work, to provide further perspective. The response of the utilities has culminated in the EPRI/SOG submittal, consisting of both 'a methodology and implementations of that methodology in assessing earthquake ground-motion hazard in the eastern and central U.S. The NRC has asked the USGS to review the submittal in terms of its suitability for use in addressing the problem of probabilistic ground motion hazard at nuclear power plants.

II.B. Nature of USGS Review and Concerns

The EPRI/SOG methodology comprises several independent complex procedures which, when followed in their entirety, carry a seismic hazard assessment from the initial step of examining the earthquake catalog to merging final hazard estimates of multiple investigation teams. In this subsection we present a number of concerns that should be considered in evaluating this new and complex methodology and its application to probabilistic ground motion hazard in the eastern U.S.

In our review, we consider the mathematical correctness of the technique and its appropriateness, in our opinion, for hazard assessment in the eastern U.S. In more detail, we consider whether the various procedures correspond with accepted principles, whether the methodology, using comparable assumptions, can produce results comparable to those produced by simpler methods of seismic hazard analysis, and whether various results are intuitively reasonable.

An analyst approaches a seismic hazard study with hypotheses, notions, and speculations regarding earthquake causal processes and/or structures, formulated through professional training and experience. The range of such hypotheses is likely to be very broad among potential analysts. Therefore, it is incumbent on the methodology to allow for freedom of scientific judgment and to properly model the various hypotheses. The EPRI/SOG methodology attempts to provide the analyst with broad flexibility in modelling and to assure that the various input choices be clearly documented for future review, thereby allowing others to track these inputs and to judge the adequacy of the various models chosen. In our review, we have tried to consider whether the results produced in various situations are consistent with the intent of the analyst when various input options are selected.

No demonstrable unique causal geological source has as yet been identified for the 1886 Charleston earthquake. Furthermore, significant research efforts in the Charleston 1886 earthquake area have not.resulted in the identification of tectonic features sufficiently unique either in their geological or seismological nature to preclude the possibility of large earthquake occurrences elsewhere in the eastern United States. This suggests the modelling of magnitudes as large as that of the Charleston earthquake, not only in a restricted zone around Charleston, or in an alternative large zone which includes the Charleston area, but also in areas which do not include Charleston.

Careful consideration should be given to the modelling of historical concentrations of seismicity. The significance of seismicity concentrations which have persisted during historical time has long concerned the NRC and the USGS. The NRC has proposed studies to determine whether areas of relatively higher seismicity in the eastern seaboard correlate with potentially causative tectonic features and processes. These areas include the Charleston region, Ramapo fault zone, the Central Virginia Seismic Zone, the Giles County Seismic Zone, and New England (particularly Moodus, Conn; New Hampshire; Massena, New York, and New Brunswick, Canada). (USNRC memorandum, Mar 02 1983, previously cited, enclosure 1, pages 9-12.)

IQ. Seismic Hazard Models

A basic output of a seismic hazard analysis is an estimate of the probability that any given level of ground motion will be exceeded at a site during a one-year time period. A set of these annual exceedance probabilities is used either to calculate the probability that a specified level of ground motion will be exceeded during a time interval of length T_1, or to calculate the level of ground motion that has a specified probability of being exceeded during the time T1. .

The annual probability that a ground motion level will be exceeded at a site is obtained by multiplying the probability that an earthquake of a given magnitude and distance will cause a ground motion of the given -level or greater, by the probability that such an earthquake will occur, summed over all magnitudes and distances. This means the analysis requires a description of seismic "sources" (the possible locations of future earthquakes, values of the sources' seismicity parameters (recurrence rates for earthquakes of each possible magnitude range), and an attenuation relationship (that specifies ground motion at a site for earthquakes of a given magnitude and distance).

M.A. EPRI/SOG Sources

In conventional methodologies, sources are either areal *source zones,* in which earthquakes are modeled as point ruptures, or *source faults, on* which earthquakes are modeled as linear ruptures, with rupture-length dependent upon magnitude. In the EPRI/SOG submittal, sources are modeled as point ruptures in areal source zones. The majority of these source zones are based on tectonic features; an area encompassing the surface-projection of one or more features is regarded as the source zone in this case. We think that EPRI/SOG's decision to use point-source models is, with the exceptions noted below, appropriate.

Source zones that treat earthquakes as infinitesimal point ruptures can substantially underestimate the calculated ground motion exceedances at sites near real faults. This is because the near-fault isoseismals, instead of being circular, become extended parallel to the rupture. It is not possible to adjust an attenuation function based on epicentral or hypocentral distance to give the same results at all sites as an attenuation function based on closest site-to-source distance in the case of finite ruptures (Bender, 1984).

EPRI/SOG justifies the choice of a point-source model by addressing the size of ruptures to be expected in the study area. "Lengths of fault rupture are relatively small in the central and eastern United States so that the dimensions of the fault rupture need not be considered' (EPRI/SOG, Vol.1, Methodology, 1987, p.1-10). `Although the reason is not known, surface rupture appears to be very rare within stable continental regions" (p.4-16). As for the first of these statements, the fault rupture length vs. magnitude relationship is not known in the central and eastern U.S.; as for the second, earthquake ruptures always have finite dimension even if there are no surface ruptures. However, we believe that a point-source model may be adequate for moat areas of the eastern U.S., for the magnitudes assumed in those areas. In the New Madrid area, however, we might expect large-magnitude earthquakes to have rupture lengths of tens of kilometers. Ground motions of 0.6 g or greater are likely to be experienced in the near field of such large, rupturing earthquakes, and one might seriously underestimate the recurrence of such large ground motions when point sources are assumed. It is unlikely that the EPRI/SOG submittal will be used to **assess** sites close enough to the New Madrid area (or other high-seismicity sources having potential for large magnitude events) for the point-source approximation to be inappropriate.

M.B. Seismic Activity in EPRI/SOG Sources

Seismic source zones have generally been. regarded as seismically homogeneous; i.e., an earthquake of any given magnitude is equally likely to have its epicenter at any point within the source. EPRI/SOG instead assumes that earthquake rates and b values can vary within a source. EPRI/SOG makes the standard assumption that earthquakes within a **given seismicially homogeneous** cell have a Poisson distribution-that is, earthquakes in this cell occur randomly in time, with an average rate that does not change with time and does not depend on when the last earthquake **occurred. In** addition, earthquakes within the area are assumed to follow a Gutenberg-Richter magnitude-frequency relationship within some magnitude range m,,,;. < **m:5 m..,** and earthquakes with magnitude greater than **m,,,s** cannot occur. The Gutenberg-Richter relationship is expressed as $log N = a - bM$, where N represents either a cumulative number of earthquakes **above M,** or the number in a fixed range around M, and a and b values are rate and slope parameters.

In the EPRI/SOG methodology, sources are derived from features, except for "background" or "default" sources. A source may be either active or inactive in a given scenario. The "net" seismic rate attributable to the source is thus the probability of a given scenario times the seismic rate the source assumes in that scenario, summed over all, the scenarios. In the submittal, the activity attributed to the source when it is active is almost always derived from the observed seismicity. Because few sources have probabilities of activity near 1.0, the "nee qty assigned to a source is generally less than the **historically-observed rate.**

When a source is active, all points within the source are capable of generating earthquakes. However, in the EPRI/SOG methodology, a and b values may be allowed to vary spatially within the source This is accomplished by allowing the source to be divided into cells with different seismicity parameters. (Conceptually, each cell may be regarded as a source which is seismically homogeneous, and therefore, computationally equivalent to source zones as usually defined.)

The Poisson and Gutenberg Richter assumptions, commonly made in seismic hazard analyses, are **usually** j ed by the fact that, in the aggregate, earthquake occurrences aver large ams appear to be Poissonian and follow **a** Gutenberg-Richter magnitude-frequency relationship. However, the assumptions may not apply when individual features **are cooneWered. For** an individual feature, an estimate of the probability that the feature is active, and a and b values based on observed seismicity may not be appropriate if the Poisson, Gutenberg-Richter model is not applicable. These assumptions, however, are conventionally made in the central and eastern U.S., and EPRI/SOG does not differ from generally current practice in this respect.

M.C. Attenuation

Ground shaking at a site is a function of earthquake magnitude and distance from the site. Equations or tables which describe the relationship between ground shaking, magnitude, and distance are called attenuation functions. At some of the EPRI/SOG workshops and in our own research, we have observed that the choice of attenuation function provided the largest source of variability in the hazard estimates. There is no detailed discussion in Volumes 1-10 of the Final Report (the volumes that we are reviewing) regarding the choice of, or variability in, the results because of the various attenuation functions that were used. Therefore, we cannot comment explicitly in this review on EPRI/SOG's choice of attenuation functions.

M.D. EPRI/SOG Innovations

We believe major EPRI/SOG innovations are the technique used to assess candidate features as possible sources of damaging earthquakes and the technique used to derive spatially-smoothed seismicity parameters from the historical earthquakes observed in the source zones. The delineation of the source zones takes into account both the uncertainty in source-zone boundaries and the uncertainty that a given candidate feature (or collection of features) was indeed a source zone (i.e., capable of generating earthquakes). Provision has been made for alternative scenarios, which express the likelihood of various alternative combinations of features being active in the vicinity of a site.

The assignment of source-zone seismicity parameters also takes into account uncertainties in maximum magnitude, a value, and b value, associated with each source. The EPRI/SOG methodologists allowed each team to select a set of alternative rates, b-values and maximum magnitudes for each active source.

The EPRI/SOG program "emphasized earth science assessments of alternative explanations of earthquakes in the central and eastern United States, and translation of these interpretations into definitions of seismic sources and characterizations of associated seismicity parameters" (EPRI/SOG, VoL.1, *Methodology*, 1987, p.1-3). In the following sections, we discuss first the methodology for assessing candidate features as sources, and then the methodoloU *for* assessing spatially-varying seismicity parameters for those sources.

IV. Developing Criteria for Identifying Seismogenic Tectonic Features

A major effort of the EPRI/SOG program was the development of procedures to identify seismic sources from among a large set of candidate tectonic features by means of a characteristic assessment process. Among the prescribed steps were to

1) identify potentially seismogenic tectonic features starting with the hypotheses for earthquake causes;
2) formulate tectonic criteria to assess the probability that a tectonic feature may be seismically active within the contemporary stress regime; Lad
3) **assess** feature-by-feature the probability of activity.

These potentially tectonic features would be the basis for feature-specific sources. To take various types of uncertainty into account in identifying and locating source zones (e.g., determining whether specific faults, rifts or other features are capable of generating earthquakes), each team was permitted to select a. number of alternative scenarios in which different combinations of source zones are active, and to assign to each scenario some probability of being correct. Each team could also select a **set** of alternative rates, b-values and maximum magnitudes for each active source. In this section we will deal primarily with the selection of criteria by which the TEC's assess the probability of the tectonic features they considered.

The EPRI/SOG program participants began by making a major effort to obtain, assimilate and evaluate the available scientific information, hypotheses and conjectures regarding the tectonic processes and stresses operative in the eastern and central United States. This effort included compilation of geo-science data sets and an in-depth assessment of the historic record. The six TEC's investigated and attempted to evaluate the relevance of such physical criteria as spatial association of a feature with seismicity, observation of recent strain and paleoseismicity, scale or vertical estent of a feature within the crust, fault orientation and allowable slip within a stress field, geologic evidence of brittle slip, and spatial or temporal changes in strength. The investigations and evaluations represented a considerable investment in time and were a sienificant part of the program; we are impressed by the thoroughness with which the teams approached this phase of the study.

After the information-gathering/evaluation phase was completed, each TEC was required to select the observable characteristics (or criteria) that it regarded as most highly correlated with the ability of a tectonic feature to generate earthquakes, and then to estimate the probability that **a *hypothetical* feature having any given combination (present or absent) of the selected characteristics** is `active. Throughout Phase I and most of Phase II, a feature was defined as **active** if it were considered to be capable of generating moderate-to-large earthquakes, i.e., $m_b \geq$ 5.0 in the current stress regime; the corresponding probability of activity was designated p'. During the latter part of Phase II, the definition of activity **was** changed to mean the ability of a feature to generate earthquakes of any magnitude; the corresponding probability of activity was then designated pA. The estimated probability of activity for a feature having each possible combination of characteristics was entered into a `feature characteristic matrix" as shown in figure MA.

MA. EPRI/SOG Tectonic Criteria

The development of observable tectonic criteria useful for identifying seismogenic tectonic features proved difficult. We note that reports of the individual teams reflect frustration, and we provide excerpts from three of these reports to illustrate the apparent dissatisfaction of the teams with their ability to identify such tectonic criteria.

> Rondout:
> "Try as I will, to find what relates potential field data, crustal thickness, geology, refraction and reflection discontinuities to the seismicity, I am almost invariably stumped Not only is the time scale too short, but also the spatial scale is also probably too large....' (EPRI/SOG, Vol.10, 1986, p.A-206).
>
> Woodward Clyde:
> "...about 50 percent of the features evaluated are believed to have no more than a probability of 0.25 of being active. This represents fairly the consensus of the team that the true tectonic explanations for observed seismicity have yet to be formulated. (EPRI/SOG, Vol. 8, 1986, p.4-15.)
>
> Bechtel:
> ".. .[W] e found it very difficult to generalize activity to "similar" historically inactive active features (those not associated historically with moderate-to-large earthquakes), and viewed background zones not as a circumvention of the proper association of future earthquakes with historically aseismic structures but rather as the logical repositoryy of our uncertainty about the proper association of past earthquakes with recognized tectonic features.' (EPRI/SOG, Vol.9, 1986, p.5-3)

In the end, the teams typically elected to include three (occasionally two) questions or characteristics in their feature characteristic matrices. AU teams (in Phase 1) included the question (characteristic), "has the feature been spatially associated with moderate-to-large earthquakes," "associated with small earthquakes only," or "not spatially associated with seismicity.' (Because of a change in the ground rules in Phase 2, some teams modified the matrices to include only "spatial association with seismicity" and 'no spatial association with seismicity.') However, all six teams also included a question in their matrices regarding whether the geometry relative to the stress field (orientation and/or sense of slip) is "favorable" or "unfavorable." Five teams included a question regarding deep crustal expression-whether deep crustal expression was present near intersections (or with a barrier), present, but not near intersections (or present with a barrier), or no deep expression present. The team that did not ask the question concerning deep crustal expression included instead a question regarding most recent age of brittle slip on a feature. (EPRI/SOG, Vol.9, 1986, p.5-3).

Several teams indicated reservations about the usefulness of one or more of the criteria. For example, several teams expressed concerns regarding the criterion related to whether the geometry of the feature relative to stress orientation is favorable or unfavorable.

Dames and Moore:
'There is a large uncertainty involved in the interpretation of the stress data and applying these data to tectonic structures of unknown seismic potential" **(EPRI/SOG, Vol.6, 1986, p.2-23).**

Law Engineering:
'It became obvious as we went through this portion of the study that there are currently not enough quality stress data available to allow stress estimates to be a major tool in judging the seismogenic potential of a tectonic feature. This is due not only to the range of possible interpretations for a given area, but also to the wide range of fault orientations for a given stress orientation that would allow re-activation.." (EPI.I/SOG, **Vol.7, 1986, p.2-2).**

All teams agreed that spatial association with seismicity, or lack thereof, is the most important identifiable characteristic for estimating the probability that a feature is active. There was no general agreement on the relative usefulness of the other criteria. For example, the Law Engineering team chose to define two feature-characteristic-matrices: one when brittle slip on feature (most recent age) is available and one when such information --is not available. On the other hand, Dames **and Mom** stated: "Our team dropped from further consideration the criterion dealing with `feature specific brittle slip.' It was considered that this particular criterion would have little or no use in assessing the potential of any particular tectonic feature for generating a moderate to large earthquake" (EPRI/SOG, Vol.6, p.4-3).

A team might view a characteristic as man or less important, depending on the availability of other information. Thus, the Law Engineering concluded, 'The geometry of the feature relative to the stress field was judged the least important of the criteria... In Matrix A (used when information can be obtained for brittle slip), the difference in probabilities between the unfavorable and favorable geometry is never more than 0.06. In Matrix B (used with no slip information available), the geometry does acquire a higher weight, but only makes an appreciable difference in the case of association with small earthquakes only.* (VoL7, p.4-1,4-6).

IV.A.1. [illegible]

The two questions in the matrices that related to geologic structure were dominated by the question that related to spatial association with seismicity. Lack of spatial association with seismicity decreased the estimated probability that a feature is active, regardless of the favorability of the geologic structure. For **camp*** most teams assigned to a feature that had been spatially associated with 'modrste-to-'large earthquakes and having unfavorable geometry' a higher probability of being active than a feature spatially associated with "small earthquakes only, but having favorable geometry.'

IV.A.1.a. Sensitivity of spatial association to assumptions of hazard model. Estimates of the probability that an individual feature is active are based on observed earthquakes in the vicinity of the feature. However, if a characteristic earthquake model is appropriate for an individual feature, that feature may have fewer small magnitude earthquakes than would be expected in a Poisson model with a **Gutenberg*Richter* magnitude-frequency** distribution. In addition, large earthquakes have occurred in areas that been previously aseismic, and large earthquakes have not always been preceeded by small earthquakes. Failure to observe small earthquakes spatially associated with a feature must adversely affect estimates of the probability that a feature is active.

IV.A.1.b. Low eastern-U.S. seismic rates drive most VA's to low values. The seismic activity rate in the eastern U.S. is generally low, so that only a small fraction of the features considered will have experienced "high spatial association with historical seismicity," and an even smaller fraction of features will have experienced spatial assocaition with moderate-to-large earthquakes. Good spatial association with seismicity is likely to occur only with features in high-rate areas or features which have experienced random clustering of events in time. As a result, most features will have low probabilities of activity, and the average p^A will be low. It seems likely to us that many features under the EPRI/SOG implementation will have a lower p^A value than if purely tectonic-geologic characteristics governed the assignment of p^A values.

IV.A.2. An example of overemphasis on historical seismicity. We believe that some teams' treatment of the Meers Fault feature illustrates how overemphasis on the criterion of spatial association with seismicity can lead to assessments of probability of activity that, in our judgment, are much too low. Although the present understanding of the seismic history of the Meers Fault was not available at the time the teams made their source zone evaluations, preliminary interpretations regarding possible Quaternary movement on the fault were in print (Donovan and others, 1983; Gilbert, 1983; Tilford and Westen, 1984). The Bechtel team states (EPRi/SOG, Vo1.9, 1986, p.3-25), "Recent field work (McKeown, oral communication to T. Bushbach) indicates Quaternary offset on this feature."

Table 1 (Appendix) shows the probabilities assigned by each TEC to the Meers Fault for that feature's "association with seismicity" and "geometry relative to regional stress". Probabilities assigned to association of seismicity with the fault for the category "moderate-to-large" earthquakes are 0.0 for two assessments. No assessment is 1.0 for this category of earthquakes.

The teams discounted the relevance of slip in assigning **pi's** to the Meers Fault. For, example, the Law Engineering team states (EPRI/SOG, Vol.7, 1986, p. D-8), "It is important to note that aseismic faults with Pleistocene-Holocene slip have relatively low probability of being actively seismogenic in our expert team's evaluation (fig. D-1). The presence of seismicity is given greater weight than geologic evidence of brittle slip. We do not consider a feature such as the Meers Fault, which to the best of our knowledge has been aseismic for a century, **to be a** significant source of seismic hazard in the next century." It seems to us that the previous interpretation is contrary to the definition of activity, which states a feature is **active** if it is capable of supporting an earthquake in the present tectonic stress regime, all TEC's agreed that this time period included at least the last several million years. In our view, known occurrences of Quaternary-Holocene (the last two million years) rupture on a fault should be considered absolute evidence of moderate-to-large earthquake occurrence on that fault and considered as evidence equivalent to that of an historic 'moderate-to-large" earthquake on the fault with no uncertainty in the causal relationship. By definition, faults with these young displacements are suitably oriented in the present stress regime and capable of generating moderate-to-large earthquakes, and must be assigned a probability of activity p^A = 1.0, even if there has been no spatial association with historic seismicity.

We believe that low pA values assigned to the Meets Fault resulted in large part from interpreting "spatial association with seismicity" as referring only to historically recorded earthquakes. However, confusion between concepts of earthquake potential of a feature **and earthquake** occurrence *rate* on a- feature appears to be at least partially responsible for some of the low p' values. Note that the low historic rate which might be assigned to a Meets fault source zone would in itself be sufficient to yield low hazard estimates. In fact some teams assigned p^A values that would be considered more in line with their estimate of the extent to which tectonic faulting had been proven.

1V.A.3. Spatial association cannot be generalized to other features,. One of the aims of the EPRI/SOG process **was** to formulate *tectonic* criteria to **assess** the probability that a feature may **be active** in the contemporary stress regime, and such that features with similar characteristics would receive similar pl values. However, 'spatial association with seismicity' is not a 'tectonic criterion' but rather an empirical fact that earthquakes can occur in an area. 'Spatial association with eeismicityA cannot be generalized to "similar" features (i.e., without **some** other additional criterion, e.g., similar orientation, **we** cannot say that a feature that has not an earthquake spatially associated with it is "similar" to **one** that has had **an** earthquake.) Hence any goal, stated or implied, of obtaining **a** characteristic by which to "generalize" seismicity from features which have had earthquakes to features which have not had earthquakes can not be achieved when "spatial association with seismicity" is in the characteristic matrix (unless one **goes** outside the matrix assessment process to make the generalization).

As an example, it can be observed that there is low-level seismicity on many of the basement arches **in** the central U.S. This seismicity is too weak and sparse for any single arch to **achieve** good 'spatial correlation with seismicity,' and, as a result, These arches are assigned low p'^4 **values.** Outside the process one might assert that the good correspondence at many arches establishes that they they ought to have high p'^4 **values collectively,** but-this is **a very** unlikely result using the EPRI/SOG matrix process.

IV.A.4. **Whv**'orientation of features" provides Door discrimination. "Orientation of features" with respect to the prevailing stress regime was included in all TEC's feature characteristic matrices. The 'rientation' criterion is based on the concept that *faults* **having a** geometry that is **favorably** oriented with respect to a prevailing stress regime for slip to occur **have at least one observable characteristic favoring the** generation of earthquakes. The criterion is a key element in feature assessments that sets the EP RI/SOG **approach apart from traditional empirical** approaches to source zone delineation. It is the key to the **seismotectonic** premise of the study, the cause-effect relationship between **geological processes and earthquake** generation. Indeed, considerable effort was expended in presentation, discussion, and data compilation related to this topic. In the end, there appeared a consensus that the continental crust of the central and **eastern** United States is **donated by generally northeast-southwest** trending (ae *N60°E)* regional compressive stress induced primarily **by a** ridge-push force originating at the mid-Atlantic spreading ridge plate boundary and, perhaps, countered in its directivity by a `pinned' western plate boundary and/or drag forces at or near the base of the continental lithosphere.

The "Orientation" criterion is stated as `Favorable fault orientation and allowable slip within a stress field" and properly places this criterion in context with individual faults (EPRI/SOG, Vol.1, Methodology, 1987, p.3-22). However, in practice this restrictive context was replaced with the general context of "tectonic feature". Indeed, most "tectonic features" defined by the TEC's are not faults and, therefore, this criterion loses the physical meaning and scientific underpinning that is presented (pp. 3-22 to 3-24). For example, there is no physical reason to **assess** "Favorably oriented geometry" for features such as the "Continental Shelf Edge " (EPRI/SOG, Vol.8, 1986, p. A-2), the "Western Quebec metasedimentary belt" (EPRI/SOG, Vol.9, 1986, p. 3-12), the Adirondack Uplift (EPRI/SOG, Vol.5, 1986, p. B-2), and the Nashville Dome (EPRI/SOG, Vol.6, 1986, p. A-24). Potential stress concentrators are inextricably mixed with faults in "tectonic features". All the above features could nave subjective probabilities assigned that they are stress concentrators. Stress release, however, would only occur on suitably oriented faults in proximity to the stress concentrators, and fault orientation may not be the same as the feature orientation.

IV.B. Subjectivity of Probabilities in Feature Matrices

The methodology requires the teams to enter in the feature characteristic matrices estimates of probabilities that features **having various** characteristics are active. Such estimates are necessarily subjective. The use of subjective probabilities in the EPRI/SOG methodology was discussed in detail by Dr. David Brillinger (1985): Dr. Brillinger noted: "The problems of projecting earthquake activity and strength and of then extrapolating to effects at given sites are very difficult ones. There is little data (and what is available is biased), there is high variability, there is only moderate physical knowledge concerning the causative processess involved and there is an inability to perform substantial experiments." He further stated "The EPRI/SOG study makes essential **use** of personalistic probabilities. I suggest that these probabilities are without significance unless they can be meaningfully related to the external 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" (Brillinger, **1985, p.10).**

N.C. Changing from p' to 4

As noted earlier, during Phase I and most of Phase II, the definition of "activity" of a tectonic feature **was** the ability of the feature to produce moderate-to-large *(Mb* greater than or equal **to 5.0) earthquakes** in the current stress regime. During Phase II, "activity" **was redefined to mean** the ability of a feature to generate earthquakes of any magnitude. To make the distinction, the notation for probability of activity **was** changed from p' to *pA,* where

pa is the probability that a tectonic feature or seismic source can generate earthquakes of **any size** within the current stress regime.

p' is the probability that a seismogenic feature is active and can generate earthquakes $m_b \geq$ 5.0 within the current stress regime.

This change in definition of activity, coming as it did toward the end of the EPRI/SOG program, created problems. Rondout stated "We did not have time to completely evaluate this change (from p' to pA)" (EPRI/SOG Vol. 10, 1986, p.3-10).

N.C.I. *Chances*could be required in characteristic vuestions. Evaluating pA rather than p' could require changing not only the probabilities in the existing feature characteristic matrices, but changing the questions themselves. During Phase I, all teams had entries in their feature-characteristic matrices corresponding to spatial association of the feature with "moderate-to-large earthquakes", "small earthquakes only" and 'no spatial association with seismicity.' Spatial association of the feature with moderate-to-large earthquakes might no longer be relevant when considering the possibility that a feature is **active,** but has a maximum magnitude mb < 5.0.

To change from p' to pA, Woodward Clyde elected to construct new matrices containing entries only for "spatial association with seismicity" and 'no spatial association with seismicity' (as illustrated in Table **1) (EPRI/SOG Vol.8, 1986, p.4-7),** but four teams retained questions regarding "spatial association with moderate to large earthquakes." Weston elected to construct separate matrices for probability of activity at magnitudes >- **3.5mb, >- 5.0mb and >- 6.Om8 (EPRI/SOG, Vol.5, 1986 p.4-4). Dames and Moore, however,** stated **"the contradiction in** assigning a magnitude dependent pA is that we actually smear out the observed seismicity for no tectonic reason. So with this in mind, our P^A estimates states our team's confidence that tectonics can explain earthquake occurrence and (1 - pA) estimates that seismicity alone can explain the occurrence of future events." (EPRI/SOG, **Vol.6, 1986, p.5-2).**

1V.C.2. Team concern about scenario weichtg. Weston states, that when the 'maximum distribution exists at a level below the lower bound magnitude of 5.0 to be used in the example seismic hazard computations, it is recommended that the cumulative weight below 5.0 be lumped [added] to the weight for magnitude 5.4 me' (EPRI/SOG, Vol-5, **1986, p.6-10). However,** doing this appears to conflict with the instructions given for recalculating p' (EPRI/SOG, Vol.3, **1987, p.4-11:4-12),** and be inconsistent with an example (EPRI/SOG, Vol.3, **1987, p.3-4)** of how p' and p" are affected by changes in maximum magnitude distribution (example enclosed as Figure 1V.B).

The team **appears** to be concerned whether a maximum magnitude distribution which spans magnitude 5.0 should be truncated below 5.0 and, in effect, renormalized above 5.0, or whether the truncated portion is to be lumped in at the lowest maximum magnitude above 5.0. Their, ecommended treatment assures that scenario weights for the higher upper bound magnitudes **do not get increased** by **the perceived** truncation and renormalization. On the other hand, the context in volume 3 is that p' values are decreased from pA values, so that recurrence rates for upper bound magnitudes **above 5.0 are** not increased (and hence, presumably, the Weston adjustment is not necessary).

IV.C.3. Chancecould be required in number of features considere4. From the first **Data Needs Workshop** in January 1984, the TEC's tailored their interpretations to the intent of identifying feature with potential for generating **mb ≥5.0** earthquakes. There are a number of other spatially distinct tectonic features that **have** some probability of being **active (pA), yet** perhaps **are** unlikely to generate m& ≥5.0 earthquakes (p'). However, in changing from **p' to pA, the TEC's** may not have had time to consider features that they had not previously considered. Had the pA definition been in effect from the beginning of the study, **we** suspect a greater number of tectonic features might have been included in the study. Strictly speaking, it would only seem necessary to consider features having a significant probability that upper bound magnitudes larger than 5.0 can occur. Practically speaking, most such sources will be marginal contributers to hazard and can probably be included in background zones.

N.D. Conclusion

The EPRI/SOG teams made an ambitious effort to identify characteristics of a feature that could be related to the ability of the feature to support moderate-to-large earthquakes. However, the problem of identifying earthquake causes is not easily solved, and the teams concluded that "spatial association with seismicity" of a feature, was the best indicator of whether a feature was potentially active. But "spatial association with seismicity is an empirical and not a causal relationship.

EPRI/SOG teams were unable to evaluate the relationship with earthquakes of **various tectonic characteristics** that they **investigated. However,** the teams selected several such characteristics as being related to earthquakes, and then estimated probabilities that a **feature having each combination of these characteristics is active. These** probability estimates varied considerably from team-to-team.

V. Estimating Probability of Activity of a Specific Feature

Until now, we have considered the problem of estimating the probability that a ***hypothetical* feature with a set of *known*** characteristics is active. (The fact that these probability estimates differ from team-to-team is said to represent scientific uncertainty.) In the **case** of actual features, it is not generally known with certainty whether a feature does or does not have particular characteristics. (This is referred to as informational uncertainty.) Probabilities must be assigned that a feature has or does not have each characteristic. (See Figure V.A.) The process of evaluating probabilities may be called ***feature assessment*, and a list of the evaluated probabilities the *feature assessment form*** for that feature. After the individual probabilities **have been assessed,** the probability that a combination of characteristics is present at the feature is calculated by multiplying together the probabilities of the individual characteristics; this is done for all possible combinations of characteristics, and the results entered into a feature probability matrix. The estimated probability pA that the feature is active is obtained by multiplying an entry in its feature probability matrix by the corresponding entry in the feature characteristic matrix, and summing over all entries.

Much of text of the individual team reports (Vols. 5-10) is **devoted** to showing, for each feature, the entries in the characteristic assessment forms and to explaining the rationale for these entries. We are impressed with the great effort made by the teams to obtain information on which to **base** their probability estimates, and the care with they documented their conclusions.

V.A. Probabilities **of Combinations of Characteristics**

The characteristics are regarded as independent, i.e., the probability that a combination of characteristics is present is the product of the probabilities that the individual characteristics are present. We do not believe questions (characteristics) should necessarily be regarded as independent when estimating the probabilities that various characteristics are present at a feature.

Suppose, for example, that **we have** no specific information about the favorability of the orientation of a feature in the current stress field. To express this uncertainty, the corresponding questions (e.g. is the orientation favorable?) may be assigned 50 percent probability that the answer is 'yes' and 50 percent probability that the answer is 'no'. **However,** because earthquakes are more likely if the geometry is favorable, if one has **observed spatially associated** earthquakes but has no information regarding the geometry, one might argue that **the *probability* of favorable geometry** is greater than 50 per cent. Peter Morris (1985) discusses similar concerns with the EPRI/SOG treatment of conditional probabilities.) We recognize that the assumption of independence of questions was probably **more a matter of convenience** than an assertion of reality, and we doubt that the impact of the independence assumption is large in the submittal, in general.

V.B. Uncertainty in `Spatial Association with Seismicity'

All teams regarded spatial association with seismicity as the single most important question in evaluating whether a feature is active. If a feature has been spatially associated with earthquakes, and if the spatial association is "real', i.e., the observed earthquakes were caused by the feature, then earthquakes can again happen on the feature in the future, and the probability that the feature is active is p^A = 1.0. However, $_{pw}$ < 1.0 is possible if the observed spatial association is "spurious", i.e., the observed earthquakes are not related to the feature. When spatial association with seismicity has been observed, and an entry in the feature characteristic matrix is p; < 1.0, then the probability that the spatial association is spurious is at least 1.0 - p;.

In discussing how they evaluated "spatial- association" for a specific feature, the Bechtel team noted "if moderate-to-large earthquakes are located very near or on a feature but no trend is indicated (single event or small cluster of events) about a 0.5 confidence is assigned to this association. ... Only if trend and spatial association are fairly well defined is a value approaching 1.0 used." (EPRI/SOG, Vol.9, 1986, p.4-27.) In the feature characteristic matrix, however, Bechtel assigned $_{pw}$ = 0.4 to a hypothetical feature that has "deep crustal association" and "unfavorable geometry" but "is spatially associated with moderate to large earthquakes". This implies that the team believes that the probability is at least 60 per cent that the observed spatially associated earthquakes were in fact, not caused by the feature.

We are surprised that a "fairly well-defined" spatial association with moderate-to-large earthquakes, in the presence of deep crustal expression, is spurious 60 per cent of the time if the geometry is unfavorable. In evaluating spatial association of a feature with earthquakes, one may not know the precise locations of either the earthquakes or of the feature, and one may be uncertain whether spatial association should be assumed. But, the feature characteristic matrices, by acknowledging that spatial association of the feature with earthquakes may be spurious, already appear to take into account this "informational uncertainty." We question whether the anticipated informational uncertainty regarding whether an individual (real) feature has **a set** of characteristics also entered into estimating the probabilities of **activity in the feature characteristic matrices** (for hypothetical features). This possible "double counting" of the same uncertainty may have a significant impact on p^A **values** for some feature combinations. Again we caution that the matrix process should not be thought of as in any way automatic, but requires constant ***examination*** of the implications of each assessment.

VI. Developing Seismic Source Zones and Scenarios

Having identified tectonic features (with their associated probabilities of activity p^), and having available a catalog of observed earthquakes, each team was required to define a set of seismic sources. *"The* basis for defining seismic sources is the identification of active tectonic features, or other scientific evidence that an area is active." "Seismic sources are composed of individual cells (as small as one-half degree squares). Seismic activity rates and b-values can be defined for each cell that lies within a source. All points within the boundary of a source are either... active or inactive.* * 'Every point within the boundaries of a source has the same distribution on maximum magnitude." (EPRI/SOG, Vol.1, Methodology, 1987, p.2-7).

VLA. Types of Seismic Source Zones and Their Probabilities of Activity

EPRI/SOG defines four main types of seismic source zones: single-feature, single source; featureless seismicity zone; default zone; and background zone. These are described briefly below.

Feature-Specific Sources. The majority of seismic sources are drawn directly to represent tectonic features and hence are termed feature-specific *sources.* A single tectonic feature may be interpreted to be an individual seismic source. The probability that the source is active is equal to the probability that the feature represented by the source is active (p" (source)= p'[4] (feature)) and comes directly from the marginal probability of activity assigned to this feature in the tectonic framework assessment. .

Default Seismic Source, Regions in which **a moderate-to-large earthquake** has occurred historically are usually interpreted to contain at least one active feature with certainty. Usually in such regions one or more potentially active features will have been identified, but none of the features will have been judged to be active with certainty (all of the values of the feature-specific probability of activity, p'[4] **are** less than unity). Thus, the state that none of the identified features is active may **have a** probability greater than zero. If so, some presently =known features must be active. *A default source* is used to represent the geographical limits within which the unknown feature (or features) is judged to lie. The probability that the default source is active is equal to the probability that none of the identified features is active.

Featureless seismicity zone. Zones of seismicity may be identified that do not appear to be associated with any identifiable tectonic feature. These zones are modeled as area sources surrounding the observed seismicity. A direct subjective assessment of the zone's probability of activity is required.

Background Source. A background source is the means to represent a region in which no distinguishable tectonic features or patterns of seismicity have been identified, but which is nonetheless interpreted to have some potential for earthquakes to occur. Background sources require a direct assessment of the probability of activity because, as for zones based solely on seismicity, the physical characteristics matrix does not apply. A background source differs from other sources in that the true state (probability) of activity **varies** with location in the source.

Both. default sources and background sources are used to address unknown sources of seismicity. With default sources, the focus is on unknown causes of known seismic activity in a relatively small area. The default source is used to confine the known seismicity to its observed area. With background sources, the location of observed seismicity is assumed to be random; hence the focus is on other areas in a broad geographical region where the observed seismicity might just as well occur. Background sources can also serve as default sources when there is no marked concentration of seismicity or geological association which might **serve as a** basis restricting the location of an unknown source of known activity.

More complete definitions of these and several other types of sources are given in EPRI/SOG, Vol.1, Methodology, 1987, **p.3-42;3-49.** The delineation of source zones is an inexact process. Background and default **zones** are designed to encompass seismicity (i.e., **a set** of observed earthquakes) that cannot **be assigned** to a specific feature or features in a given scenario, and the boundaries of such zones are typically ill-defined. In addition, the extent and location of the identifiable tectonic features is often not accurately known.

VLB. Joint Probability of Source Activity.

"Multiple tectonic features (interpreted as seismic sources) ... may be active in any one region. As these individual sources are generally not **assessed** to be active with certainty, there exist several alternatives as to which sources represent the 'true" set of active features in a region. P" (the probability that a particular combination of seismic sources is simultaneously active and capable of producing earthquakes above the lower point used for hazard calculations) is assessed using the marginal probabilities of activity, p^A, for the individual source, a specification of any dependencies on the state of activity among sources, and the maximum magnitude distribution of each source." (EPRI/SOG, Vol.1, Methodology, 1987., p.3-3). (Recall that 'the probability that a feature is in active **state,** p^A ... represents a marginal probability that the feature is in an active state as it is **assessed** without consideration of the state of other features (whether they are active or **inactive).' (EPRI/SOG,** Vol.1, Methodology, 1987 p.2-7).j

For example, if two features A and **B are** identified, possible alternative interpretations might be that both A and ***B* are active; A is active** and B is not; B is active and A is not; neither A nor B is active-all earthquakes occur in a "default" **zone.** If the features **are independent, and p^A =0.6 and p^B =0.3,**

$$p''(AB) = p^A p^B = 0.18$$
$$p''(A\bar{B}) = p^A(1-p^B) = 0.42$$
$$p''(\bar{A}B) = (1-p^A)p^B = 0.12$$
$$p''(\bar{A}\bar{B}) = (1-p^A)(1-p^B) = 0.28.$$

Sources may be dependent, and the probabilities of various combinations may be specified rather than calculated. In any **case,** the probabilities that a source is active in various configurations must sum to the assumed value of p^A for that source.

VLB.1. <u>Possible inconsistencies in the formalism for scenario probabilities.</u> The formalism may lead to inconsistencies. Let us imagine that two features **have been** identified as mutually exclusive causes **of a large observed earthquake. We** hypothesize that either F1 or F_2 must be active, but **F1 and F2 are not active** simultaneously. Using the feature characteristic matrix, we have evaluated that $p^A(F_1) = p^A(F_2) =$ 0.80. In order to satisfy the marginal probability that each feature is active and a feature is active in all scenarios, we obtain $p''(F_1F_2) = 0.60; p''(F_1ts) = p''(P_1F_2) = 0.20$. But F_1 and F2 jointly active is contrary to assumption, and we cannot satisfy our assumptions using the methodology. EPRI/SOG acknowledges the possibility of such inconsistencies, and permits the TEC's to select their own probabilities p" whenever they are not satisfied with the probabilities assigned by the methodology. This effectively changes the constituent p'a's but probably not significantly. This was not done frequently in the implementation.

VLC. Source Zone Rates, etc. Based on Observed Earthquakes

Having delineated the seismic sources, each team was next required to estimate a set of alternative rates, b.values and maximum magnitudes for each source (under the assumption that the source is **active).**

VLC.1. <u>**Physical considerations** and analogies were generally ignored.</u> In discussing how rates are derived, EPRI/SOG states 'The spatial distribution of future earthquakes and their magnitudes in seismic sources is assumed to be derivable from historical seismicity, crustal stress information, geophysical data, analogy with other regions, and earth **science interpretations:' (EPRI f SOG,,** VaLl, Methodology, 1987, p.1-9). In the submittal, teams did not make much use of physical **considerations,** and earthquake occurrence rates were based almost solely on historic earthquakes. In addition, apparently the only determination of rates "by analogy with other regions' was provided by Rondout, when they considered scenarios in which rates were interchanged between Anna Ohio and intersecting basement features in Tennessee and in Southeast Michigan (EPRI/SOG, Vol.10, 1986, p.C-3).

VLC.2. <u>Inconsistency in role of uncertainty.</u> Reeall.that spatial association of a feature with seismicity is used in estimating the probability that a feature is active, but **because of uncertainties in the locations of both the feature and earthquakes, the probability** must be estimated that a feature has been spatially associated with earthquakes. However, in assigning seismicity to a source, 'Only those earthquakes that lie within the **geographical boundary of the source** are used to compute seismicity parameters for the source' (EPRI/SOG, Voles, Methodology, 1987, p.3-41). This means that the same feature that **had uncertain spatial association with seismicity and uncertain location,** when pA **was** evaluated for the feature, is given a well-defined location for the subsequent hazard analysis, and is assigned seismicity based on a specific **set** of historic earthquakes 'that lie within **the geographical boundary of the source".**

VLC.3. <u>**Effects of source zone boundaries.**</u> **Rates and b-values can be defined for** cells as small as a one-half degree square. Within a cell, rates are uniform, but the rates may change sharply and discontinuously as one crosses a cell boundary. We have observed **that sites a few kilometers apart near the boundary of a source zone can have** significantly different **calculated ground motion exceedance probabilities** for high ground-motion values, because of abrupt changes in seismicity at a source sane boundary (Bender, 1986). Since source boundaries **are generally not known** with certainty, sharp changes in ground motion exceedance probabilities calculated at sites a few kilometers apart are unrealistic. The USGS Golden staff, for example, now smooth earthquake rates at source zone boundaries, to avoid troublesome discontinuities (Bender and Perkins, 1987).

By allowing different rates in each 1/2° cell, the EPRI/SOG methodology in effect creates many small sources, and most sites will **have a** high probability of being near a boundary at which a and b values change, and hence ground motions change, possibly by a small amount, for low ground motions or for high spatial smoothing, but possibly very substantially for high ground motion values.

VI-C.4. Selection of *contributing* sources. "For applications, all sources within approximately 100 km of the site are usually included. If a source represents high seismicity, and it is located within 200 km, it should be included. For the Charleston, New Madrid, and LaMalbaie regions, sources representing these high seismicity areas generally will be included for sites located within 500 km of them, for completeness" (EPRI/SOG, Vol.1, Methodology, 1987, p.2-28). This implies that if the source is affected primarily by earthquakes within . t1° around the source, assumptions regarding the features and rates in the cells immediately surrounding the source dominate the hazard results. Any included active feature will probably have considerably higher seismicity than **does** the surrounding background. The precise location of a feature could be important; the location of the feature might be uncertain by 10 or 20 km, and a change in distance of 10 or 20 km of the feature from the site might significantly affect the calculated ground motions for those scenarios in *which* the feature is active.

The higher ground motions at a site probably result from the earthquakes within 100 km, and omitting sources at distances greater than 100 km may be reasonable in general when one is calculating exceedances of the higher ground motion levels. It is not obvious to us that sources at distances greater than 100 km should be neglected when calculating probabilities of exceeding lower ground motion **levels. The** calculation depends on relative rates and maximum. magnitudes in the included, and excluded areas, on the attenuation function, and on the assumed ground motion variability for earthquakes of a given magnitude and distance. The effects on a specific ground motion level of including or excluding a source (e.g., at distance $100 < d < 200$ km) may not **be obvious** without doing the calculations. The results will **depend** in part on the characteristics of the attenuation function used.

Our own calculations suggest that the changes in the exceedances are probably not larger than a factor of two for the lower ground motions, and **may be as** low as 20 to 50% when sources within 200 km rather than 100 km are included. For higher ground motions the errors will be much smaller. **These conclusions are based** on studies using conventional attenuation functions. Other attenuation functions may produce different - results. EPRI/SOG **has** recently funded work **investigating "real** attenuation," in which crustal properties, earthquake depth, mechanisms, and dominating phases are all taken into account (Barker and others, 1988) **Many of** these "real **attenuation"** show significant ground motions coming from **between 50 to** 200 km epicentral distance. Should such attenuations **be used, the zone** exclusion distances should be increased, unless it can be shown that using an increased distance has no significant impact on site hazard results.

VI.D. Using Background Sources to Maintain Seismicity

Let us assume that n features have been identified; feature F, has some probability of activity p', and any, all or none of the features may be active in a given scenario. Each feature is assigned a rate of earthquakes, given that the feature is active. This means that in scenarios in which some of the features are inactive, fewer earthquakes will contribute to the seismic hazard, than in a scenario in which all features are active, unless the earthquakes that were assigned to the "inactive features" are somehow accounted for. Four of the six teams elected to keep the total seismicity relatively constant for each scenario as follows.

> In any scenario in which the *iih* feature F;, is not active, the seismicity that **was associated** with FF is instead assigned to the background. If none of the features is active, the entire seismicity is assigned to a default source or background. (Default and background sources may possibly be the same.) In this approach, a background source is **always active, i.e.,** p" =1 for background sources; however, the boundaries of the background source must be redefined in each case to exclude the active features. This means that the background source is in effect a whole set of distinct sources, the boundaries of which depend on which features are **active.** This approach in the implementation has two important consequences:
>
> a) By red`3atributing earthquakes during various scenarios, approximately the same regional seismicity may be maintained, but if lower maximum magnitudes a**are** assumed for **background-sources** than for feature-sources, the rate of larger earthquakes in a **scenario will** depend on the number of features that are active in that scenario. This could reduce the estimated recurrence rates of earthquakes similar in size to that of the Charleston earthquake.
>
> b) The rates and b-values used for the background for **a given** scenario depend **on the specific** set of earthquakes that are not on features that are active in that scenario, and hence, different b-values as **well as** different rates **may be** obtained for the same background cell for two scenarios. The redefining of background sources and the recalculation **of rata** and b-**values** for each background source for each scenario can significantly increase **the computation** time and complexity. To really appreciate this complexity, consider **the follawing** example. If 3 features have been identified in a region, there are 8 combinations of being "active" and "inactive" for these features, and 8 **sets** of backgrounds must be calculated for **each choice of** smoothing options, prior on 6, maximum magnitude, etc.

VLD.1. <u>Larne earthquakes tend to be diverted from features to the backsround.</u> If two or more features have been identified, and the **observed** earthquakes are divided among them in assigning rates, no feature can **ever be the sole** explanation of all the possible large earthquakes in the 'area (because each feature has been assigned only a fraction of the total seismicity). This implies that, although one of four identified features may have been responsible for the 18,88 Charleston earthquake, for example, there is no allowable scenario in *which* **one** of these features can be the sole cause of future large earthquakes in the Charleston area. Thus, if each of four features has 1/4 the total number **of earthquakes** ***when tae*** **feature** is active and only a single feature is active, to maintain a more-or-less constant seismicity, the remaining 3/4 of the earthquakes an placed in a default or background zone; if two features are active, 1/2 the earthquakes are placed in a default or background zone, etc. This means seismicity tends to be diverted from the features to the background, and, hence, the location and areal extent of the default or background zones can be quite important in determining hazard at a site near a possibly active feature (the larger the area of the background zone, the lower the area-normalized seismicity rate becomes).

VI.D.2 Concentration of seismicitv only on active sources,. In the previous example, seismicity **was** divided among four features in such a manner that no individual feature had a.sufficiently high rate of earthquakes to produce recurrences of "the Charleston earthquake" at a rate comparable to that which would have been assigned a single feature with a rate equal to the observed seismicity. An alternative which can be modeled within the methodology is that of considering the possibility that all the large earthquakes are in fact related to a single (unknown) feature. To preserve the rate, then, among the various scenarios, **we** might divide the seismicity in such a manner that it 1s always attributed to the features that are active during a each given scenario, rather than a portion going into background. If F1 alone is active, all earthquakes are assigned to F1; if F1 and F2 (but no other features are active) all the seismicity is divided between F_1 and Fs, etc. If none of the features is active, all the seismicity is assigned to the default source. This interpretation retains a constant total seismicity, but now earthquakes tend to be associated with features rather than with the background, and scenarios are possible in which a single feature can account for all the large earthquakes.

VI.D.3 Anticipation of future hither seismicitv. . We do not regard keeping the number of earthquakes (approximately) constant during all scenarios as necessarily desirable in estimating possible future seismic hazard. If an area has had low historic seismicity, and contains features that have had few or no earthquakes, .the features cannot be assigned much seismicity in any scenario in which rates are based on local historic seismicity. In the ***case*** of features which have high **pi's** but low historical seismic rates, one may want to **assign seismic rates derivable from geologic information. (The faults in Idaho or the Meers** fault are good **examples.)** The methodology permits these assignments, and in the implementation a non-historic seismic rate was assigned in Rondout's treatment (see section VLC.1.).

VII. Estimating Seismicity Parameters from Historical Data

Basic unit of treatment is the cell. In Phase II, the teams used the locations and magnitudes of historic earthquakes as given in the EPRI/SOG catalog to estimate earthquake rates and b-values for each cell in a source, and for each individual feature. (The EPRI/SOG catalog **was** not available during Phase L) Estimating a- and b-values for individual cells allows rates and b-values to vary within a source. In Phase 1, the cells were limited in size to 1° in latitude by 1° in longitude; in Phase 2, half-degree cells were permitted. Estimation was done -sing grouped mIgnitudes, i.e., earthquakes in a given cell identified as having magnitude **me** >_ 3.3 **were** grouped by magnitude in intervals, Am = 0.6 magnitude units apart. Each team had available a number of options for estimating and smoothing a- and b-values for the cells in a source. These are described below.

Smoothing probability of detection. **Because** the historic record is incomplete for most time periods, especially for the lower magnitude intervals, the number of earthquakes recorded in each magnitude interval **was** adjusted by (an estimated) 'Probability of **detection" to account for earthquakes that may have happened but were not recorded. The probability of detection was permitted to vary by area, by time, and by magnitude** interval. Each team was required to specify a level of smoothing for the probability of detection.

Soatial Smoothing of a and b values. Rather than estimate a and b-values for each cell individually, a team could spatially "smooth' estimates of a and b-values within a set of cells, by **selecting values** of "penalty functions" PENA and PENB.

To do spatial smoothing on a, the probability of the observed **set** of earthquakes in a cell is multiplied by a normal density function f (a) such that

$$f\,(a) = 2ao\ Mp(\ \frac{(a2cz^{\cdot})^{S}}{1}\ ,$$

where a is the **average** of the a-values in the ***neighboring* cells, and** the standard deviation o is determined by the **value of** PENA. Similarly, to smooth the b-values, the probability of the sample **observed in each** cell is multiplied by a normal density function whose mean value is the **average** of the b-values in the neighboring cells, and whose standard deviation is determined by the value of PENB.

Weighting Earth a u in an Interval. In estimating the a-value (rate) and b-value for' a cell, a team co assign **different** weights to earthquakes in different magnitude intervals, to account for the team's **assessment** of the relative quality of the data in each interval. For example, the **Rondout** team stated that **Because** the **rates** of larger, infrequent earthquakes are poorly **determined,** these earthquakes, should not be given as much weight as smaller **earthquakes'** (EPRI/SOG, Vol.10, 1986, p.5-3), and the Law team noted "The completeness correction, which is applied to the intervals has no effect in an empty interval, and **we** did not want this to influence the calculation **of a-** and b-values. Therefore, in some **cam, we gave** zero weight to this first magnitude interval' (EPRI/SOG, Vol.7, 1986, p.6-7).

Prior on b. A team could specify a prior estimate of b, ranging from "strong" to "weak" to make the estimate of *b* less data dependent. The prior on *b* is in the form of a normal density function with mean *b'*, and a user-specified constant that determines the standard deviation of b'.

Note that different normal distributions are being specified for the spatial smoothing of estimated b-values and for the "prior" estimate of b. These distributions may have different mean values and different variances. Both variances and the prior mean b' are specified by the analyst; the mean used in spatial smoothing is the mean of the b-values estimated for the neighboring cells in a given iteration, Lad changes from iteration-to-iteration. A sufficiently "strong prior will force the estimates for all cells to be close to the prior, regardless of the **degree** of "spatial smoothing" specified. The likelihood equations must find a best (in a likelihood **sense)** compromise estimate of *b* to satisfy the various conditions, and the effects of various strengths of prior and smoothing cannot be evaluated independently.

Tolerances. Because a system of nonlinear equations must be solved iteratively to estimate *a*, b and *PD (1, z, t)* (probability of detection for interval *I*, area z and time t), "tolerances" must be specified (i.e., the solution is obtained by making an initial estimate of the parameter values and then iteratively improving the estimates; when the estimates for two successive iterations differ by less than the specified tolerances, the process stops, and the values produced by the last iteration are accepted as the solution.)

VII.A. Some Apparent Questionable Effects of Smoothing

VII.A.1. Unpredictability of results of smoothing probability of detection. The estimated probability of detection for earthquakes in each magnitude interval may be affected in unexpected ways by the smoothing option selected. For example, in an example provided by EPRI/SOG (Vol.4, 1987, Table **4-13, p.4-46),** the probability of detection for earthquakes in a given magnitude interval estimated for "moderate smoothing" did not lie between the estimate obtained for "weak smoothing" and that for "high smoothing". This seemed counterintuitive to us and we questioned EPRI/SOG. (See question 9, round 2, and response, in EPRI/SOG, Vol.11, supp.2, 1987, p.2-15) EPRI/SOG replied that this effect does not happen in practice when results are better "anchored", i.e., when there are more intervals **for which *PD(i,=,t) the*** *probability of* detection at time t for interval *I*, area z, is fixed at 1.0. Thus we 'anchor the results by specifying the (magnitude, time, area) combinations for which the probability of detection is assumed to be 1.0, and these anchored values do not change during the computation.

The highest magnitude interval always is assumed to have *PD (I, z, t)* = 1.0. "As the smoothing on the probability of detection increases, the final estimates should converge to the **fixed value** of 1.0" (EPRI/SOG, Vo1.4, 1987, p.4-8). Thus, if **we** do not specify *PD(I, z, t)* = 1.0, **we** probably believe the record is not complete for time period t and magnitude interval i, in area z. Thus **we** should not select "very high" smoothing, because it results in final estiimates of *PD (I, z, t) = 1.0* for all times and intervals. We cannot predict the **consequences** of **other choices of smoothing level. Nevertheless,** the choice of smoothing level is important **because the smoothing level alters the** estimated probability of detection which, in turn, alters the "corrected" **observed** numbers of earthquakes.

VII.A.2. Unpredictability of results of smoothing a and b estimates. Estimates of a and b values for a number of values of PENA and PENB are shown in Vol. 4, Table

4-7, for three cells. We noted that if PENA=PENB=O represents no smoothing, *and* PENA=PENB=5000 represents high smoothing in a and b, **we** would have expected estimates of a and b for intermediate smoothings to lie between those obtained for the extreme cases, but this was not necessarily true (e.g., when PENA=50 and PENH=O). We felt this **was** counterintuitive and questioned EPRI/SOG, **(See** question 8, round 2, and response, in EPRI/SOG, Vol.11, supp.2, **1987, p.2-12)** who responded in part that "if different degrees of smoothing are imposed on a(x) and b(x), the seismicity parameter with the higher smoothing will tend toward the homogeneous solution and the other parameter will become more variable and adjust to satisfy the maximum penalized likelihood equations."

For example, et us imagine **that one** cell contains **(16,8,4,2,1)** earthquakes in successive magnitude intervals, and a second cell contains **(32,16,8,4,2)** earthquakes in the corresponding intervals. The second cell contains twice as many earthquakes as the first cell, but both cells have the same magnitude-frequency distribution, and hence, the same b-value would also be estimated for the two cells if no smoothing were done. The same b-value would be estimated if the earthquakes from the two cells were combined **(48,24,12,6,3** earthquakes in the respective intervals), and a single b•value were estimated for the joint data.. **However,** if **we** request "smoothing on a, no smoothing on b", the algorithm causes the estimated b-value for one cell to increase, and the estimated b-value for the other cell to decrease. This **seems** both counterintuitive and undesirable to us. The fact that "this is a consequence of the algorithm" suggests to us a problem with the algorithm.

Even if PENA and PENB are assigned the same **values,** the estimate of b, for example, for an intermediate value of PENA and PENS does not necessarily lie between the more extreme **values.** (For example, the estimated b-value for cell 10 in Table 4-7 ***when*** **PENA=PENB=20 does** not **lie** between the estimate obtained when PENA=PENH=O and that obtained **when PENA=PENB=50.)**

Unexpected results are also illustrated in the computer printout provided by the Bechtel group (EPRI/SOG, ***Vo1.9, 1986,*** Figure ***6-3, p.6.11)*** showing the "observed cumulative count mb >- 3.3" in each 1° **cell** in a large background zone (zone BX8) and the corresponding "expected cumulative count mb >- 3.3" predicted when PENA= P ENB =999 .00 ***Bechtel*** **referred** to this option as "constant a and b, no prior on b" (EPRI/ S O G, VoI.9, 1986, p.6-10). Here a n ee **of cilia at** 60° - 63° had **zero** earthquakes observed, and as many as 3.7 earthquakes expected; but a **cell (64'**°,43°) that had one earthquake observed, has zero expected, and a cell ***(62°,* 45°)** that had 2 earthquakes has 0.7 earthquakes expected.

VILB. The EPRI/SOG Algorithm

As **we have noted above,** in the **EPRI/SOG** algorithm for estimating a and b-values, if a-values are spatially smoothed, the estimated &-values are also altered. Smoothing the rate alters the estimated **b,** so that the cell that had fewer **observed** earthquakes gets a steeper b to compensate for the fact that the estimated rate has increased after smoothing, and conversely the **cell** that had a larger number of observed earthquakes, has a lower predicted rate after smoothing, and hence, a flatter fitted b.

In reality, a-values do not define b-values-b values depend only on the magnitude distribution of the data. We can write maximum likelihood equations in which the estimate of b does not depend on the estimate of a, even undei conditions of incompleteness. To illustrate why the EPRI/SOG equations cause estimates of b-values to be altered when spatial smoothing is done on a-values, let us consider a simplified situation in which magnitudes in the range 0 < m < oo are possible, and magnitudes are recorded exactly. In this case, the maximum likelihood estimate is b = 1/ift., where *eh,=mean* sample magnitude. This follows from

$$E[n] = \int_0^\infty m b \exp(-bm) dm = \frac{1}{b}.$$

Let us assume A=rate of earthquakes with m >- 0, and N=number of earthquakes observed in a given cell. EPRI/SOG in effect solves for b using the relationship

$$Nm_1 = \frac{\dot{}}{b}$$

All is well in the previous equation so long as **we set k =** N (A = N is the usual maximum likelihood estimate of A), in which case & = , as it should. However, if a TEC elects to "smooth" the rate estimates, then A o N, and when one **uses** the previous equation to estimate b, the estimates of the b-values will be altered. However, one can derive the maximum likelihood equation in such a manner that one obtains

$$NM. = \frac{}{bN}$$

and the the estimated rate *I* does not enter into, the equation for estimating b. Thus, one ***continues*** to estimate b = it., when the rate **estimates** are smoothed. As we noted, the two formulations yield the same results when no spatial smoothing is done on a estimates, but different results when spatial smoothing is done. **We believe** EPRI/SOG could avoid some of the troublesome **behaviors** if EPRI/SOG chose the formulation that uses observed numbers (or observed numbers corrected for probability **of detection) of earthquakes** in the equation for estimating b-values rather than using estimated smoothed rates. (In addition, we believe the computation time required would be significantly reduced in the second case.)

VILB.1. Methodoloev iDermits undesirable olDtions. The teams were aware that spatially smoothing estimates of one parameter would alter the estimates of the other parameter, and they typically smoothed both a and b estimates simultaneously. However, inasmuch as the results of requesting various degrees of smoothing on a and b estimates appear to be unpredictable, the effects of a particular choice for one parameter cannot **be evaluated independently** of the choices made for other parameters. Some choices (e.g., no spatial smoothing on b-estimates and no prior on b) lead to excessive cell-to-cell variability in recurrence rates above magnitude 5.0, giving an impression of unstable and unreliable estimates. Because, in the implementation, teams rarely, if ever, chose parameters giving little or no spatial smoothing and weak priors on b values, we do not expect that this problem will produce a significant effect on overall site hazard estimates, although unexpected results may occur for a rare individual scenario. Inasmuch as the methodology does not prevent poor choices of smoothing parameters, future use should ensure sufficiently strong spatial smoothing or strong priors on b values.

VII.B.2. For most cells, data is inadequate for direct estimation of a-and b-values. As previously noted, EPRI/SOG initially aimed its methodology at estimating a and 6-values for one degree cells, and then later extended the methodology to include one-half degree cells. Most 1^0 cells contain 2 or fewer earthquakes of m_b > 4.5. Half-degree cells (which encompass 1/4 the area of a 1° cell) would generally contain 0 or 1 earthquake of $m_b >$ 4.5. When all the cells in a source are combined, and all the recorded earthquakes $m_b \geq$ 3.3 included, "for most of the source zones considered in this study, fewer than 50 earthquakes are included within their boundaries. For about one-quarter of the zones, less than 10 events are encompassed within their perimeter" (EPRI/SOG, Vol. 8, 1986, p.6-9).

We asked what EPRI/SOG regarded as "adequate data" for estimating a and b (See question 10, round 2, and response in EPRI/SOG, v.11, supp.2, 1987, p2-17). EPRI/SOG's response was, in part, that "if no earthquakes have been recorded over a long period- in a cell, this provides relevant statistical information with which to estimate the rate of earthquake occurrences. The a-value (or seismic activity rate) for that cell would be very low. In this case the estimation of the b-value is problematic; however, the value of b is unimportant for seismic hazard due to the very low value of a. It should be noticed that, due to the capability of EQPARAM to impose spatial smoothing, data from neighboring cells are used in estimating the a- and 6-values. in each cell."

If cells are sufficiently small, almost all cells will necessarily have few earthquakes, and the b-value will almost always be "problematic" if b-values are estimated for individual cells using the observed earthquakes. Even if a team requests high spatial smoothing, we believe the estimated b-values will be "problematic" when as few as ten earthquakes, for example, are contained within the source for which the smoothing is being performed. To obtain stable results, a team may be forced to specify a strong prior on b; however, although the results obtained **using** a strong prior may be stable, they are not necessarily an accurate assessment of the underlying b-value of a given cell.

Inasmuch **as we cannot obtain a** reliable estimate of *b* using the observed earthquakes in a cell, if only **a few earthquakes have been observed,** we have little or no basis for **assuming the** ***b-value*** *is,* in fact, different in neighboring cells. However, 'even when spatial smoothing is **done on a and** *b-* estimates, or when a prior estimate b' is assumed, the maximum likelihood equations give different estimated b-values for different cells, and one may, therefore, be tempted to believe that the methodology has enabled one to recognize cell-to-cell differences in **b-values.** When a "strong" prior on b is assumed, the cell-to-cell differences in the estimates may be quite small, **e.g.** b = 1.17 in one cell, b = 1.18 in an adjacent cell. We do not believe the **data are** adequate to make these distinctions.

VII.B.3 Maximum likelihood results can be "correct" but not useful,. EPRI/SOG obtains its results using a penalized maximum likelihood technique. This is a very sophisticated tool. Why shouldn't the results of the use of this tool be accepted as correct? It must be remembered that one can always estimate parameters using maximum likelihood equations, but the solutions may not be useful. For example, the maximum likelihood solution for the magnitude of the largest possible earthquake in a region is the magnitude of the largest observed earthquake, even if only a few earthquakes have been observed. We do not believe that anyone would assert that the fact that this is a maximum likelihood result makes this result very meaningful. Independently of the question of whether the EPRI/SOG equations are formally correct, we do not expect that the EPRI/SOG methodology equations will supply meaningful results unless a sufficiently large amount of data serve to constrain the results. In the absence of sufficient data, the priors will drive the results; the meaningfulness of the results then depends on the reasonableness of the priors.

VII.B.4. Smoothing on logarithm of rate rather than on rate. The a-value for a cell represents the logarithm of the number of earthquakes in the magnitude interval $3.3 < m < 3.9$, and the algorithm for smoothing a assumes that the logarithm of the number of earthquakes observed in that interval is normally distributed. We do not believe this assumption is correct. If the rate of earthquakes is the same throughout an area, the total number of earthquakes observed in various cells represent repeated samples from a Poisson distribution with a constant mean. If the rate is sufficiently high, the law of large numbers will apply, and the number of earthquakes **observed** in various cells will have appaximately a normal distribution, but this does not mean the logarithm of the rate in an interval will be normally distributed. Furthermore, the estimated number of earthquakes in the magnitude interval $3.3 < m < 3.9$ depends on the current estimate of the b-value, thus rendering this a **value more sensitive** to b value than an a value based on the total number of earthquakes above magnitude 3.0 would be. Finally, it appears to us that spatially smoothing the log rates in the above interval rather than rates will not give the same relative cell-to-cell rates of earthquakes with magnitude $m \geq 3.3$.

VII.C. Other Effects

VI1.C.1. D_ecraase in Earthquakes Predicted in Most Active Cell. Spatial smoothing will necessarily **decrease** the predicted number of earthquakes in the cell that had the highest number of earthquakes recorded. In the Bechtel example cited previously, one cell had 36 earthquakes **observed,** but only 7.1 expected; (the **cell** that had 21 observed, however, had **9.8 expected).** If **we** believe in the Poisson assumption and stationarity, the standard deviation in n, the number of earthquakes **observed,** is o,, = f (or 6 earthquakes in the case of **36 observed).** When as many as **36** earthquakes have been observed, we might question whether a scenario in which the number of earthquakes in a cell is So below the **observed** number should be permitted. On the other hand, the smoothing options do not allow the number of earthquakes in the most **active cell to increase,** and, although the expected number in that cell in various scenarios may be lower than the number observed, it will never be higher. Thus smoothing must **always** predict lower numbers of earthquakes than those observed historically for the most active cell. (Fitted smoothed parameters may predict earthquakes larger than were observed, which would somewhat increas the hazard above that calculable from historical earthquakes, but the decrease in the cell rate tends to counteract this effect.)

VII.C.2. Normalization of prior with cell size. The prior on b is in the form of a normal density function with mean b' and a user-defined variance. (The smaller the variance, the more confident we are of the prior.) However, EPRI/SOG 'ormalizes' the variance of 6' by the area of the cell, so that the "strength" of the prior does not diminish as the data set increases (e.g., a one-degree cell would be expected to contain four times as many earthquakes as a one-half degree cell). EPRI/SOG intends this procedure to make the methodology insensitive to cell size. However, normally, we would expect a prior to have less effect as more data becomes available.

VIII. Estimating Maximum Magnitude

Maximum magnitude is regarded as a significant seismicity parameter in most seismic hazard analyses. If one increases the maximum magnitude used in the calculations, the largest ground motion values are increased, and, in most methodologies, the total number of earthquakes increases. However, because of the assumption of a Gutenberg-Richter magnitude-frequency relationship, the number of earthquakes added becomes exponentially smaller as the maximum magnitude gets larger. For this reason, and because of magnitude saturation in many attenuation functions, probabilistic ground motions are most sensitive to small changes in maximum magnitude when the maximum magnitude is low ($mb < 6.0$) and the *b* **value** is low ($b < .85$).

In assigning seismicity parameters, each team was required to estimate a set of alternative maximum magnitudes for each source. However, "in the eastern United States, where no moderate-to-large earthquake in the historical record has produced a documented surface rupture, intuition and methods based on seismicity play a large role, rather than methods tailored to feature dimensions or actual rupture **plane properties"** (EPRI/SOG, *Vol.* ***8, 1986, p.6-12).*** The teams assigned maximum magnitudes according to three kinds of principles. (1) Where there **was** sufficient geophysical or geological information to associate a feature with structural properties or tectonic characteristics that could be related by analogy to observed maximum magnitudes for active sources anywhere in the world, maximum magnitude **was** assessed in accordance with some geological criteria. (2) Where seismicity was sufficiently great that some estimate of a Gutenberg-Richter relation could be made, maximum magnitude was assessed according to some long recurrence rate. (3) In some cases, the estimated maximum magnitude was based on maximum observed magnitude.

VIII. A. Geologic Basis for Maximum Magnitude

The TECs' structure-based procedures for determining maximum magnitude yield magnitudes in the mid-seven to low-five range. In light of the poor correlation of seismicity with geologic structure throughout most the EUS, and the random occurrence of moderate magnitude earthquakes (Sharpsberg, Ky., 1980, $mb = 5.1$; Miramachi, New Brunswick, 1982,, rna = 5.71, **we** prefer approaches to estimating $\mathbf{m}_m$ that assign at least moderate earthquake potential (say, mb = 6.0) to background zones, as well as to types of geologic **structure. Some TEC's allowed structure-based** maximum magnitudes well below this value in their distributions of maximum magnitude. Because of the lack of prominent structure at Charleston that can be identified with large earthquake occurrence, that is, because the source of the Charleston *1886* earthquake is not known, it would seem that Charleston type earthquakes could occur elsewhere in the eastern U.S.

VIII.B. Recurrence Basis for Maximum Magnitude Estimates

Some teams considered using the magnitude of the earthquake with an estimated 1000 year-recurrence time as the maximum magnitude. At least one team allowed the maximum magnitude (in one option) to be determined directly from the a values, where a lower value of a resulted in a lower estimated maximum magnitude. The teams estimated the 1000 year earthquake by using a least-squares fit to the data to obtain the coefficients in the magnitude-frequency relationship log $N = a$ - ***b(m - m,,,,,,). (This*** relationship assumes m..,Q= = oc; the a value represents the rate of earthquakes m >- m,,,;,,, where m,,,,,, = 3.3 was assumed.)

VULB.1. Return period for near-maximum magnitudes is too *lone.* We believe that if the maximum magnitude is calculated from the magnitude-frequency relationship described above, magnitudes below this calculated maximum may well have a return period considerably longer than 1000 years. We present the following example to show what might happen. We assume that b = 1.0 (or $_{O}$ = 2.3) and that 0.500 earthquakes with m >- 3.3 per year have been observed in a 100,000 square km. area. In this **case,** the expected exceedance rate of magnitude m = 6.0 earthquakes is

$$R(m >- 6.0) = .500 \int_{6.0}^{G0} 0 \exp(-p(m - 3.3)]dm = .001$$

This means we would select m,,,ss = 6.0 for this area. Let us consider the rate of earthquakes that exceed magnitude 5.9, when an infinite maximum magnitude is assumed:

$$R_I(M >- 5.9) =.500 \sim' \int_{as}^{CD} iB \exp(-O(m - 3.3)(dm = .00127$$

and when m,,,s= = 6.0 is assumed:

$$R2 (m >- 5.9) \_ .500 \int_{s.s}^{a.0} {}_{O} \exp (-/3(m - 3.3) (dm = .00027$$

Thus the return period of a magnitude m = 5.9 earthquake increases from less than 800 years (when **m,,,s** = oc) to 3700 years when **m,,,s** = 6.0 is assumed, and an m = 6.0 earthquake has an infinite return period.

Two teams recognized **a need** to deal with this difficulty, observing that the EPRI/SOG method of cutting off upper-bound magnitudes affected the recurrence of earthquakes oe<a *magnitude* unit *below* the cut-off ma. itude. These teams added 0.3 units **to their upper-bound magnitudes to counteract** this effect. In response to USGS question number 2 in the second round (for question and response, **see** EPRI/SOG, Vol-11, supp.2, 1987, p.2-2) **EPRI/SOG** furnished a table (Table VM.A. in this review) showing the change in calculated exceedances of various ground motions, when 0.3 units is added to upper bound magnitudes of 6.0 and 7.0. The change approaches a factor of two increase for **large ground motions** for the upper-bound magnitude 6.0, illustrating the importance of the truncation effect. (The table also illustrates the sensitivity of large ground motions to changes in upper-bound magnitude.)

We also note that the 1000-yr recurrence earthquake in a source zone is larger than the 1000-yr earthquake in a one-degree cell within that source **zone.** Accordingly, the team which allowed maximum magnitudes to be based on the 1000-yr recurrence rate in individual cells could have quite low values compared to values that would have been assigned based on to the 1000-yr recurrence earthquake for the whole zone.

[Incidentally, one of the teams states, "A source zone with spatially-varying a would necessarily have spatially varying m,,, .." (EPRI/SOG, Vol.6, 1986, p. 6-5) This appears to conflict with the stated EPRI/SOG model definition that, "Every point within the boundaries of a source has the same distribution on maximum magnitude" (EPRI/SOG, Vol. 1, Methodology, 1987, p. 2-7).]

VIII.C. Observed Maximum Magnitude as a Basis for Maximum Magnitude

In some cases the teams based their estimates of maximum possible magnitude on the maximum observed magnitude in an area, possibly allowing as alternate choices a value lower than the maximum observed (to allow for the possibility that the estimated magnitude of the largest observed earthquake **was** in error and that such large earthquakes could, in fact, not occur), the actual observed maximum, and **a value** greater than the observed maximum.

VIILC.1. <u>Maximum observed magnitude is a boor statistical estimate.</u> The maximum likelihood estimate of the maximum magnitude is the observed maximum in a sample. For a sample of size one, the maximum likelihood estimate is clearly useless. Indeed, unless a sufficiently large number of earthquakes has been observed in the sample, the maximum observed magnitude is likely to be considerably less than the maximum possible magnitude.

In a paper currently under preparation, Bender shows that unless the maximum observed magnitude is sufficiently *small (i.e.,* sufficiently close to the minimum magnitude), one cannot statistically discriminate among various possible maximum magnitudes. For example, if the sample contains 40 events .greater than the minimum magnitude, the observed maximum magnitude is likely to be close to the true maximim magnitude (i.e., within 0.1 or 0.2 units), only if the observed maximum magnitude is less than one magnitude unit higher than the minimum magnitude. In other words, for a sample this size, for a minimum magnitude of 3.3, only if the observed maximum magnitude is 4.3 or less is it likely to be a good estimate of the true maximum magnitude. For samples as large as 160 to 320 events, for the same minimum magnitude, the observed maximum magnitude must be 5.3 or less for it to be a good estimate of the true maximum magnitude. Few, if any source zones in **the EPRI/SOG implementation, could meet the** conditions for asserting maximum magnitudes of 5.0 or **less.**

For the data sets in the Eastern United States, observed maximum magnitudes higher than 5.0 are essentially meaningless in estimating true maximum magnitude (except to the extent that the maximum **observed** magnitude might be regarded as a lower bound for the maximum possible magnitude). In samples of a given size, the maximum observed magnitude becomes more variable, and the probability of a maximum observed magnitude close to the true maximum magnitude decreases, as the true maximum magnitude increases. The net effect is that one cannot in general add any single constant (e.g., 0.5 magnitude unit) to the magnitude of the largest observed earthquake to obtain a reliable estimate of maximum magnitude.

VIII.C.2. <u>Converted magnitudes are unreliable for determining under bound.</u> In many cases, magnitudes have been obtained by converting intensity values to magnitude values. One *intensity* unit corresponds to about 0.6 magnitude unit, and the variability in the conversion between intensity and magnitude has a standard deviation of at least the same amount. Hence a converted magnitude value is highly uncertain. This makes estimates of maximum possible magnitude based on the largest observed earthquake more uncertain than indicated above.

VULD. Conclusion

Although it might be argued that the range of maximum magnitudes and their associated distributions assigned by the TEC's represent the range of opinions regarding m„„ , in the EUS, our opinion is that the lower end of the maximum magnitude distributions is generally too low. We have argued statistically that the seismic history is too short for maximum observed magnitudes to give good estimates of maximum possible magnitude where the seismicitT is low. We also believe that the distributions of maximum magnitudes based on structure often extend to values which are too low, considering the random occurrence of magnitudes approaching e.Q in **areas** where there **was** no previously recognized seismogenic structure. We believe the recurrence-based maximum magnitudes yield recurrence rates on the remaining magnitudes that are too low. In our opinion, the result is that some of the seismic hazard estimates will be relatively low and very sensitive to the maximum magnitude used in the calculations.

a.. Importance of Minimum Magnitude and Ground Motion Variability

We have mentioned that implementations in the EPRI/SOG submittal contain scenarios in which TEC's selected maximum magnitudes that seem to us to be too low. In addition, however, the minimum magnitude used thus far (m_b = 5.0) is relatively high compared to those maximum magnitudes. Obviously, if EPRI/SOG had used a lower minimum magnitude, ground motion **exceedance** rates would have increased. We have two additional concerns which arise from the relatively narrow ranges between minimum and maximum magnitudes. One is that the use of a high minimum magnitude makes the **calculated exceedance rates** of some ground motion levels more sensitive to the choice of maximum magnitude than these rates would be if the minimum magnitude were lower. The second concern is that this sensitivity to minimum magnitude itself depends on the choice of standard deviation of the attenuation function. In this section we provide estimates of these sensitivities.

IX.A. Sensitivity to Minimum Magnitude

In response to our concerns, EPRI/SOG provided a table showing the effect of minimum and maximum magnitudes and of a on the calculated **exceedances** of 150 cm/sect at a site in a 200 km by 200 km source (EPRI/SOG, Vol.11, supp.3, 1988, p.97). (This table is included as Table DLA in this review.) The calculations assume that ground motions resulting from earthquakes of a given magnitude and distance are lognormally distributed with standard deviation o in log (natural logarithm) of ground motion, and that a is the same for earthquakes of all magnitudes and distances.

In EPRI/SOG's table, if a = 0.60 and the maximum magnitude is 5.5, the exceedances increase by 60 per cent as minimum magnitude decreases from 5.0 to 4,0. This example illustrates the extent to which minimum magnitude can affect the calculated exceedance rates of low-level ground motions. Looked at another way, the table shows that if a = 0.60, and the minimum magnitude is 4.0, the calculated exceedance rate increases by 73% when the maximum magnitude **increases** from 5.5 to **6.5. However,** if the minimum magnitude is 5.0, the exceedance rate increases by 100% for the same change in maximum magnitude. This example illustrates that a high minimum magnitude renders the exceedance rates more **sensitive** to the maximum magnitude chosen. (At higher ground motions, the exceedance rates will be less sensitive to minimum magnitude, but considerably more sensitive to maximum magnitude.)

If some magnitude mo can produce ground motions of engineering interest, we should set $m_{min} \leq m_0$. For example, if **we** believe that some earthquakes of magnitude m_b = 4.5 can produce damaging ground motions, we should not **set** m_{min} = 5.0. On the other hand, if **we** select too low **a value** of m_{min}, we will include in the calculations relatively high ground motions from low magnitude earthquakes (i.e., motions that are several standard deviations greater than their median values), when in fact such motions might not be damaging. The potential damageability of small magnitude earthquakes remains an **unresolved issue (e.g., Proceedings of Workshop on Engineering Characterization** of Small Magnitude Earthquakes, 1987). Small magnitude earthquakes can, by virtue of their large numbers, significantly affect calculated results. This issue appears to us to be a significant source of uncertainty at some ground motion levels, and one uncertainty which EPRI; S0G has not modeled (but no one else models this uncertainty either).

IX.B. Sensitivity to Ground Motion Variability

As a, the standard deviation of the log ground-motion attenuation function, increases, the exceedance rate increases and is more sensitive to changes in minimum magnitude, at some ground motion levels (e.g., at 150 cm/sect for the site in Table IX.A). For a fixed maximum magnitude, the calculated exceedances of higher ground motion levels are more sensitive to the choice of o than are the **exceedances** of lower ground motion levels (e.g., at 40 per cent gravity, the exceedances increase by a factor two as a increases from 0.3 to 0.5, and by another factor two as a increases from 0.5 to 0.7 at the site in Fig 3., Bender 1984). However, at 0.15 g, the effect of different estimates of a are comparable to the effects of changes in maximum magnitude of 0.5 units. EPRI has modeled the effects of uncertainty in maximum magnitude on ground motion exceedances but not modeled the effects of uncertainty in a. At higher levels of ground motion **(0.4 g** and higher), we estimate the effect of the (unmodeled) uncertainty in a on exceedance rates to be several times greater than the (modeled) effect of changing maximum magnitude by 0.5.

X. Magnitude Conversions

Earthquake sizes have been recorded in various ways *(mbL₀*, *ML, M,, mc,* 1_0, etc.). For many of the earlier earthquakes, the only size measure is epicentral intensity Io. EPRI/SOG assumes that various magnitude scales are linearly related and "converts" earthquake sizes recorded in various ways to a common scale. EPRI/SOG first determines the coefficients *c1* and *c2* in the relationship $mb = c_1 + ezm.$ using observed earthquakes for which both an *mb* and m_s value have been recorded (where m. is an arbitrary size measure), and then applies these fitted relationships to estimate an *mb* value for each earthquake. **EPRI/SOG** then uses these ***mb* values** to estimate for each earthquake, a magnitude *mb,* where *mb* is "the magnitude that **has the same exceedance** rate as *mb."* The teams then use the mb values and earthquake locations to estimate a and b values for each cell. We find some problems with the estimates of ***mb* values,** and the failure of EPRI/SOG to weight the converted magnitudes *(mb* or *mb* values) when estimating a and b-values.

X.A. Determination of mb

To obtain mb from *mb,* **EPRI/SOG assumes a Gutenberg-Richter** magnitude-frequency relationship, a doubly infinite magnitude range, and normally distributed errors in "observed" earthquake sizes *m..* In this model, more earthquakes will be "observed" at a given magnitude than actually happened at that magnitude. For example, an earthquake with apparent magnitude mo might have been produced by an earthquake with true magnitude m_o - 0.1 units and an "observational" error of +0.1 units, **or by** an earthquake with true magnitude m_o + 0.1 units and an **observational error of** -0.1 units. But there are more earthquakes with true magnitude "to - 0.1 than with true magnitude mo + 0.1. If the magnitude range is infinite, for any **size error e, there will be more earthquakes** with true magnitude m_o – e that have observed magnitude m_o, than earthquakes with true magnitude m_o + e that have observed magnitude *mo.* The net result is that a given observed magnitude mo is more likely to have been produced by an earthquake with a true magnitude less than "to than by an earthquake with true magnitude greater than mo. In this **case,** one can calculate a number to add to the fitted *mb = e1 +* ezm. to obtain the uniform magnitude **value *mb.***

- **However, the previous conclusions are not valid, and** the correction is not appropriate, if the data do not **follow the** model. For example, if the **magnitude range** terminates at **a** finite **value of m,,,;,,, there are** no earthquakes with magnitudes m < ***m***1,,," that could have produced an **"observed"** magnitude m_o >- *m,,,;,.* In this case, fewer earthquakes will be observed at magnitudes in the vicinity of *m*m,,, than **are** predicted by the model.

In practice, the assumptions of the **EPRI/SOG** model are not met.

(1) The magnitude range is not infinite. On the upper end, the magnitude range is assumed to terminate at m,,,,. < oo; on the lower end, a decreasing fraction of smaller magnitude earthquakes is **observed, and even** if magnitudes m = -oo are possible, they are not observed, and there is an effective magnitude cutoff.

(2) If m. = Io, Io assumes only the **values** 1 <- **Io** <- 12, and a one-to-one relationship between *Mb* and I_o cannot hold if the magnitude range for *Mb* is doubly-infinite. In

addition, the analysis is based on the assumption of a continuous distribution of *mb* and m_2 values, and Io is a discrete variable, and errors in to cannot be normally distributed, except in some limiting sense (Bender, 1987).
(3) If m_s = lo, and an earthquake has a recorded Io value, but no mb value, **we** cannot use the earthquake in fitting the relationship between to **Lad** mb. The number of earthquakes having both mb and lo values recorded tapers off at low magnitudes, and the set of earthquakes that have both mb and to values do not follow a Gutenberg-Richter magnitude-frequency relationship.

Failure of the data to follow the postulated model results in biases in the fitted relationship between mb and m_s, and could mean that the correction term used to obtain mb from the fitted mb value is inappropriate. The biases that result when the data are restricted to a finite magnitude range, and when earthquakes are selectively missing at lower magnitudes, are minimized if only pairs (mb, m_s) that lie well within the interior of the range for which earthquakes have been completely recorded are used to fit the coefficients. In this **case, the** EPRI/SOG "correction" to obtain mb may be valid in the interior of the range, but not near the lower and higher ends of the magnitude range.

Figure X.A reproduced from Bender (1987) illustrates the different lines $mb = a+bI_0$ that may result for the same **set of** earthquakes when different ranges of Io values are **used to** fit the lines. It is assumed the Io **values** contain errors and a fraction of the earthquakes with low intensity **values are** missing from the data set. Figure X.A illustrates that 'missing" earthquakes affect the values of the fitted coefficients **even** if the missing earthquakes are outside the **range** of magnitudes used to fit the coefficients. Similarly, Table X.A. illustrates the range of a and b values in the relationship **inb** = a + blo that may result when intensities in various ranges are used to it the coefficients. Results shown **are** for two models in which the_ maximum magnitude is infinite and one model in which the maximum magnitude is 7.3. **A friction** of lower ma nitude earthquakes is missing in each case, and no earthquakes with magnitude mb < 2.7 **have been** recorded. The true slope of the line is 0.6, but the fitted slope may be as low as 0.36 if low intensities are used in the fit. 'I pSe true a is 1.54, and in the doubly infinite model, the expected value of the fitted a = 0.82. The correction to obtain mb is based on the assumption that a = 0.82. **However, we** observe that a may be greater than 2.2, and is **never a** small a 0.82. Thus, **the correction may never be applicable to real data.**

EPRI/SOG obtains mb **from the relationship m` = me + boa/2, where now b represents log,(10)b of Gutenberg-Richter b-value. If a correction is, in fact, appropriate, we believe** the correction should be $b(c=o_s)^2/2$ instead of $bo^2/2$, where ez is defined in the relationship **mb = el + elm$_s$**. Here o_s represents only the standard deviation of the variability in m_s rather than, a EPRI/SOG **asumes,** o, the variability about the regression line and the **variability of** the regression line also. (Following Bender (1987), we lump together **various sources** of variability in the 'observed" mb and Io values, and call this **variability "observational' error in mb and lo. We** regret if this terminology is misleading.)

If "different focal depths will logically lead to different **values** of ***mb*** for a given lo" **(EPRI/SOG, Vol.11, supp.3, 1988, p.16),** the equation relating mb and Io should contain a term representing focal depth. This means a linear relationship cannot be assumed between mb and lo, with- normally distributed errors, unless the missing focal depth term= can be "absorbed" into the linear equation as **a** normally distributed error term: the differences in mb for a given to (or in 10 for a given mb) resulting from focal depth should be normally distributed. Our analysis shows that when M_b is fitted as a linear function of $\mathbf{I}_o$, normally distributed errors in mb do not bias the fitted coefficients, and do not affect the "correction" to obtain mb. On the other hand, if differences in focal depth result in a different 1_o for a given mb, and these differences can be approximately represented as normally distributed errors in Io, the fitted coefficients in the relationship mb = $c_1 + c2 1_0$ will be biased, and this bias should be taken into account in estimating mb.

From EPRI/SOG's statement "different focal depths lead to different values of mb for a given Io," it appears th .t EPRI/SOG believes the variability resulting from focal depth is associated with mb, and hence should not affect the "correction" term to obtain my from the estimated mb. If, instead, EPRI/SOG associates the variability from focal depth with 10, the variability should be taken into account in estimating mb.

X.B. Discretization of mb Intervals

After "converting" magnitudes to mb values, EPRI/SOG groups these magnitudes into intervals of width Am = 0.6. We disagree with EPRI/SOG's justification for setting the magnitude value converted from intensity at the center of this interval rather than at a value corresponding to the mean magnitude of the earthquakes that produce that intensity, which is less than the center by an amount which depends on the b value and the interval width. However, EPRI/SOG's choice is conventional, and, if $_6$ = 2.3 or 6 = 1.0, and Am = 0.6, then the expected shift from the center range to the mean is 0.07 units, corresponding to a change in estimated rates of about 15%.

X.C Fitting b-values using "Converted" Magnitudes

"Converted" magnitudes mb are used in fitting a- and b-values for mb, and all earthquakes are given equal weight in the fitting. If mb values obtained from lo are used to estimate b, an error in the interval **size** (or equivalently, an error in the estimate of **c2** in the relationship mb = c_1 + c210) will **"carry over"** into the estimate of b. The mb values obtained from directly recorded **mb values** are known with more certainty than mb values obtained from **converted_** intensity **values,** for example. It can be shown that in some cases, one can obtain a more reliable estimate of b using only the my values for the directly recorded mb values than by using the mb **values** from both the recorded mb values and mb **values** "converted" from intensity **values,** if the two sets of magnitudes are not properly weighted (Bender, 1987).

X.D. Conclusion

EPRI/SOG obtains mb values by making "corrections" **based on** an analysis that we do not believe applies to the real data. Under some conditions, the `corrections" may be approximately valid for magnitudes near the center of the magnitude range, but cannot be used when m= values lie outside this range. In any **case we** believe the fits are dominated by incompleteness at either end of the data, and the analysis and any corrections should be based on this fact. Errors in magnitude values near the upper and lower ends of the range could become important, for example, in estimating b-values. Errors in magnitude values might also cause the earthquake to be placed shove or below some threshhold value used in assessing the probability of activity of a feature, or in estimating the rate for a cea. However, the change in definition of activity from p' to P^{I} in the latter part of the development of the methodology (which lowers the threshold magnitude) probably renders this latter concern not very important.

We believe that different weights should be assigned to my values obtained in various **ways (e.g.,** ms values obtained from "converted" intensity values should receive less weight than mb values obtained from directly recorded **m6 values)** in estimating b-values. Errors in the fitted coefficient c2 in the relationship mb - el +czm $_s$ will affect the b-value estimated for mb using magnitudes converted from m_s. The uncertainty in a2 depends in part on the number of magnitude pairs (mb, m_s) used to fit the relationship between mb and m=. This means that even if a large number of m_2 values are converted to mb via the previously fitted relationship, the estimate of b will be limited by the accuracy of a2. Failure to take this into **account** by weighting the mb values derived for earthquakes having various size measures could be important in estimating a "best **overall** fit of b" for **a set** of cells. In the EPRI/SOG implementation, in the seismic parameter methodology, the fitting of b values is generally driven by strong smoothing and strong priors, and the data are sufficiently sparse in most cells that **even** with conversion errors data are <u>unlikely</u> to drive fits far from the priors.

XI. Consensus Best Estimate

Given a range of estimates by each team of the annual probability of exceeding a given ground motion level at a site, these estimates must be combined to obtain a single "best" value. EPRI/SOG combines the estimates by first obtaining mean log hazard (MLH) estimates for each team and then uses a complex weighting procedure on team MLH's to arrive at a single "best" estimate value of hazard. We shall comment on both parts of this procedure.

XLA. Best Single-team Estimate

The EPRI/SOG methodology for determining consensus best hazard estimates uses the mean log hazard to provide **a single-parameter team best site hazard** estimate. The use of mean log estimates rather than mean estimates of hazard tends to decrease the apparent site hazard. This happens because, at **a given** ground motion level, for different scenarios, a team's site hazard estimates vary widely (usually over more than an order of magnitude), and the team mean log hazard is more sensitive to the lowest estimates than is the mean hazard. As an extreme example, let us imagine that **we** toss a coin and receive one dollar if a "heads" comes up and nothing if a "tails" results. The expected value or mean is M = 1/2(1.00 + 0.) = 0.50 but an estimate based on the mean log value $m_L = 10^{1/2(\log 1.00 + \log 0)}$ is undefined (log(0) = -oc). The mean hazard cannot be less than some fraction of the maximum estimate, **even** if all the other estimates are zero.

Analogously, if a single feature is near a site, the calculated ground motion levels may be considerably higher for scenarios in which the feature is **active** than for scenarios in which the feature is inactive, and the seismicity dispersed to the background. A single scenario in which there is no (or low) seismicity near the site, could, in fact, result in no (or low) predicted **exceedances** of a ground motion **level. A** single low estimate could unduly reduce the apparent hazard when log values **are used** in the estimation. This is not an. idle Concern. For example, in showing "sensitivity to Earth Science Team, peak ground acceleration", for the River Bend Site **(EPRI/SOG, Vol.4,** 1987, Figure 6-8c) one team's values were not included because they were so low that they were below the margin of the illustration-more than two orders of magnitude lower than consensus site values. We question whether possibly a single estimate for this team for a single scenario resulted in the off-scale values in computing a mean log hazard.

Recognizing that no point estimate of ground motion exceedance probability can reflect the variability of the hazard estimates at the site, **we believe** it is desirable that **means rather than mean logs or medians be used, in order to prevent under-representation of site hazard** in those aspects of the analysis in which point estimates are combined. A team's mean hazard estimate is also more **consistent** with an expected-value interpretation of "best team **estimate' In** Computing mean hazard at a site, the hazard associated with a feature does not depend on the specific scenarios in which the feature is active. This means that a well defined hazard is associated with a given feature, and we can sum the contribution to the mean hazard on a feature-by-feature or source-by-source basis. In contrast, in computing mean log hazard, the log hazard must be associated with scenarios rather than features; we cannot separate out the total hazard due to an individual feature

In the EPRI/SOG submittal, one team monopolizes the weight. We think this is inconsistent with the likely relative goodness of team estimates. A substantial amount of this monopolization appears to result from the adjustment of the consensus means using team weightings from the initial consensus and then recycling. Weights with less contrast are obtained under inverse-variance weighting based on the initial variance matrix, without further cycling.

Team weights are also important in representing the overall variance of the consensus estimate. The true extent of the variability of the consensus estimate may be not be represented if the range of estimates contributed **by a** team is also weighted by the high-contrast weights assigned to the team under the EPRI/SOG preferred methodology.

XLB.1. Tests of the Dreferred methodology,. To justify the weightings, EPRI/SOG did some simulations, for example, in which there **was** no systematic bias for any team and all teams had the same **variance about** the **average.** EPRI/SOG stated that the weightings were quite variable for different samples, but the final combined estimates were quite good in all cases. We note that when no **team has a** systematic bias and all teams have the same variance, almost any weighting should be expected to give reasonable results, in general. Weightings become important if substantial biases or significantly different variances are present. The fact _that_ the results are not particularly **sensitive to** the weightings in the equal variance, no bias case, should not be taken as confirmation that the algorithm behaves correctly when systematic biases are present and variances **are unequal.**

We tested the methodology on simulated random data with known properties and found that **the methodology** did not have the behavior expected. If **we** shifted one team's estimates by a constant amount (only the team's **systematic deviation** changed), the consensus estimates changed; the other teams' TSD's changed; their relative variances changed; and the weights changed. This seems counter to **EPRI/SOG's** intent to have the weights ignore systematic **deviation.**

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EPRI/SOG, Volume 4: See Jack R. Benjamin and Associates, 1987b.

EPRI/SOG, Volume 5: See Weston Geophysical, 1986.

EPRI/SOG, Volume 6: See Dames and Moore, 1986.

EPRI/SOG, Volume 7: See Law *Engineering,* 1986.

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TABLES AND FIGURES

Tables and figures are labeled by section number and, within each section, by successive letters of the alphabet. Thus, the first table of section IX would be labeled by "Table IX-A."

Figure NA Feature Characteristic Matrices

(A) Feature Characteristic Matrix-Bechtel Team

(B) Feature Characteristic Matrix-Dames and Moore Team

(C) Feature Characteristic Matrix 1-Law Engineering Team

(C) Feature Characteristic Matrix 2-Law Engineering Team

(C) Feature Characteristic Matrix 2-Law Engineering Team

(D) Feature Characteristic Matrix-Rondout Team

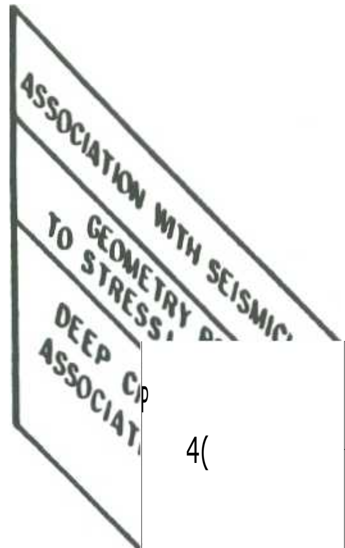
(E) Feature Characteristic Matrix 1-Weston Team

(E) Feature Characteristic Matrix 2-Weston Team

(E) Feature Characteristic Matrix 3-Weston Team

(F) Feature Characteristic Matrix-Woodward Clyde Team

MATRIX



In

	MODERATE TO LAR EARTHQUAKES	
	Favorable	Unfavor
YES	0.80.	0.4
NO	0.64	0.2

D
b
lli
a
X
m

(A) Feature Cha

CRUSTAL EXPRESSION	MODERATE I0 L	
	FAVORABLE	UN
CRUSTAL EXPRESSION W1 AN INTERSECTION OF FEATURES	0.8	
CRUSTAL EXPRESSION WITHOUT INTERSECTION	0.6	
NO CRUSTAL EXPRESSION	0.1	

FEATURE SHOWS PERSISTANCE OF DEFORMATION THROUGHOUT A SIGNIFICANT PORTION OF GEOLOGIC TIME	0.75	
FEATURE DOES NOT SHOW PERSISTENCE	0.3	

(B) Feature Chara

P41

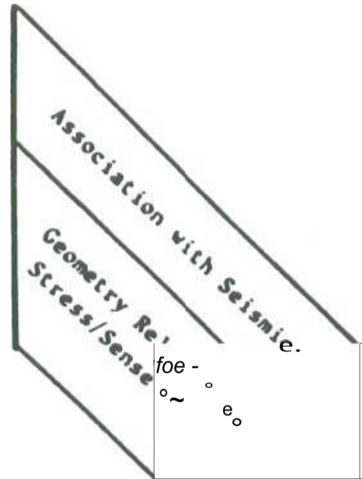
(4

Moderate-to-La
Earthquakes

e	Favorable	Jnfav
Pleistocene-Holocene Slip	0.98	0
Miocene-Pliocene Slip	0.75	0
Pre Miocene Slip or No Brittle Slip	O.SS	0

Matrix A Probabi
recent

(C) Feature Ch

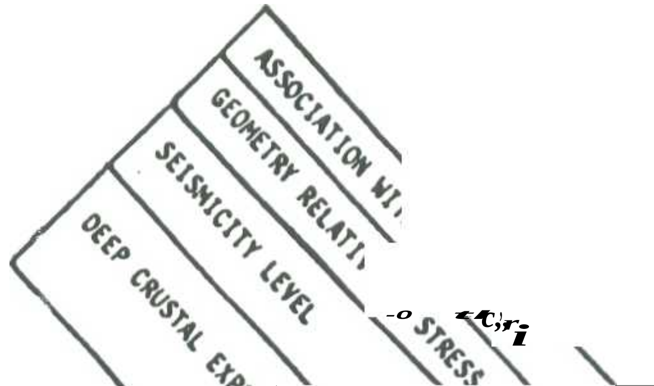


	Moderate-to-Large Earthquakes
Favorable	0.9
Unfavorable	0.18

Figure 4-2. Matrix B - Probability
brittle sli

(C) Feature

al
Vi



		MODE... / FAVO... GEOM...
DEEP CRUSTAL EXPRESSION NEAR INTERSECTIONS	HIGH	[illegible]
	LOW	[illegible]
DEEP CRUSTAL EXPRESSION NOT HEAR INTERSECTIONS	HIGH	[illegible]
	LOW	[illegible]
NO DEEP CRUSTAL EXPRESSION	HIGH	[illegible]
	LOW	[illegible]

(D) Feature Chara

n
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b
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a
x
w

SPATIAL ASSOCIATION WITH SEISMICITY

GEOMETRY R... REGIONAL FABRIC, ST... and/or SENSE

DIMENSION AND NAT... OF TECTONIC FEATU...

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DEfi CRUSTAL IRIOAEUSRM1 WITHOUT A SARRRIER	1 ,OO
JU9T *MALLOW CRUSTAL EXPRESSION	1.00

Matrix c
Rppltcat

(E) Featur

SPATIAL ASSOCIATION WITH SEISMIC...

GEOMETRY REL... REGIONAL FABRIC, STR... and/or SENSE ...

DIMENSION AND NAT... OF TECTONIC FEATURE

W

=r` _/e A rl+~~ A- 04,0 ~ BT.tl RE^E	MODERAT... EARTH... 28...
	fAYORABIE...
OUP CRUSTAL EIIPREBaKm WITH A BARRIER	Bs
DEEP CRUlIAL EKfRE>IIKTN WITHOUT A BARRIER	.B0
JUST SHALLOW CRUSTAL EXPRESSION	.e0

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(E) Feature...

SPATIAL ASSOCIATION WITH SEISMICITY

GEOMETRY & REGIONAL FABRIC, and/or SENSE

DIMENSION AND RATE OF TECTONIC FEATU

414414w WASOnuD1 W0~I0	• 0.0	
	0AY00A011	"of 0A000A01
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(E) Feature Ch

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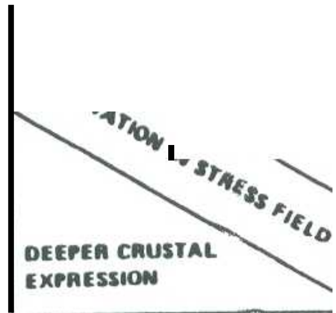


	FAVORA
WITH PROXIMITY TO STRUCTURAL INTERSECTIONS	0.99
WITHOUT PROXIMITY TO STRUCTURAL INTERSECTIONS	0.95
NO EXPRESSION	0.00

(F) Feature Ch

FEATURE ASSESSMENT FORM

Physical Characteristic	Feature i EIA1	Feature S EIAZ	Feature EIA3
	Probability that the Given Feature Exhibits a Given Level of Each Characteristic		
1. Association with Seismicity			
1. Moderate-to-Large Earthquake	0.00	0.10	0.00
2. Small Earthquakes Only	0.05	0.40	0.65
3. No Seismicity	0.95	0.50	0.35.
	1.00	1.00	1.00
2. Geometry of Feature Relative to Stress Orientation and/or Sense of Slip			
1. Favorable Geometry/Sense of Slip	0.50	0.80	0.80
2. Unfavorable **Geometry/Sense** of Slip	0.50	0.20	0.20.
	1.00	1.00	1.00
3. Brittle Slip on Feature			
1. **Pleistocene-Holocene** Slip			
2. Miocene-Pliocene Slip			
3. Pre Miocene Slip or No Brittle Slip			
	1.00	1.00	1.00
Probability that feature is selamogenic	0.02	0.32	0.38

Figure V.A Sample of feature assessment form that each team filled out for each feature for **estimating the probability that a feature** is active (seismogenic).

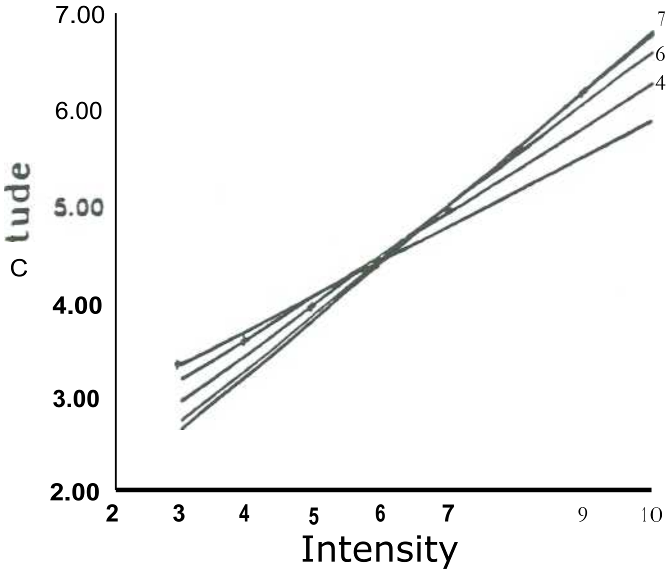
Acceleration	Mrnax * 6.0			M_{max} = 7.0		
	b.O.7	b*O.9	b=1.1	b=0.7	b=0.9	0=1.1
0.3g	1.39	1.32	1.25	1.10	1.07	1.04
0.5g	**1.64**	**1.52**	**1.42**	1.21	1.15	1.09
0.7g	1.87	1.73	1.60	1.32	1.23	1.16

Table VIII.A.

HAZARD RATIOS FOR 150cm/eec^{2} AT SITE LOCATED
IN 200km x 200km SOURCE
DEPTHS = 10 * *(-1.73 + 0.456m)

Magnitudes:		Sigma:			
Min.	Max.	0.70	0.60	0.50	0.40
5.0	**6.5**	1.15	1.00	0.86	0.75
4.5	6.5	1.46	1.22	1.04	0.95
4.0	**6.5**	1.67	1.39	1.16	0.98
5.0	**6.0**	**0.92**	**0.76**	0.63	0.51
4.5	6.0	1.20	0.97	0.78	0.63
4.0	6.0	1.41	1.12	0.89	0.7?
5.0	5.5	**0.63**	**0.50**	0.39	0.31
4.5	**5.5**	0.87	**0.66**	0.51	0.40
4.0	5.5	1.06	0.80	0.61	0.43

Table IX.A.



(cut tines fitted to magnitude u a function of intercity m - + b/ when the range of intanaities rl is k S I S 10. (3 S S 7). Earthquake magnitudes follow a (iuunber~ 'Richter maprituda.drequ*m teiewmahip with o • 2.0, but the probability of ubaerving ixuh a waruuude and in angry for a random aarthquaka is riven by equation (20). Magnitudes in the rang 1.9 + 0.6(k - 1) a m < 1.9 + O.6k produce "true" intensity k (for 1 < k), but 'observed" intenuues contain a normally diatributad **error.** with e, • 0.6. The '+ symbols show the mean magnitude of sarthquaku 'uhaarved' in each intercity interval

Figure X.A

ErrEcr 0V MISSING 0wr;xvATIoNa ON THE Exrtcri;o VALUL., OF COErnCIENTS a AND b FIrrEU TO A Str oF Oesexveu MAGNiTUDIE.-INTENSITY NOW IN THE RELATIONSHIP

In-a+61

a	Mull 1		Mudd Y		A4ud.1 1	
	i	(t	i	6	•	1
3	2.28	0.36	2.21	0.38	2.29	0.36
4	1.88	0.44	1.83	0.46	1.90	0.43
5	1.39	0.52	1.43	0.5'2	1.41	0.51
6	1.00	0.58	1.16	0.56	1.12	0.56
7	0.85	0.60	1.06	0.57	1.17	0.55

The fraction of earthquakes recorded fur each magnitude is riven in the text for each of the three models. In each case, k is the lowest intensity that was used in the fitting; e, - 0.6 and $ - 2.0. The 'true" relationship is m - 1.54 + 0.601; the expected fated relationship, assuming an infinite magnitude range and no nlisoinr earthquake . is m-(1.51-pe.) +0.601-0.82+0.601.

In the first model, the probability $p_d(m)$ of detecting earthquakes with m_e is 3.7 is unity, and this probability decreases linearly to zero for magnitudes 2.7 < m_e < 3.7, i.e., in model 1,

$$Pd(m)me \begin{cases} 10, & m < 2.7, \\ m-2.7, & 2.7AmA3.7, \\ 1\ 1 & 3.7 < m. \end{cases} \tag{20}$$

In the second model, the probability of detecting an earthquake increases with magnitude for magnitudes in the range 2.7 < m < 5.5. In model 2,

$$Pd(m) - \begin{cases} 0, & m < 2.7, \\ (m-2.7)I5.5', & 2.75 \text{ in } 3.7, \\ 5.5' & 3.7\ 5\ m\ S\ 5.5, \\ 1\ 1 & 5.5 < m. \end{cases}$$

Models 1 and 2 assume that earthquakes of all magnitudes are pusulihle, i.e., m,,,,, _ x. Model 3 is the same as model 1, **except** that m,,,,1 = 7.3.

Table X.A

APPeCIX

Summary of Team ApProachss

I. SUMMARY OF APPROACH: LAW ENGINEERING TEC

A. TYPES OF SOURCE ZONES: TECTONIC FEATURES, SEISMICITY ZONES, SEISMOTECTCNIC REGIONS (Background Zones)

1. P_a cut-off for feature assessment - 0.25

B. RECURRENCE PARAMETERS

Smoothing Options		Weights	Priors
Cam No.	One Case for Each Source Zone		
1.	a-value: strong smoothing b-value: constant, strong prior	For cases 1 and 2, weights on magnitude intervals are all 1. Magnitude intervals - Mb 3.3 - 7.5.	Priors on b-value *vary* between 0.9-1.05 for zoneA except Charlevoix zone where prior - 0.7.
2.	a-value: constant b-value: constant, strong prior	A m-0.6	
3.	a-value: strong, smoothing b-value: constant, strong prior	For cases 3 and Y weights on magrUtude inter-vals are: 0,1,1,1,1,1,1	
v.	a-value: constant b-value: constant, strong prior		
5.	SPECIAL CASE: **Selected** mafic pluton5		

C. MAXIMUM MAGNITUDE

CRITERIA:

1. m_b • 7.4: Well developed rifts that can support fault length. greater than 30 km and have been reactivated in last 100 M.Y. Rifts open to oceanic or extended crust.

2. m_b • 6.8: Rift structures surrounded by continental crust, or, poorly developed. If activity is low (1,000 year event <<6.8) use 1,000 event.

3. m_b • 6.8: Significant thickness of brittle crust with inhomogene tie= of structure and stress field (e.g. Charleston, S.c.)

4. m_b - 5.7: Crystalline rock areas. Depth of focus typically less t`:ar. 10 km (e.g. New Brunswick).

5. Mb • 5.5: Upper-limit background event; used for, 1) most background areas, 2) zones with no events m_b>3.3, or 3) zones having 1000 year event <5.5 mb.

6. m_b • 4. g: Upper-limit background where they felt they had sufficient information to imply mb(max)<5.0.

7. For zones based on seismicity, mb(max) is the maximum historically observed or the 1,000 year event, whichever is larger.

Case	Probability Distribution
1. $m_{b(max)}$ ' $m_{b(hist.)}$	$Pm_{b(max)}$ - 1.0
2. $m_{b(max)}$ >$m_{b(1,000\ Yr.)}$ >$m_{b(hist.)}$	$Pm_{b(max)}$' 0. 3 Pmb(1,000 Yr.' ' 0.5 Pmb(hist.) .2
3, $m_{b(max)}$ ' $m_{b(1,000\ Yr.)}$ >$m_{b(hist.)}$	$Pm_{b(max)}$ - 0.8 Pmb(hist.) ' 0.2
4, $m_{b(max)}$ >mb(1,000 Yr.) ' mb(hist.)	$Pm_{b(max)}$ - 0.5 $Pm_{b(hist.)}$ ' 0.5

NOTE: When two maximum magnitudes were within 0.1 m_b, their probabilities were added and the higher magnitude used.

D. SPECIAL CASE: SELECTED MAFIC PLUTONS, APPALACHIAN REGION

METHODOLOGY

1. Obtain average a-value for given background zone. The a-value uAe~~ represents seismic activity per 1 • cell.

2. Align 70S to each pluton source zone in the background. Adju!t for area so a-value iA in units of activity per 1 • cell.

3. Adjust a-value of pluton: If 3-value of background cell is a, and average background zone **value iA a 2**, multiply pluton a-value by a 1 /a~ 1.

4. Adjustbackground zone so that the seismicity budget iA not affected.

NOTE: According to the *TEC,* modeled plutona are responsible. for 70% of the seismicity located within 50 km of them.

II. SUMMARY OF APPROACH: RONDOUT ASSOC. TEC

A. TYPES OF SOURCE ZONES: TECTONIC FEATURES, BACKGROUND ZONES, SEISMICIT ZONES, FEATURES HAVING ONLY GEOLOGIC EVIISENCE OF EARTHQUAKES

1. P_a cut-off for feature assessment - 0.0.

B. RECURRENCE PARAMETERS: Used only TEC team assessments of activity, not tr,e assessments provided by EPRI.

1. Used Weichert (1980) methodology for b-value assessment.

2. As in traditional approaches, used complete a- and b-value smootnini for all zones.

3a. Zones with 40 or more events: assessed b-value directly.

3b. Zones with fewer than 40 events: imposed a weak prior on b of 1.0.

C. MAXIMUM MAGNITUDE

Case No.		Method	Distribution
1,		m_b - 7.3 Great earthquake zones. (New Madrid, LaMalboie)	7.4 - 0.10 7.3 - 0.80 7.0 - 0.10
2.	a)	m_b - 6.8 Large earthquake zones. Assigned to 11 zones.	7.0 - 0.10 6.8 - 0.60 6.3 - 0.30
	b)	Mb - 6.5 Large earthquake zones. Assigned to 12 zones NOTE: No obvious criteria given for distinguishing 2a zones from 2b zones.	6.8 - 0.25 6.5 - 0.60 5.8 - 0.15
3.		Mb - 6.3 Diffuse seismicity. No discernable tectonic features. Assigned to 19 zones.	6.5 - 0.15 6.3 - 0.55 5.2 - 0.30
4.		m_b - 5.5 Background zones (areas not considered to be in a specific zone).	5.8 - 0.20 5.5 - 0.60 4.8 - 0.20

NOTE: Allowed the posmibility that activity rate and b-value appropriate Anna, Ohio area may be more appropriate in other areas of intersecting basement features in the next 50-100 years according to assigned probabilities ranging from 10% to 90%.

III. SUMMARY OF APPROACH: DADS AND MOORE TEC

A. TYPES OF SOURCE ZONES: TECTONIC FEATURES,_ DEFAULT ZONES, SEISMICITY ZONES, REGIONAL SOURCES

1. P_a cut-off for feature assessment - 0.0.

B. RECURRENCE PARAMETERS

1. Constant a-values for zones with a tectonic basis.

2. Variable a-values for zones with no tectonic basis.

NOTE: For source zones having a tectonic basis, the effect of a ccnsta a-value is required in their hazard computation *with* probability P_a art the effect of a variable a-value *is* required with probability $1-P_a$. For zones not **having a** tectonic basis (no P_a assigned during tectoni^ framework assessments) a P_a of 0.5 was arbitrarily assigned and .:aa used as the probability of constant a-values in these zones. P'obab'lity of variable a-values in these zones then is $1-P_a$, or, 0.95. "We thus account for all earthquakes in each source zone anc+ also directly adhere to the results of the tectonic assessment." (v. 6, p. 6-2).

Case No.	Smoothing Options All Cases Used for each Zone	Weights	Priors
1.	Mmax - Historical: a-constant b-strong prior	On m_b:	1.04 on b for all
2.	Mmax , 7.5: a-constant b-strong prior	3.6 - 0.1 4.2 - 0.2 4.8 - 0.5	
3.	Mmax - Historical: a-constant b-strong prior	5.4 - 1.0 6.0 - 1.0 6.6 - 1.0	
4.	Mmax - 7.5: a-constant b-weak prior	**7.2 - ?** (Tabulation of **values** is not complete in v. 6, p. 6-3.)	
5.	Mmax - Historical: a-variable (but little smoothing) b-strong prior		
6.	Mmax - 7.5: a-variable (but little smoothing) b-strong prior		

C. **MAXIMUM MAGNITUDE**

Case	Probability Distribution
1. $M_{b(max)}$ - 7.0 - T.5	1. 7.0 • 0.25 7.2 • 0.50 7.W • 0.25 7.5 • 0.00
2. Mb(max) • computed from a-value' at the m_b • 3.3 to 3.9 level Mb(max) ' (a •0 .094(1.04x7.2))/1.04 NOTE: A$aumer New Madrid Mma.x - 7.2 This iA the best a timate (BE) value computed for each 1 °x1O cell:	2. BE - 0.2 Mag. Units ~ 0.25 BE - 0.5 BE • 0.2 Nag. Units • 0.25 BE + 0.3 Mag. Unit.m • 0.0

D. NOTES

1. **Spatial amsociation of tectonic feature with any neismi=ity izdi^_ite= a potential for moderate-to-large earthquake.**

IV. SUMMARY OF APPROACH: BECHTEL TEC

A. TYPES OF SOURCE ZONES: TECTONIC FEATURES, SEISMICITY ZONES, BACKCRCUN: ZON

1. P_a cut-off for feature assessment - 0.05.

B. RECURRENCE PARAMETERS

Smoothing Options		Weights	Priors
Case No.	All Cases for Each Source Zone	On cases 1-4	
	a-value: constant b-value: constant	0.333	None on b
2.	a-value: low smoothing b-value: high smoothing	0.334	None on b
3.	a-value: low smoothing b-value: low smoothing	either/or 0.333	None on b
4.	a-value: low smoothing b-value: low smoothing		Weak prior of 1.05 on b

C. MAXIMUM MAGNITUDE

	Case	Weights
1.	mb(max) - Maximum historical in zone.	
2,	mb(max) - Maximum historical near zone that could could be in zone due to location uncertainty.	Case t or 2 0.1
	MCTE: Case 1 or 2 Is the base case *(BC)* mb(max but in no **case** way mb(max) **adopted** lower than 5.4.	
3.	BC + 0.3 **mag.** unit	0.4
4.	BC + 0.6 mag. unit	0.
5.	mb(max) - 6.6	0.1

V. SUMMARY OF APPROACH: WODWARD-CLYDE CONSULTANTS TEC

A. TYPES OF SOURCE ZONES: TECTONIC FEATURES, DEFAULT ZONES, BACKGROUND ZONES

1. Pa out-off for feature assessment - 0.0.

B. RECURRENCE PARAMETERS

Case No.	Smoothing Options: Combinations of cases used for each Source Zone (See below) a-value	b-value	Weights	Priors	
			On magnitude **intervals.** All are 1.0.	On b-values. All priors are moderate.	
1.	**low smoothing**	high smoothing		1.	None
2.	high	high		2.	None
3.	high	**high**		3.	1.0
4.	high	high		4.	0.9
5.	**high**	high		5.	0.8
6.	**low**	**high**		6.	1.0
7.	low	high		7.	0.9
8.	**low**	**high**		8.	0.8

Number of Zones	Smoothing Combinations Used	Weights for each Zone
29	Ca.e No's. 3, 4, 5	1/3 each
26	Case No's. 2, 3, 4, 5	1/4 each
9	Weichert (1980) methodology plus 3 or 4 smoothing options.	Weighti on Weichert solution range from 1/5 to 7/10. Option weigntn range from 1/10 tc 1/5 each to sum t-- 1.0 with the assigned Weichert wei gnt .
Regional Background Zones	Case 1 and Cases 6, 7, 8	1/4 1/4 each

C. **MAXIMUM NACNIViDE**

1. Used combination of empirical methods for each source.

Case No.	Method	Distribution
1.	Maximum historical	la. If based on intensity: P . 0.5 • 0.25 in _ 0.5 magnitude interval= 1b. If based on magnitude: P • 0.5 _ 0.25 in _ 0.25 magnitude intervals NOTE: If maximum observed is thought smaller than expected upper bound, then weight lies within + 1/2 magnitude unit category. For maximum observed < 5.0 m_b use 5.0 m_b.
2.	Deep crustal feature	2. Center of distribution range from 5.25 m_b to 7.25 m_b.
3.	Seismic source dimensions (length of features)	3. Centers of distribution range from: 30 km • 5.0 m_b to 200 km • 7.0 M_b NOTE: If tectonic feature on which source zone i. based is not favorably oriented with respect to stress field (feature assessment of 25% or less) then characteristic length is not included in maximum magnitude distribution.

u.	Seismic flux for source zone. (Average rate of earthquakeA greater than 3.3 m_b per unit area per 300 years.) NCTE: Estimate is sensitive to source area.	L.	Center of distributions are at m_t • 5.0 for seismic flux of 10 and range up to m_t • 7.5 for seismic flux of 700 or more.
5.	·1,000 year earthquake	5.	Di!tribution range is • 1/2 magnitude unit of the determined 1,000 year event.

2. Final maximum magnitude distribution: Sum results of cases 1 through 5 for each source and normalize. Assume equal weights for all cases. Case 1 weight was split evenly between 1a and 1b.

VI. SUT44ARY OF APPROACH: WESTON GEOPHYSICAL TEC

A. TYPES OF ZONES: TECTONIC FEATURES: SEISMOGENIC ZONES, BACKGROUND ZONES

1. Pa cut-off for feature assessment - 0.0

B. RECURRENCE PARAMETERS

Smoothing Options			Weights	Priors
Cane No.	One for Each Zone			
1.	a-value:	constant	On magnitude categories Mb 3.6 - 7.2 in am intervals of 0.6. All 1 0.	On b-value 0.7 for LaM3lnoie region.
	b-value:	constant		2. 0.9 for all zones except backgroun~ zones.
2.	a-value:	medium smoothing		
	b-value:	medium smoothing		3. 1.0 for background zones.

C. **MAXIMUM MAGNITUDE**

1. Various maximum magnitude distributions between m_b 4.8 - 7.2 with weights 0.05 and 1. To assure that frequency of maximum magnitude events approximate that determined from the lin?ar recurrence model, 0.3 magnitude units are adoed to **values** for hazard computation.

TABLE 1: TECTONIC FEATURE ASSESSMENT PROBABILITIES ASSOCIATED WITH THE MEERS FAULT FOR THE C
CHARACTERISTICS OF "ASSOCIATION WITH SEISMICITT" AND "GEOMETRY RELATIVE TO REGIONAL

TEC CHARACTERISTIC	DAMES AND MOORE v.6,p.A-39	LAW v.7,p.D-6 .	WESTON v.5,p.B-40	v.8.p.A-92	BECHT v.9,p.4
I. Association with seismicity				0.01	
a) Moderate-to-large EQ's	0.5	0.0	0.7	--	0.(
b) Small EQ's only	0.3	0.4	0.2		0.1
c) None	0.2 (Background)	0.6	0.1	0.99	0.9
2. Geometry relative to regional stress					
a) Favorable	0.7	0.9	0.6	0.90	0.7
b) Unfavorable [For stress concentration to occur.]	0.3	0.1	0.4	0.10	0.2
3. Evaluated P_a	0.45	0.34	0.39 (For P_a bm_b)	0.085	0.7