SUMMARY OF THE MAY 17-18, 1993, CNWRA ADVISORS MEETING AND REPORTS ON FAULT DISPLACEMENT AND SEISMIC HAZARD ANALYSIS

Prepared for

Nuclear Regulatory Commission
Contract NRC-02-88-005

Prepared by

Renner B. Hofmann

Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas

September 1993

ABSTRACT

Several internal draft Staff Technical Positions (STPs), which included analysis of fault displacement and seismic hazard analyses (FD&SHA), were prepared by NRC staff during recent years. The earliest drafts were prepared on the assumption that analyses would be based primarily on deterministic methods. However, during this period, probabilistic analysis methods were being refined and applied to reevaluate nuclear power plant seismic design criteria in the eastern U.S. Reevaluation of several nuclear facilities elsewhere in the U.S. also employed probabilistic principles. A program to review probabilistic methods and acquire and adapt a probabilistic seismic hazard analysis (PSHA) computer code to the Yucca Mountain area was assigned to CNWRA. Available codes had been developed and applied to the eastern U.S. NRC staff subsequently separated positions on fault and earthquake investigations from those applicable to analysis, e.g. McConnell et al. (1992). A draft STP specifically for analysis of fault displacement and seismic hazards was prepared by NRC and CNWRA staff to include requirements for both probabilistic and deterministic analyses.

Because probabilistic analysis methods were developing rapidly, a review of the internal draft Analysis STP (also referenced as the STP annotated outline) and the CNWRA PSHA program by acknowledged experts was desired. The purpose of this report is to summarize a meeting held May 17-18, 1992 at the CNWRA in San Antonio, Texas, and reports prepared by the five participating expert consultants on these topics.

The experts' principal recommendations, though not unanimous, may be summarized as follows:

- The draft Analysis STP should require that probabilistic methods be the basis for design criteria.
- Although there were differences of opinion, deterministic analyses were also recommended because they emphasize the need for data and are more easily understood by non-probabilists (non-statisticians).
- Comparison of deterministic and probabilistic results, however, was recommended by only one expert.
- Studies should be conducted or supported to make probabilistic methods more "transparent."
- FD&SHA should be more tightly integrated with iterative performance assessment (IPA), geohydrological and volcanological analyses. The draft Analysis STP should indicate these inter-relationships.
- There is no alternative to expert judgement in the estimation of uncertainty in models and in the interpretation of data. Therefore, the draft Analysis STP should address the use of experts and methods for proper elicitation of opinions.
- Alternative models and expert opinions should be weighted through the use of the publication and peer review process or by experts in the technical and geographical areas being addressed. Clearly noncredible hypotheses must be eliminated from consideration.

- Stability of the tectonic regime (e.g., the direction and levels of stress, amounts of fault displacement and fault type, and magnitudes and frequency of earthquakes) at Yucca Mountain over a 10,000 year period is doubtful and this should be addressed in the draft Analysis STP.

- To effect these recommendations, risk levels below which a hazard may be ignored must be set. The risk level, e.g. probability of an acceleration over a specified time, used with a hazard curve derived from a site-specific PFD&SHA, dictates design criteria. The acceptable risk level should be addressed in the draft Analysis STP.

CONTENTS

CONTENTS (Cont'd)

PREFACE

This report is provided in fulfillment of Geologic Setting (GS) Element Subtask 2.1.1. It is 20-5702-002-130-100, Intermediate Milestone "Letter Report on Seismic Hazard Advisory Group Discussions," for Task 2, in the CNWRA FY 93-94 Operations Plan, Rev. 3 Change 0.

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

Please note, that author's comments in this report that are within or adjacent to quotes are in italics surrounded by square brackets. Abbreviations are sometimes used in Advisor's reports. Abbreviations are defined in Section 7.

ACKNOWLEDGMENTS

The author wishes to acknowledge the efforts of CNWRA's advisors on fault displacement and seismic hazard analysis (FD&SHA), Professors, C. Allin Cornell, Anne S. Kiremidjian, George A. Thompson and M. Nafi Toksöz and Dr. Martin W. McCann Jr. for their dedicated efforts. Also acknowledged is the concern and guidance of Ronald L. Ballard and Drs. Keith I. McConnell and Abou-Bakr K. Ibrahim of the U.S. Nuclear Regulatory Commission, who initiated these efforts. Drs. Wesley C. Patrick, H. Lawrence McKague, and Stephen R. Young, are acknowledged for their review, comments and advice concerning the preparation of this report.

This report was prepared to document work performed by the CNWRA for the NRC under contract NRC-02-88-005. Activities reported here were performed for the NRC Office of Nuclear Material Safety and Safeguards (NMSS), Division of High Level Waste Management (DHLW). This report is an independent product of the CNWRA and does not necessarily reflect the views or regulatory position of the NRC.

1 BACKGROUND AND SUMMARY

1.1 BACKGROUND

A meeting of CNWRA's advisors on Fault Displacement and Hazards and Seismic Hazards Analysis (FD&SHA) was convened on May 17-18, 1993. In preparation for the meeting, NRC and CNWRA staff jointly prepared and reviewed material which they would present to the board. Several of the staff presentations asked specific questions of the advisors with regard to the positions taken or not taken by the staff in development of the February, 1993, Internal Draft of the Staff Technical Position on the Analyses of Fault Displacement Hazards and Seismic Hazards as they Apply to Design of a Geologic Repository. This document will be referenced henceforth in this report as the draft Analysis STP. Advice in the advisor's reports, which apply to these questions, are summarized here. CNWRA comments on the meeting and the advisors' reports are given in the conclusions of this report.

At the end of the second day of the meeting, each advisor was asked to summarize his or her position on the draft Analysis STP. Each advisor agreed to send a summary report of his or her advice concerning development of the draft Analysis STP, by June 18th and circulate their initial reports among the other advisors to ensure that no pertinent subject was omitted. Two advisors revised their reports after this process.

1.2 SUMMARY

1.2.1 Advisability of Requiring a Deterministic Analysis

Most of the expert group believed that the draft Analysis STP should be based on probabilistic procedures. Use of deterministic methods was discouraged by most experts because definitions of maximum credible earthquake (MCE), maximum credible fault movement (MCFD) and similar terms are not universally agreed upon and their values would be the subject of debate. Further, based on their experience with nuclear power plants in the eastern U.S., they argued that deterministic methods may provide difficult-to-support design criteria whose probabilities of occurrence are different for different sites and for various phenomena resulting in a design that may not be easily incorporated into performance assessment in a defensible manner. One expert, Dr. Cornell, indicated that recent changes in the position taken by NRC's Office of Nuclear Reactor Regulation with regard Appendix B to 10 CFR Part 100 being developed by NRC, would eliminate the requirement for a deterministic analysis. Reports from several advisor's including Dr. Cornell's (Appendix C), however, indicated that there may be a place for a deterministic analysis. It was suggested that a deterministic analysis forces a focus on data gathering which is also important for a credible and convincing probabilistic analysis.

1.2.2 Advisability of Requiring a Probabilistic Analysis

The expert panel recommended that the draft Analysis STP requirements be probabilistic for seismic hazards and, except for one advisor, for fault displacement as well. This requires that a level of probability be set for which seismic and fault movement design values may be selected. Probability level setting is recommended to be iterative with performance assessment. Note, that this would change the basic criteria for licensing from a maximum or near maximum event like the Safe Shut Down Earthquake (SSE) used for nuclear reactor licensing, to a "probability level" below which, effects or events may be ignored. This approach is used in Canada and several European countries.

1.2.3 Need for Data

Most advisors argued that more data were needed to implement a probabilistic analysis than a deterministic one. Two advisors, Cornell and McCann, believed that a probabilistic analysis would provide the means to justify bringing data collection to a close when an adequate amount had been identified.

1.2.4 Analysis Cost

There was concern over increased project costs and delays brought about by information that became available after an initial analysis. Arguments centered on the lack of stable design criteria over the life of a project because of new information or hypotheses. Such information or hypotheses would represent an additional expert opinion in a probabilistic analysis and would therefore not be likely to change design criteria greatly in reanalysis. It is implied that the several-order-of-magnitude increased cost of a probabilistic analysis over a deterministic one, would be easily offset by total project cost reductions attributable to increased design criteria stability. This implication remains to be tested in the hearing process for the licensing of new nuclear facilities. Its implementation requires that a probability level for the determination of design criteria be set as part of the regulatory process. For a high-level waste repository, this level might be controlled by iterative performance assessment (IPA) calculations by the applicant.

1.2.5 Integration of FD&SHA with Iterative Performance Assessment (IPA)

The advisors expressed concern that IPA and geoscience data analyses were not coordinated but were being addressed separately.

2 TOPICS ENCOMPASSING QUESTIONS POSED IN STAFF PRESENTATIONS AND PERTINENT RESPONSES BY THE ADVISORS

Forty one questions were asked by NRC and CNWRA staff during their presentations (Appendix B) at the May 17 and 18 1993 meeting. The questions were not always answered directly but general topics, under which questions could be categorized, were often addressed in advisors' concluding comments. Consequently, questions concerning the same general topic are usually summarized together in this report.

Responses from advisors' reports that appear particularly relevant to the 41 questions follow. The questions asked, and the general topics in which they were grouped, did not encompass the entire spectrum of concerns or advice provided by the advisors. Their reports should be studied carefully to understand the extent of their message regarding the draft Analysis STP and NRC/CNWRA PFD&SHA efforts for a HLW repository.

2.1 DETERMINISTIC ANALYSIS

Question 1. What is understood by application of "primarily a deterministic approach" for fault displacement analysis?

Question 2. Is a deterministic approach both reasonable and doable?

Comments from Advisors' Reports

Thompson — ". . . deterministic studies are needed to establish basic data, distinguish among hypotheses, test models, and provide reality checks. But recognizing that complete data and physical models are never achievable, probabilistic analysis is important and necessary."

"Any deterministic finding is vulnerable to surprises from new information or unanticipated rare events, or simply from the concerted attacks of interveners. It is generally impossible to prove a negative." "On the other hand, the gathering of facts and data that is usually motivated along deterministic lines is absolutely essential."

Toksöz — "Most experts who provide input to probabilistic hazard studies do not carry out a sensitivity analysis. Even if such studies are carried out, they are done late in the process of hazards calculations. It is important to evaluate carefully those features that contribute most to the hazard. In this respect a comparison of deterministic and probabilistic approaches may help. The probabilistic approach can identify a set of significant features based on sensitivity analysis. Then the deterministic approach can be used to evaluate the hazard from most obvious individual features. The comparison of the two sets of results provides reassurance and gives an indication of the effects of using alternate hypothesis etc." "The preference of probabilistic methods over deterministic methods is due to the fact that the probabilistic approach can accommodate input data with uncertainties, alternative hypotheses, and logic tree frameworks, as well as inputs from a wide variety of sources (experts) by assigning proper weights."

Kiremidjian — "The use of deterministic models can easily be justified in cases when little variations are observed, when there is good control over the experiment and its forces of influence, when the data are numerous and more than sufficient to conduct verification experiments or when the variations in the model, design and imposed forces have insignificant consequences. None of these criteria apply to the analysis of high level radioactive waste repositories. Perhaps I can accept the extreme value approach described in the STP Annotated Outline which indicates that fault displacement hazard, for example, is to be evaluated for the "Maximum credible earthquake." The following questions, however, come immediately to mind that would undoubtedly be raised during licensing:

(i) How was the maximum credible earthquake estimated?

(ii) Since the value selected was based on limited earthquake occurrence data and limited geologic exploration, how can we be sure that a larger event will not be possible?

(iii) How many of these events are likely during the next 100 years and the next 10,000 years?

(iv) What differential fault displacements and ground shaking levels will result from each of the hypothesized events? and so on.

The answers to these questions are most frequently educated guesses based on very limited and unreliable data. When attempting to model such highly uncertain phenomena, it appears only prudent that a probabilistic approach be considered. . . . I would agree that a deterministic analysis provides a simpler, more understandable or transparent approach and results in a single value that can be used when developing design criteria. This single value approach, however, is not defensible in light of all the model, parameter and phenomenological uncertainties."

[NOTE: Dr. Kiremidjian also listed a number of questions that could be raised when predicting the amount and type of differential fault displacement and further stated that most of the questions cannot be answered reliably because information is not presently available.]

"A deterministic approach will not be defensible in the light of all the uncertainties and the inherent randomness of earthquake phenomenon. A probabilistic approach should be considered for assessing both the fault displacement and ground shaking hazard."

McCann — "The dual deterministic-probabilistic approach for assessing fault displacement and seismic hazards is not well defined in the STP. The idea of a dual approach is inconsistent with the concept of having a stable (e.g., technically defensible) licensing process that is workable by both the applicant and the USNRC Staff. . . . the dual approach is out of sync. Eliminate the dual deterministic-probabilistic approach. Use only a probabilistic FD&SHA. . . . Recommending that the applicant perform a deterministic and a probabilistic assessment is inconsistent with current efforts to develop and apply probabilistic methods in the evaluation of natural hazards."

"In the draft STP the Staff has taken the position that a dual probabilistic-deterministic approach should be used. The STP states that the probabilistic assessment should be used to supplement the deterministic method. Recommending this approach puts the staff and the applicant in an inherently untenable and confrontational situation."

Cornell — "Under the circumstances, I do not think that a traditional approach, namely one based on scientifically undefined concepts such as the MCFD and MCE, can be defended."

"RECOMMENDATIONS FOR WHAT NRC SHOULD REQUEST OF THE APPLICANT (DOE).

. . .Initial Deterministic Investigations

Do a "reasonable" site investigation per the previous STP. Support this with "reasonable" deterministic studies, interpretations, etc.

"There is nowhere a definition of the MCFD or MCE. Even its proponents, e.g., Bob Rothman at NRC, agree that it's not (in Appendix A practice) the maximum possible event. Therefore it has been a case dependent, i.e., dependent on failure consequence and lifetime duration of the facility, as well as on qualitative adjustments for frequency of occurrence, e.g., less than the maximum possible magnitude at less than zero distance in the EUS. This is why it is not a scientific concept; it is a disguised implicit engineering decision, i.e., one that reflects a cost/risk/benefit/frequency/uncertainty trade-off."

"The NRC staff must recognize that deterministic criteria (e.g., the MCE) are largely untested in this portion of the Basin and Range. With respect to the EUS the Basin and Range is different because it has identifiable features and a shorter historic record of seismicity. With respect to California it is different because the deformation rates (and hence presumably the seismic "threat") is 100 to 1000 times smaller. Therefore, an MCE could be doubly conservative here.

"We all agree deterministic site investigation is necessary (although knowing when to stop getting data is just as necessary.)"

2.2 CONSERVATISM OF THE DETERMINISTIC APPROACH

Question 3. Is the deterministic approach overly conservative?
Question 14. Will the MCFD provide overly conservative design bases for fault displacement hazards?

Comment From Advisors' Reports:

McCann — ". . . If the deterministic assessment drives the final determination of the seismic design basis, it is not clear whether this will be overly conservative relative to the EPA goals (and thus unnecessarily more costly)."

2.3 UNCERTAINTIES

Question 4. Should uncertainties in data and models be treated through the use of supplementary probabilistic criteria?
Question 11. How important is consideration of data and model uncertainties in analysis of fault displacement hazards?
Question 12. If uncertainties exist, how can they be quantified?
Question 21. Would uncertainty in parameters have a significant effect on seismic hazard analysis?
Question 38. Is it adequate to rely on only 3 means of accommodating uncertainty?
Question 39. Do multiple barriers accommodate uncertainty?

Question 40. Is uncertainty adequately accommodated by using the mean or median of available data to predict earthquake and fault movement 10,000 years into the future?

Comments from Advisors' Reports:

Cornell — "Under the Circumstances, I do not think a traditional approach . . . can be defended any longer. These circumstances include:

. . .the need for incorporating systematically and consistently these two issues, i.e., alternative models and explicit uncertainty recognition into the evaluation and the criteria."

"Analysis of Trees: MPM/MPFD Uncertainty, and More.

. . .The weights on the branches can be multiplied to produce uncertainty distributions on the MPM and MPFD for each fault. This uncertainty is "epistemic" uncertainty, i.e., it reflects "limited current knowledge" about the scientifically definable quantities maximum possible magnitude and displacement. These distributions will be used below.

. . .Do the same for maximum likely (mode or median) magnitudes and fault displacements (MLM, MLFD) and ground motions at the surface and at depth, in several specified future windows (e.g., the next 10, 100, and 10,000 years). The MLM reflects "aleatory" randomness (e.g., how many, how often, when, how big, where, etc., will events occur in a given time). The trees will provide the degree of epistemic uncertainty in these measures of the aleatory/random behavior of nature. Examples are the uncertainty bands produced on seismic (aleatory) hazard curves in current SHA practice.

. . .Study and use the trees to suggest effective ways to reduce the uncertainty in the MPFD and the MLFD, etc. Any proposed additional site investigation will presumably have as its purpose finding new information about known features or looking for potential, new features. The trees can be used to show the benefits of reducing uncertainty. It will reduce design values . . ."

"Focus on 10,000 years problem (the rest is more "familiar"). One approach is just to time re-scale California. Another is systematic look at issues such as: . . .

What elements are new (e.g. is there potential for significant change in the current geological "steady state"? How can they be addressed by science, logic, analogy, common sense, etc. "Address" includes: gain understanding, seek evidence about, assess likelihoods, develop engineering solutions to mitigate consequences of unlikely but uncertain events, provision with long-term robust (i.e., simple) monitoring."

Kiremidjian — "A deterministic approach will not be defensible in the light of all the uncertainties and the inherent randomness of earthquake phenomenon."

Toksöz — "There are uncertainties about the time intervals at which faults may rupture, sense (mechanism) of fault displacement, magnitude of displacement, changes of fault dislocation and coupling or interaction between faults. Fault trenching and other analysis may provide some data on geological recent movements of these faults. Given the geologic experience from other parts of the world, there will be large uncertainties with these data." "To accommodate these uncertainties, alternate tectonic models and questions . . . require careful analysis"

McCann — "The Staff has taken a big step in calling for the explicit consideration of "credible alternative models." This reflects a clear recognition of the uncertainties associated with the interpretation of earth science data. The recognition of the need to account for these uncertainties may be the most difficult step, from a philosophical perspective."

"In preparing the draft outline of the STP, the Staff has recognized the uncertainties associated with modeling geologic and potentially seismogenic structures. Further, the Staff recognizes the uncertainties involved in performing fault displacement and seismic hazards analysis (FD&SHA) and has taken the position (at least in the Internal Draft of the STP) that an applicant should formally identify and consider implications of alternative interpretations of available earth science data."

"Uncertainties in FD&SHA - As part of the STP there is a direct recognition of the technical uncertainties associated with the assessment of natural hazards. Thus, the STP calls for the evaluation of alternative models in the FD&SHA. This is a positive and important part of the STP."

". . . a probabilistic assessment is based on the fact that fault displacement and ground motion hazards are random events whose time and location of occurrence are not known. Furthermore, due to limitations in the available data and our understanding of the physical processes being modeled there are uncertainties associated with modeling these events. These uncertainties lead to multiple, scientifically credible (are consistent with current understanding) models (assessments)." "As a result of conducting these types of assessments in parallel, a probabilistic assessment identifies and enumerates the randomness and uncertainties in the problem whereas the deterministic approach in effect denies that they are part of the problem." "Having taken the position of recognizing uncertainties in the FD&SHA, the STP should focus on how to provide information (an assessment of the hazards) that provides a basis to logically incorporate them in the decision making process (i.e., determination of the design basis)."

"Recent experience in performing seismic hazard assessments where a comprehensive measure of uncertainty is required clearly indicates the need to utilize earth scientists to interpret available information and to provide parameter estimates. This need is equally as great in the assessment of fault displacement and seismic hazards at a geologic repository." "Experience suggests that within the context of having to identify and quantitatively assess the uncertainty in data and more importantly in models they develop, the earth scientist is not well versed." ". . . . to utilize the experience and interpretive and modeling capabilities of the experts, an elicitation process must have at least the following attributes:" *[A list is provided - see section 3.2 of McCann's Report]*

"One of the difficulties posed by multi-variate probabilistic assessments that involve dual probabilistic characterization of random variables (in terms of their randomness and uncertainty components) is the fact that the physical characteristics of the problem remain obscure. In contrast, a benefit of deterministic assessments is the fact that they are more transparent and easily understood."

Cornell — "Defense in Depth (Engineered and Natural Barriers). It should be said somewhere that the earthquake is a phenomenon that challenges <u>both</u> barriers simultaneously, reducing the effectiveness or dependability of this redundancy."

McCann — No matter how many data are acquired, there will still be uncertainties and it will be necessary to interpret the data. To what level do we investigate and then stop collecting data?

Cornell — The top-down and bottom-up approaches must be considered simultaneously. Uncertainties will be great, and you should consider a top-down risk analysis to determine if you can live with the uncertainties involved. If not, then the answer is to change the design and undertake a relative hardening of some components. The other option is to pick another site.

McCann — I don't think the deterministic method should be carried through by the applicant. It may be used as a sanity check for and by the staff. I think there is uncertainty in the western U.S. and the differences *[between deterministic and probabilistic]* may be hard to explain.

2.4 EXPERT JUDGEMENT

Question 5. Can probabilistic assessments be done without formal expert judgement elicitation?

Question 23. Re. mean, median or a std. deviation and limiting expert opinion choices in response or providing expert education and ground rules - which of these criteria are preferred for design?

Question 36. Can expert judgement now be shown better than in the past to predict future events and can it be relied upon to quantify probabilities 10,000 years hence considering:

a. 10,000 years is longer than the history of known civilizations?
b. California's seismic hazard was not publicly recognized in 1906 and the Little Skull Mountain earthquake occurred in what was thought to be a seismically quiet zone?
c. Management of expert opinion is a new science (art)?
d. Futurists predictions of 100 years ago have proved to be of variable accuracy?
e. Although the geologic record is a history of the past, its interpretation by experts to predict the future produces varied probabilities?

Question 37. Are there viable alternatives to expert judgement?

Question 41. Will use of expert judgement to obtain the full breadth of opinion drive engineering design to excessive levels?

Comments from Advisors' Reports:

Cornell — "On expert opinion. This letter report hardly permits a long response. In brief, our profession's experience in similar projects suggests that, with guidance and caution, it can be very effective. It should be reconfirmed that it is not a substitute for hard data. We all agree "deterministic" site investigation is necessary (although knowing when to stop getting data is just as necessary.) Formal expert "opinion" assessment is simply (at any given time, given the data and information available at the site) the best way to process complex, conflicting evidence. It displays where there is consensus and where not, where there remains major uncertainty and where not, etc. The seismic area has, it is reported in the literature, some of the most significant experience in the area of use of expert opinion in a highly technical context such as this. Some of the experience has been negative, but I believe we have learned from it. A current joint NRC/DOE/EPRI project is working hard to improve the process. Given the situation at hand, the "answer" is going to rest on judgement in any case. It can only help to make sure that it is indeed expert judgement and the process of gathering and using and documenting it is the best available."

McCann — "The use of experts is a critical part of the FD&SHA. As a result, the STP should provide guidance regarding acceptable methods and procedures for the use of experts. Unfortunately, the EPRI and LLNL seismic hazard experience in the EUS indicates that when it comes to the use of experts, general guidance is not adequate. Both EPRI and LLNL started with the same general guidance, however the approaches they used and the results they obtained were dramatically different.

Guidance in the use of experts for the FD&SHA should address issues such as:

... Establish rules (if possible) or guidance regarding the development of alternative models.

... Development of a framework for the following areas:

- training and education of experts
- development of communication tools/methods to facilitate the expert assessments
- addressing extreme outlier opinions or parameter assessments

... Documentation of the process that was used to acquaint the experts with the data, including the facilitation of their understanding of data and its alternative interpretation.

... Documentation requirements for expert interpretations and models that document the evaluations performed, the role of alternative data sources in the assessment, relationship of alternative models.

... Aggregation of multiple expert inputs."

[Note: Dr. McCann provided considerable additional detail on the topic of expert opinion on pages 6 through 8 of his report which is included in Appendix C of this report.]

Toksöz — *[In regard to probabilistic analysis.]* "Extensive education and discussions and even confrontation between experts may increase awareness. On the other hand, this approach has been criticized by some for interfering with the process of obtaining unbiased input from the experts. Based on my experience, assisting the experts by providing them with all the information that may be available is useful, since each expert may not be able to undertake a comprehensive study on his own."

2.5 ALTERNATIVE TECTONIC MODELS

Question 6. Are alternative tectonic models essential because of complexities of tectonic setting at Yucca Mountain and consequent uncertainties in characterization of tectonic hazards? Is it necessary to identify all tectonic models or just bounding models?

Comments from Advisors' Reports:

Cornell — "Under the circumstances, I do not think a traditional approach, namely one based on scientifically undefined concepts such as Maximum Credible Fault Displacement (MCFD) and Maximum Credible Earthquake (MCE), can be defended any longer. These circumstances include:

. . . the need for incorporating systematically and consistently these two issues, i.e., alternative models and explicit uncertainty recognition into the evaluation and the criteria."

"The call for alternative models is good. There is no proposal for what to do with them, however."

Thompson — "Well formulated alternative models or hypotheses are important to focus data gathering efforts. The testing and interpretation of hypotheses then needs to be subjected to intensive peer review. Journal publication is perhaps the most efficient way to obtain wide critical review and should be encouraged. One must also realize that judgement is required in selecting models to test; there are unlimited numbers of ill-informed or crackpot hypotheses that could wastefully divert much effort."

Kiremidjian — "The lack of knowledge and understanding of the geologic and hydrologic environment of the repository requires that alternative models be used to represent different possible scenarios. As new information is gathered and data are collected at the repository site new scenarios will become apparent for representing the behavior of faults and potential consequences of their movement. Thus the alternative models should be an essential part of the repository risk assessment methodology. Furthermore, for design purposes, alternative models can provide valuable information on the range of possible values and rational decisions can be made on this basis."

"I support the alternative modeling approach proposed in the STP outline with the recommendation that a logic tree approach be used for the systematic treatment of the different models. In addition care must be taken to identify highly unlikely scenarios and yet not to omit ones that are plausible."

McCann — "The staff has taken a big step in calling for the explicit consideration of credible alternative models. This reflects a clear recognition of the uncertainties associated with the interpretation of earth science data. The recognition of the need to account for these uncertainties may be the most difficult step, from a philosophical point of view."

"The STP does not address the role of experts in the fault displacement and seismic hazard analysis (FD&SHA). Assuming experts are used in the development of alternative models, experience suggests that the process to elicit their input can be as critical as other technical aspects of the assessment."

". . . the staff recognizes the uncertainties involved in performing a fault displacement and seismic hazards analysis (FD&SHA) and has taken the position (at least in the Internal Draft of the STP) that an applicant should formally identify and consider the implications of alternative interpretations of available earth science data. This is an important step forward. There is however no guidance provided as to how this should be done."

"Assessment of Alternative Models - The STP is silent on the issue of how to develop alternative models. Must a group of experts be used or can a single expert or contractor develop the alternative models?"

"How are credible alternatives considered in the probabilistic assessment? In the deterministic assessment? It is not clear in the STP, nor was it clear in the discussion at our meeting with the staff how credible alternatives are developed. The statement that they be considered and developed seems too open ended. How should credible alternatives be developed? Can/should/must earth science experts be used? There is no mention of the use of experts in the STP. While it would seem obvious that experts should be used, the STP doesn't seem to take a position on this. This is a drawback and gives the applicant the flexibility to avoid using a group of experts."

Toksöz — *(Regarding fault displacement analysis.)* "To accommodate these uncertainties, alternate tectonic models . . . require careful analysis."

2.6 ELEMENTS OF AN ACCEPTABLE RISK ANALYSIS

Question 8. *[With regard to Position 2 of the STP]* Are these elements necessary and sufficient to provide reasonable assurance relative to fault displacement hazards?

Question 9. Should this list *(of elements for an acceptable risk analysis for fault displacement hazards)*be modified by inclusion of new elements or exclusion of existing elements? *[The list includes fault geometry, segmentation, distributive faulting, coupling between faults, volcanism, slip rates and directions, recurrence intervals for faulting, the MCFD, the MLFD, regional stress fields, and the effect of the MCFD on hydrology.]*

Question 18. Is the staff approach adequate to identify the DBE?

Question 19. Are there other approaches to be considered?

Question 20. Are there parameters (other than those listed) needed for consideration in ground motion analysis?

Question 22. Are there other seismic elements to be considered for the design of facilities important to safety?

Question 24. *[Re. source zones, a & b values, M_{min}, M_{max}, A_P cutoff, site effects.]* Are any of these more critical than others in development of design input?

Comments from Advisor's Reports:

Cornell — "THE CASE AGAINST THE MCE AND MFD.

Under the circumstances, I do not think a traditional approach, namely one based on scientifically undefined concepts such as the Maximum Credible Fault Displacement (MCFD) and Maximum Credible Earthquake (MCE), can be defended any longer. These circumstances include:

> . . .progress on many fronts away from the MCE (or its equivalent the "Minimum Incredible Earthquake," *[this concept has relevance to peak accelerations high enough to cause damage which are implied from the tails of probability distributions for small earthquakes]* a Clarence Allen observation that reveals the weakness of the concept). These fronts include the expertise

and experience in using a probability/frequency format for seismic assessments in many fields and for safety assessments and criteria-basis for many hazards etc.

. . .the ultimate need (in order to meet EPA criteria) of a quantitative description of the randomness and uncertainty faced, e.g., for the IA process. . . .

. . .the existence of alternative procedures that are consistent both with this ultimate need and with the evolving practice in seismic and other engineering fields. Examples: The latest NRC (reactor) and DOE criteria. *[apparently in reference to NRC's development of 10 CFR Part 100, Appendix B, and perhaps to evolving DOE regulations]*

. . .the commendable incorporation already in the STP draft of the need for alternative models, and the admission already of major uncertainties in virtually every element of the FD and SHA problem.

. . .the need for incorporating . . . alternatives models and explicit uncertainty recognition into the evaluation and the criteria.

. . .the untested character of the MCE/MFD for this portion of the Basin and Range. . . "

Cornell — "Develop the Basis for Quantitative Criteria.

Issues include:

. . .Format and level, the 84% of the MPFD . . . and/or the 84% of the MLFD in 10,000 years . . ."

. . .a basis for criteria could be established by re-scaling time (via relative slip rates) to use broader California experience as a guideline. Slip rates are 100 to 1000 times less; this implies that at Yucca Mountain 10,000 years look like 100 to 10 California years, or typical conventional project window lengths in California.

. . .one would also have to look at the likelihood of a major/sudden change in the slip rates in the neighborhood in 10,000 years. This is a doable problem. Think of the Wallace Basin and Range study *(Wallace 1985 and 1987)*. Think of analogies in space/time elsewhere."

Cornell — "There is nowhere a definition of the MCFD or MCE." "What ground motion fractile (84th?) is to be used with the maximum credible magnitude in a deterministic criterion? Recall Appendix A and hence the Standard Review Plans do not necessarily apply." "The shopping list in section 4.2 (e.g., interaction, coupling, stress increases induced by heat and from the waste, spatial-temporal clustering, segmentation based on paleo-seismic studies, etc.) is a scientists dream." "At least when dealing with probabilistic models (what you call MLFD, MLE, etc.), it must be remembered that what is conservative with respect to MCFD and MCE is not necessarily conservative with respect to MLFD and MLE. For example, a smaller maximum magnitude implies more frequent events if the moment rate is known, and this may imply increased ground shaking hazard at a site." "Is there enough regionally specific data to produce a Yucca Mountain specific ground motion model? Sub-surface motion prediction deserves more attention. Finite-length-source ground motion prediction models may be needed. Local site effects and SSI *[soil-structure interaction]* seems to be mixed together." ". . . the

CNWRA/NRC staff may not themselves have thought in depth about MCE definition, especially in context of a range of options/opinions/evidence (i.e., implicitly or explicitly a suite of more and less plausible (likely) values ranging from the maximum observed in the historic or the paleoseismic record to the lunatic upper fringe."

Toksöz — "The Draft STP (Section 3.2, pp. 5-6) contains most relevant items that should be considered on fault displacement hazards. A few items need to be added or clarified. Tectonic deformations could change over a period of 10,000 years. Large earthquakes occurring on the Mojave Plate, and some increased rate of seismic activity in Mammoth and Owens Valley may signal a change. Magma upwelling, doming and other processes could occur, that might result in uplift and a changed state of stress. Some faults that would have remained locked could become unlocked and move. These possibilities need to be built into the fault displacement Model." "Section 3.3 of the STP provides good coverage of the elements that should be included in the seismic hazard analysis. I would like to reemphasize some important aspects and add a few additional items for consideration.

- The probabilistic method is the proper approach for seismic hazard analysis.
- Large earthquakes on the Mojave block and possible changes in the tectonic regime of eastern California and western Nevada should be included in seismic sources.
- The effects of crustal structure on geometric spreading of seismic energy at regional distances (especially in $\Delta = 100\text{-}200$ km range) should be included.
- 3-D structural effects should be considered.
- Attenuation is highly variable in the region. All data, including laboratory measurements being made from cores, should be used. Generally it is appealing to go with a generic California attenuation model. This project deserves more detailed and specific study.
- It is implied in the STP that ground motion at depth is smaller than the surface value. This is not always true. A highly attenuating, thick near-surface layer could decrease the ground motion at the surface.
- Ground motion modeling should include 3-D structural effects near the repository. Lateral heterogeneities are such that peak ground motion could vary by a factor of ten over relatively short distances.
- Since there are other experts on the applicability of the Poisson model, I will not comment on these at this time. Personally, I do not believe that the seismicity rate will remain stationary over a 10,000-year period and I would choose input parameters to represent this uncertainty.

Kiremidjian — "The questions that can be raised when predicting the amount and type of differential fault displacement include:

- Can the general stress regime of the region be estimated to determine the direction of possible rupture (vertical, horizontal or combined)?

- Over the next 10,000 year time frame, is it possible for new fissures or new faults to form in the vicinity of the repository or across the repository?

- Is the estimated total slip from the Quaternary the result of a single event or the cumulative slip of several events?

- If there is a potential for more than one seismic event over the life of the repository (primary for the post-closure period), what displacement can each event produce (amount and type of differential displacement)?

- Are surface fault displacements representative of displacements at depths? And if not what is the difference?

- Can variations in fault displacement along the rupture zone be quantified? Is this distribution triangular with a maximum at the midpoint of the rupture zone and decreasing towards the ends, or is it skewed? Where will the maximum displacement fall in relationship to the repository?

- Do we have sufficient information to correlate the displacements of the size hypothesized maximum earthquake (provided the MCE approach is considered)?

- If several en echelon segments of fault are present, is it possible for rupture to extend across segments?

- Given a series of fault displacements over the postclosure life of the repository, what is the likelihood that water reaching the repository either through water table elevation changes or through rock dewatering?

- Given a fault displacement, what engineering measures can be taken to mitigate its effect on the repository?

A comprehensive fault displacement methodology should address each of these questions."

"I agree with the view that subsurface groundshaking has caused little if any damage to underground structures. Groundshaking hazard, however, becomes important in the more global picture of the hydrologic regime of the repository. Of particular concern are potential crack initiation or expansion in the host rock providing pathways for groundwater or rock water to reach the repository through a dewatering process as pointed out by Thompson during our meeting. . . . Assessment of potential ground shaking from nearby and distant faults is also required for more reliable characterization of ground motions at the repository site. Partial information may be available from recordings of past nuclear explosions."

McCann — "Design Basis Strategy - Develop an approach to determine the design basis for fault displacement and ground motions that is based on the EPA risk criteria. To do this, the staff will require a:

- global risk model for the repository, including its response to fault displacement and ground motion, and the

- measure of the capability to provide margin in the repository design for fault displacement and ground motion.

The staff should develop a design strategy for fault displacement and ground motion that satisfies the EPA criteria and provides practical design."

2.7 ACCURACY OF REQUIRED INFORMATION

Question 10. What concerns exist related to accuracy of required information, e.g., subsurface fault geometry, age of faulting, determination of slip amount and data uncertainties?

Comments from Advisors' Reports:

Kiremidjian — "If we cannot determine how many events have occurred in the past 10,000 years even with the most sophisticated current geo-exploratory tools, can we predict with sufficient precision how many will occur in the next 10,000 years? A single value estimate will lead to suspicion . . ."

Toksöz — "In probabilistic analysis . . . An expert may feel that if he/she is not quite accurate, other experts will provide correct inputs. Thus there is no pressure to dig into the matter . . ."

2.8 QUATERNARY EVENTS AS A BASIS FOR POST CLOSURE CRITERIA

Question 13. Is it reasonable to use the Quaternary record in the YM area to establish the MCFD for faults at the site?

Comments from Advisors' Reports:

Cornell — ". . . all the excellent information about Paleo-seismic events at Pallett Creek and Wrightwood seem to leave us more confused than ever about future event likelihoods and locations!" *[These Paleo-seismic events are all Quaternary and most are Holocene in age.]*

Kiremidjian — "Is the estimated total slip from the Quaternary the result of a single event or the cumulative slip of several events?"

Thompson — ". . . the proposed repository site at Yucca Mountain is unique in both is location, hundreds of meters above the water table and also in its location near small basaltic volcanoes, one of which is Quaternary in age."

2.9 ANALOGS

Question 15. Is it reasonable to consider analog faults elsewhere in the geologic setting if the MCFD cannot be determined from faults at the site?

Comments from Advisors' Reports:

Cornell — "What elements are new (e.g. is there potential for significant change in the current geological steady state?) How can they be addressed by science, logic, analogy, common sense, etc."

Toksöz — "Fault trenching and other analysis may provide some data on geological recent movements . . . Given the geologic experience from other parts of the world, there will be large uncertainties associated with these data."

2.10 PRE- AND POST-CLOSURE CRITERIA

Question 16. Is the combined deterministic and probabilistic approach appropriate for use in both the pre- and post-closure periods of performance, 100 and 1000 years respectively?

Question 17. If not what are the alternatives?

Comments from Advisors' Reports:

None found.

2.11 PROBABILITY DISTRIBUTION FUNCTIONS

Question 34. What do you recommend regarding the position that the Poisson distribution is adequate for large data sets over long time periods?

Question 35. What do you recommend regarding the position that a time dependent distribution improves prediction for times past the median return period? and that a truncated distribution represents earthquake data better than a Poisson distribution although seismic history is relatively short?

Comment from Advisors' Reports:

Kiremidjian — "The choice of Poissonian or time-dependent models of earthquake occurrences is dictated by the relationship between the average interarrival time of events, the forecast time and the estimated time of the last major event. Non-Poissonian models are appropriate when the average interarrival time between events is of the same order of magnitude as the forecast time. If, in addition, the sum of the time since the last occurrence and the forecast time approaches the average interarrival time of events, then a Poisson model has been shown to be non conservative (see Kiremidjian and Anagnos, 1984 and Anagnos and Kiremidjian, 1984). For faults in the Yucca Mountain Region, the average interarrival time is 10,000 years according to my understanding from the presentations during our May meeting. For such long interarrival times, the probability of occurrence of at least one event in the next 10,000 years if estimated from the time dependent model is likely to be considerably higher than estimates that would be obtained from a Poisson model. Thus it is recommended that the selection of occurrence model be done with care and understanding of the tectonic mechanism. It appears that the simple time-dependent model may be more appropriate for the Yucca Mountain faults than a Poisson model."

2.12 ATTENUATION DATA FIT AND EXTRAPOLATION

Question 25. How should data extrapolation be addressed to large earthquakes or long time periods?
Question 26. How should attenuation or velocity be extrapolated where data are inadequate?
Question 27. How should data be extrapolated to short distances for large earthquakes?
Question 28. Should data be fit to attenuation curves or extrapolated by fault type subsets?
Question 29. Should attenuation data be fit or extrapolated by foundation material subset?

Comments from Advisors' Reports:

Cornell — "Is there enough regionally specific data to produce a Yucca Mountain specific ground motion model? Sub-surface motion prediction deserves more attention. Finite source motion prediction models may be needed. Local site effects and SSI seem to be mixed together."

Toksöz — "Attenuation is highly variable in the region. All data, including laboratory measurements being made from cores, should be used. Generally, it is appealing to go with a generic California attenuation model. This project deserves more detailed and specific study." "It is implied in the STP that ground motion at depth is smaller than the surface value. This is not always true. A highly attenuating, thick near-surface layer could decrease the ground motion at the surface." "Ground motion modeling should include 3-D structural effects near the repository. Lateral homogeneities are such that peak ground motion could vary by a factor of ten over relatively short distances."

3 OTHER TOPICS ADDRESSED BY THE ADVISORS

3.1 TRANSPARENCY

Transparency is a term which means that a process is clear or obvious to a non-technical person. The lack of transparency of probabilistic analyses was cited as a reason for mistrust of probabilistic methods by non-specialists in statistics. All the advisors agreed that there should be efforts made to improve the transparency of probabilistic analyses of fault displacement and seismic hazards. During the meeting the term "disaggregation" was mentioned. It was stated that NRR staff had disaggregated PSHA calculations for the EUS to better understand the process. A PSHA calculation may be disaggregated into several independent sets of assumptions which appear much like deterministic analyses which have probabilities and uncertainty estimates attached to or calculated for the parameters used. In their reports several of the advisors, who had not been enthusiastic about the use of deterministic analysis in any form, indicated that a deterministic analysis may be appropriate. Two aspects of the hazards problem appeared to influence this attitude: (1) a deterministic analysis forces a focus on data, ensuring that adequate data are considered in the probabilistic analysis; (2) a deterministic analysis would therefore, provide a basis for understanding the probabilistic process and results by those who are not specialists in statistics.

Toksöz — "Most earthquake hazards studies that have been carried out in the past two decades have employed the probabilistic approach. . . . There are pitfalls to this approach. These result not because the methodology is unsound, but because of the poor quality of the input data and implementation. . . . It is like having a puréed vegetable soup at a French Restaurant. It tastes OK to everyone but no one can identify the ingredients."

McCann — "**Transparency of FD&SHA Results** - One of the difficulties posed by multivariate probabilistic assessments that involve a dual probabilistic characterization of random variables (in terms of randomness and uncertainty components) is the fact that the physical characteristics of the problem can often remain obscure. In contrast, a benefit of deterministic assessments is the fact that they are more transparent and easily understood. . . . It is recommended that the STP provide definitive guidance regarding the development of a seismic hazard information base." *[Note, that McCann has a great deal more to say about transparency and proposed details to implement improved transparency in probabilistic analyses.]*

Cornell — "Transparency: there is a need to make logic-tree based seismic hazard analysis more scrutable by scientists (as opposed to analysts), without losing its complete integrating analysis benefits. There is some potential to do this, but it needs research.

Kiremidjian — "It is important that all methods and analysis techniques are transparent, reproducible and the results are verifiable."

Thompson — "The data base needs to be incorporated as transparently as possible into the probabilistic analysis."

3.2 FAULT TREES

The use of fault and event trees was highly endorsed by Dr. Cornell as a means of keeping track of parameters in a PSHA. Their use, or use of a functionally similar mechanism, was supported by most of the advisors. Fault and event tree analysis has evolved to a complex state and is often accompanied by or is a part of decision analysis which may also play a part in probabilistic analyses.

3.3 INTEGRATION OF FD&SHA WITH IPA AND GROUND WATER MOVEMENT

Every advisor recommended that the investigation of groundwater effects be integrated with FD&SHA. Most were concerned that the draft Analysis STP did not indicate a strong interface with IPA which they felt would ultimately drive probabilistic design criteria. Two advisors believed that volcanism was so intrinsically linked to fault displacement and seismic activity that volcanic hazards should also be integrated with FD&SHA.

3.4 OTHER PROBLEM AREAS IDENTIFIED BY THE ADVISORS

These problems do not necessarily have obvious solutions but there is in implication or statement by the proposing advisor(s) that the problems should be addressed:

- Weights should be assigned to proposals advanced by experts who are elicited in FD&SHA. An acceptable weighting scheme, perhaps based on peer review, should be established.

- Guidance needs to be developed regarding what to do with alternative tectonic models in FD&SHA.

- Terms such as MLFD, MCFD, MCE etc. should not be used. Rather an acceptable probability level should be set and the corresponding hazard selected. If such terms must be used, they should be carefully defined.

- The only experienced consultants in FD&SHA are already employed by DOE.

- Interaction with NRR and DOE, in the rapidly developing probabilistic analysis area, is insufficient to keep current.

- Changes in seismicity/tectonic activity may occur within the next 10,000 years at Yucca Mountain and this should be accommodated in analyses.

4 ADVISORS' RECOMMENDATIONS FOR THE DRAFT ANALYSIS STP

Many recommendations were made by advisors in their reports. The reports should be examined carefully for pertinent details. Advice specifically directed toward draft Analysis STP changes is summarized here.

McCann. — "The STP should provide a clear definitive framework for evaluating and reporting fault displacement and seismic hazards. The framework must provide the applicant with the flexibility to use new methods and data and alternative interpretations of regional and local tectonics, while at the same time insuring computational and reporting requirements are satisfied. Recommendations are provided in the following areas:

- Terminology
- Deterministic Analysis
- Elicitation of Expert Input
- Applicant Submittals
- Transparency of FD&SHA Results"

[Statements which address these respective points follow. See McCann's report for a complete description.]

- "Eliminate . . . terms such as: maximum credible fault displacement . . ."
- ". . . it is recommended the deterministic part . . . be eliminated . . ."
- ". . . incorporate reporting milestones . . . for . . . plans to deal with critical issues."
  ". . . the applicant could be requested to report on the approach to elicit expert input."
- ". . . STP provide definitive guidance regarding the development of a seismic hazard information base . . .This includes intermediate and final results . . . It is important that a probabilistic FD&SHA be equally transparent to the earth scientist (non-probabilist) and to the seismic hazard analyst . . ."

[Regarding the last item] ". . . the following should be provided as a minimum . . . :

1. Seismic hazard results for the total hazard and for specified magnitude-distance pairs. *[The seismic hazard from each source zone should be estimated independently in addition to a final aggregated hazard.]*
2. Fraction contribution of each magnitude-distance pair to the total hazard (probability of exceedance) for each ground motion level.

3. Fraction contribution of each seismic source to the total hazard for each ground motion level.

4. Fraction contribution of the input provided by individual experts to the total hazard, including the contribution of the expert source combinations and ground motion models.

5. Analysis of variance of the primary components (experts) and parameters in the seismic hazard assessment."

[Note: McCann also provides suggestions for guidance in the use of experts.]

Cornell — "RECOMMENDATIONS FOR WHAT NRC SHOULD REQUEST OF THE APPLICANT (DOE).

1. Initial Deterministic Investigations

Do a reasonable site investigation per the previous STP. Support this with reasonable deterministic studies, interpretations, etc.

2. Information Management via Logic Trees

(a) Maintain in a logic tree format (See, for example, applications for Diablo Canyon NPP *[Pacific Gas and Electric Co.]* (1988) and elsewhere) the current information and alternative hypotheses. . . .

(b) Conventional trees should be expanded to include branches associated with potential multisegment events (San Francisco 1906 and Landers 1992), and to include potential undiscovered faults (on and off-site). . . .

3. Analysis of Trees: MPM/MPFD Uncertainty and More.

(a) The weights on the branches can be multiplied to produce uncertainty distributions on the MPM and MPFD for each fault. . . .

(b) Do the same for maximum likely (mode or median) magnitudes and fault displacements (MLM, MLFD) and ground motions at surface and at depth, in several specified future windows (e.g., the next 10, 100, and 10,000 years). . . .

(c) Study and use the trees to suggest effective ways to reduce the uncertainty . . .

(d) Supplementary analysis and judgements can be used to estimate the likelihood of, for example, finding a new fault if it exists . . . .

4. Analysis of Decisions.

Decisions that have to be made include (1) site investigation details and continuation (See 3(d) above), (ii) design decisions, and (iii) what to do if significant unidentified features are found during construction, etc. The logic trees supplemented by decision trees and analysis can facilitate such decision making. In fact anticipating such decisions that might need to be made during construction (and their cost impacts) should be part of the decision as to when site investigations can stop.

5. Provide Input for Ongoing (Scenario-based) Performance Assessments at DOE and NRC. This implies a closer coupling between the current NRC IPA (Integrated Performance Assessment) and the STP.

6. Criteria Evaluation.

As soon as NRC establishes its numerical criteria . . . it can ask DOE to provide current design values. These will include design values for fault displacement, ground motion, etc. They may be in the form of percentiles (e.g., 84%) of the MPFD and or of the MLFD, etc. The results of the analysis in B(3) above will provide the numerical values."

Toksöz — "I urge, therefore, that the importance of the data collection effort be conveyed either as part of the STP or as a separate memorandum. *[With regard to the many DOD, DOE and DOI and their contractors, seismic and fault displacement hazards data bases that are available but difficult to access and present.]*

"The draft STP . . . contains the most relevant items that should be considered on fault displacement hazards. A few items need to be added or clarified. Tectonic deformations could change over a period of 10,000 years. . . . Magma upwelling, doming, and other processes could occur that may result in a change state of stress. Some faults that would have remained locked could become unlocked and move. These possibilities need to be built into the fault displacement model. . . . The term "fault segmentation" is used in the STP. . . . Several recent examples . . . showed that fault rupture occurred over several segments, and surface fault displacements were much larger than those predicted by fault segmentation models. In considering maximum credible earthquake or maximum credible fault displacements it would be prudent to consider the total length of all segments and larger displacements than one might anticipate from a geometric simple straight fault. . . . The secondary effects of faulting on groundwater are not emphasized in the STP. It is important that this aspect of fault displacement be thoroughly covered between the hydrology STP and fault hazards."

"Section 3.3 of the STP provides good coverage of the elements that should be included in the seismic hazard analysis. I would like to reemphasize some important aspects and add a few additional items for consideration.

- The probabilistic method is the proper approach for seismic hazard analysis.

[An additional seven bulleted items follow. These have already been listed in Section 2.6. The concerns are for a 3-D analysis of structural geology effects on ground motion and strain. The latter can influence whether a fault is likely or unlikely to slip. He expresses concern about reducing ground motion values with depth and repeats the concern that a change in the tectonic regime is possible over a 10,000 year period.]

Kiremidjian — "It is my opinion that NRC should ask for the following information and procedure to be followed for high-level radioactive repositories licensing and design:

- A detailed geo-hydrologic exploration and data gathering should be conducted. The only constraint would be economic feasibility of certain types of exploration. However, I strongly believe considerable amount of additional exploration and testing can be performed to better understand the geo-hydrologic regime and the potential for fault displacement and ground shaking.

- A deterministic approach will not be feasible in light of all the uncertainties and the inherent randomness of earthquake phenomenon. A probabilistic approach should be considered for assessing both the fault displacement and ground shaking hazard.

- It is important that all methods and analyses techniques are transparent, reproducible and the results verifiable.

- A logic tree approach should be used to represent the alternative models and to assess the relative weights of various models.

- The repository hazard and risk evaluation should include consequence scenarios to assess the overall risk of release.

- Design parameters and methodologies can be best selected on the basis of minimal risk of failure of alternative mitigating solutions. This will require that there is direct communication between the user, engineer and assessor of the potential risks."

Thompson — *[Comments specifically directed toward changes in the draft Analysis STP were not made. However, there are a number of applicable points, some of which follow.]* "Well-formulated models or hypotheses are important to focus data-gathering efforts. The testing and interpretation of hypotheses then needs to be subjected to intensive peer review. Journal publication is perhaps the most efficient way to obtain wide critical review and should be encouraged." ". . . two non-traditional aspects of seismic-coupled hazard, hydrology and volcanism, deserve special attention . . ." ". . . deterministic studies are needed to establish basic data, distinguish between hypotheses, test models and provide reality checks. But recognizing that complete data and physical models are never achievable, probabilistic analysis is important and necessary." ". . . logic trees or some similar scheme can provide a useful and efficient means of managing information. New or alternative information can be inserted and propagated through to probabilistic conclusions." "As the water table . . . varies by hundreds of meters over the Yucca Mountain area, assessment of earthquake consequences needs to be anticipated in regulatory guidance."

5 RECOMMENDATIONS FOR RESEARCH

Some of the advisors recommended that research or studies be carried out in certain technical areas.

Cornell — "RECOMMENDATIONS FOR RELATED NRC/CNWRA TASKS

Some topics that NRC/CNWRA should make efforts on directly or via contractors include:

1. NRC Logic Trees

Keep up to date NRC versions of the site description in the logic tree format . . . discrepancies . . . will target areas for discussion and reconciliation . . . will provide ongoing NRC IPA input also.

2. Development Work

Conduct and/or commission background research and development with respect to:

(a) Elements of the logic tree and its analysis . . . with which the profession has less experience, e.g., branches for undiscovered faults, and analysis of the likelihood of finding them.

(b) Probabilistic fault displacement analysis.

(c) Probabilistic hazard analysis for long time windows.

(d) Criteria development issues . . . the role of the IPA, top-down criteria, long windows etc.

(e) Expert opinion treatment in this context.

3. Develop the Basis for the Quantitative Criteria.

[Four issues are listed. These appear in Section 2.6. They include (a) developing the format and level for setting an MLFD acceptable hazard in probabilistic terms for a 10,000 year period of time, (b) the concept of rescaling time in proportion to slip rates so California analyses might be transposed to Yucca Mountain, (c) incorporation of logic to accommodate a sudden change in slip rates in the Basin and Range tectonic province as proposed by Wallace, 1985 and 1987, and (d) research to make logic-tree seismic hazard analysis more transparent without losing its integrated analysis benefits.]

Toksoz — "Attenuation is highly variable in the region. All data, including laboratory measurements being made from cores, should be used. Generally it is appealing to go with a generic California attenuation model. This project deserves more detailed and specific study."

". . .develop a design strategy for fault displacement and ground motion that satisfies the EPA criteria and provides practical design."

"Establish a Seismic Hazard Design Probability Level. Based on the development of an overall design strategy, the Staff should develop a position regarding the procedure for determining the design basis for the waste repository. As part of this process a design probability level must be determined."

McCann — "Recommendation . . . USNRC Staff:

[These recommendations could be taken to be areas for NRC research and development or as approaches to use in further development the draft Analysis STP. However, this consultant provided a separate section on "Comments on the STP". Because probabilistic methods for earthquakes and fault movement hazards are clearly items of development by those who use them, these comments are interpreted as recommendations for research or further study the NRC/CNWRA staff.

". . .It is my recommendation that the staff take a strong position with regard to the framework of what is considered an acceptable FD&SHA. . ." "The staff should make every effort to remain up-to-date regarding the status of changes taking place in SHA. In particular, they should remain up-to-date with respect to the ongoing DOE/EPRI/DOE/USNRC seismic hazard resolution project.

[Taking a strong position on FD&SHA, obviously will require, as a minimum, keeping up with the research and development efforts that are on-going and may require exercising the proposed analysis methods to determine requirements for an acceptable result.]

"Develop an approach to determine the design basis for fault displacement and ground motion that is based specifically on the EPA risk criteria . . . the staff will require:

- global risk model for the repository, including its response to fault displacement and ground motion. . .

- measure of the capability to provide margin in the repository for fault displacement and ground motion. . ."

6 CONCLUSIONS AND RECOMMENDATIONS

The advisors agreed on some points and not on others. These are summarized in the following.

6.1 DETERMINISTIC ANALYSIS

Two advisors argued that there is no longer any place for a deterministic analysis. Others argued that a deterministic analysis brings focus to alternative hypotheses and the data required to resolve them. Further, they provide a clearly understandable "transparent" analysis that a hearing board can comprehend. Only one advisor stated that it was a good idea to perform a deterministic analysis and compare results with a probabilistic analysis. Some did say that a deterministic analysis should be required. The two are really not comparable. A probabilistic analysis provides a hazard curve which yields a design acceleration or spectra for a given risk level. That level could be specified as the earthquake or fault movement that occurs once every 1000 years or some other time period. A deterministic analysis simply provides, if there is a risk at all, an estimate of its potential level. It matters not whether that level be frequently occurring or rare.

All advisors recommended that probabilistic FD&SHA should be required. The EPA remanded regulation requires by inference that probabilistic analyses be input to PA. Further, there are arguments that new hypotheses or data may be introduced late in a licensing process or even after operation has begun. With a probabilistic analysis, such new information could be included as just one more expert opinion and the calculation made again. Little change would be likely to result. This rationale, however may not always hold. If the new information is in the form of substantially improved data or sufficiently credible new models, other experts may change their opinions and the resulting probabilistic analysis could change substantially. This could have been the situation for the Diablo Canyon nuclear plant and the Hosgri fault which even PG&E's consultants eventually regarded as a valid risk generating earthquake source. Although probabilistic risk analyses were not made early in the Hosgri controversy, there clearly were two disparate camps of expert opinion, e.g., see Crouch (1987).

A possible approach to take in the draft Analysis STP is to require that each expert opinion combination for fault displacement and vibratory ground motion be also defined in deterministic terms but with probabilities also presented. The deterministic presentation would include the rationale and supporting data. This procedure would limit many arbitrary and confusing combinations of various expert opinions whose shear numbers could weight the probabilistic analysis towards a higher or lower probability. Clearly divergent hypotheses would be identified and, if credible, included in a final aggregation. More sophisticated statistical analyses might also be permitted, but significant differences between the aggregation of analyses based on data statistics associated with the deterministic analyses of various experts, would have to be explained.

6.2 ELICITING EXPERT OPINION

One advisor provided detailed advice concerning elicitation of expert opinion. Training of experts on giving estimates of probabilities and self assessments of uncertainties was an acknowledged requirement. Such a requirement could be a part of the draft Analysis STP. NRC has funded research in expert elicitation which may be used as a basis, e.g., Bonano et al. (1990) and DeWispelare et al. (1993). The latter addresses elicitation techniques as well as technical aspects of climatology. Experts need feedback regarding the consequences of the models they propose. Two approaches were tried in the

EUS nuclear power plant elicitations, teams and panels of individual experts, e.g., see EPRI (1989) and Bernreuter et. al, (1989). An NRC/NRR program to further examine and resolve differences between results of these two methods is underway as proposed in Nuclear Regulatory Commission (1992). Monitoring of these activities by DHLWM is recommended. The team approach permits ideas to be exchanged in the development of models where some experts are more competent in one or another aspect of the model. The panel approach adheres more closely to the original Delphi concept which forbids identification of experts and confrontation to minimize the effects of dominant individuals and group dynamics.

6.3 DETERMINING CREDIBILITY OF EXPERT OPINION

Several advisors suggested ways in which credibility of expert opinion could be established. One recommended that peer review in journals was the only form of critique that is well respected. Some means would have to be devised to determine if the peer reviews, taken together, advocated credibility of a particular analysis and to what degree. Another advisor suggested that experts on the subject and the region should make the determination of expert opinion credibility. This is precisely the role of NRC staff in reviewing license applications in specific technical areas. This somewhat onerous task is likely to remain the ultimate responsibility of the NRC. If a proposed tectonic model or FD&SHA is deemed not credible, it should not be accepted as a deterministic analysis or included in a probabilistic analysis. Whether a proposal is included or excluded from a probabilistic analysis may well become the purview of hearing judges if the proposer will not accept NRC staff decisions in the matter. Hearing judges are not likely to accept controversial probabilistic analyses that are not "transparent". Therefore, the draft Analysis STP should advocate a methodology that is likely to be acceptable in a hearing. Casting a probabilistic analysis in the form of multiple deterministic analyses with their probabilities of occurrence and individual hazard curves carried along to a final aggregation may provide such a methodology.

6.4 TREES

The advisors agreed that some means of managing information and alternative models for a probabilistic risk analysis was needed. Most agreed that logic trees were an accepted methodology for that purpose but at least one advisor also acknowledged that in their current state of usage, the logic they impart is not very transparent. Fault/event/decision trees, although simple in concept, have become more complex with the addition of probabilities, distribution functions and estimates of uncertainty. When trees are applied to many inputs and combined with the currently used PSHA methods, results may be perceived as less than a clear development of risk. Dr. Cornell recognized this problem as non-trivial by recommending research into methods to make the use of trees more transparent. Clearly, what is research now, may become *de rigueur* by the time a high level waste repository goes to hearing. The draft Analysis STP should address the need for managing information in some formalized way which will permit hearing board and public scrutiny. Obviously, probabilistic methodologies are currently in a state of flux. Latitude in using the best available at the time of the hearing may have merit.

6.5 COOPERATION/COORDINATION/KEEPING UP WITH TECHNOLOGY AND EVENTS

One advisor stated that all the best consultants in probabilistic analysis were compromised by working for the DOE. This implies that there may be a deficiency in what is available to the regulatory side. This may or may not reflect a universal opinion but a more concerted and identified effort in this area by NRC/CNWRA should eventually improve the perception. The same advisor also laments the lack of cooperation between NRC and DOE and perhaps within NRC on probabilistic analysis issues. Again a more concerted effort to have appropriate DHLWM/CNWRA staff attend and at appropriate times participate in meetings where these problems are being discussed would help correct this problem. That these efforts must not be viewed as collusion between regulator and license applicant is acknowledged.

6.6 DATA

All advisors recognized that even more data is required for an effective probabilistic analysis than for a deterministic analysis. One advisor suggested that for the probabilistic analyses he had been involved with, data and accuracy were not always of paramount concern because participants believed that inaccuracies would be averaged out or another expert might provide a more correct answer. The draft Analysis STP should address the issue of adequate data including the problem of existing but not quality assured data. This has been a principal concern in the development of the draft Analysis STP. Perhaps presentation of this aspect in the draft Analysis STP should merit a separate section. Dr. Toksöz, in particular but others as well, were concerned that the large amount of NTS data acquired by DOE, DOD, USGS and contractors would not be used in the analysis of the site for security reasons or simply because the data is scattered and difficult to obtain and present. These data sources should be identified and requested in the draft Analysis STP. Consideration of the FD&SHA advisor's report may suggest revisions in data requirements of the draft Format and Content Regulatory Guide (Nuclear Regulatory Commission, 1991) which is referenced by the draft Analysis STP.

6.7 STABILITY OF THE TECTONIC REGIME

Several advisors commented that they thought that there was a good possibility that the tectonic regime could change significantly over a 10,000 year period. One cited the papers by Wallace which identified paleoseismic activity changes on about 1000 year intervals within the Basin and Range tectonic province. This suggests that data from the entire Basin and Range province may have to be investigated to ascertain the probability that seismicity at Yucca Mountain could change significantly in a 10,000 year period. Another advisor expressed concern over the effects observed after the Landers earthquake of 1992. He believes that stress fields should be known and analyzed to determine the consequences of major movements on large California faults on the likelihood of changes in seismicity in adjacent areas, e.g., Nevada. That these concerns exist could be acknowledged and a requirement to address them included in the draft Analysis STP.

6.8 UNCERTAINTIES

The advisors appeared to agree that uncertainties in models and interpretation of data could only be estimated by expert judgment. Because of the short period of seismic history compared to the performance period of an HLW repository, and the uncertainties associated with inferring fault movement and seismic history from age dating of geologic faults offsets, virtually all pertinent data is interpreted by experts to some degree. Dr. Cornell pointed out that both the geologic barrier and engineered barriers were challenged simultaneously by the earthquake hazard, and for that reason the effectiveness of this redundancy is reduced. In Nuclear Regulatory Commission (1983), this redundancy is stated to accommodate uncertainties (See Staff Response to Comment No. 441). Therefore, uncertainties must be reduced by other means, e.g., through research, the acquisition of additional data and the use of conservative design criteria.

6.9 COUNTERPOINT

The scope of the advisors' deliberations was broadened from an initial concern with PFD&SHA to include consideration of deterministic methods, as well. Several advisors are well known experts in probabilistic risk assessment. However, no well known advocate of deterministic methods for hazard analysis participated in the May 17-18 meeting. Consequently, negative advice concerning the deterministic methodology is to be expected. There are experienced hazard estimators who have published on this topic. Notable is Dr. Ellis Krinitzsky of the U.S. Army Corps of Engineers. He has published a two-part paper as a consequence of his Richard H. Jahns Distinguished Lecture in Engineering Geology (Krinitzsky, 1993a and 1993b). He presents several severe problems which have been observed with the use of probabilistic methods, as currently practiced, in Part 1. He outlines in some detail, the extensive complexities that accompany any real hazard assessment for a particular facility in Part 2. Although perhaps not so stated, including data probabilities and expert judgement uncertainties with every aspect of such an analysis is likely to render it opaque rather than transparent. These problems appear to be recognized by several of the advisors who recommend fault trees to track the many models, uncertainties etc. Fault tree analysis is a form of probabilistic risk analysis by itself. When combined with methods like that used by LLNL in the SEISM 1 PSHA code, the complexities of the analysis may seem to overwhelm the senses; hence the comment by one advisor: "It is like having purééd vegetable soup at a French restaurant. It tastes OK to everyone but no one can identify the ingredients."

There is also the very real matter of costs. Probabilistic analyses with expert elicitations are iterative and very expensive. Advocates of the method believe that the often several-orders-of-magnitude increased cost of the hazard analysis is more than offset by improved stability of design criteria after the analysis is made. This may be true for projects in the $1,000,000,000+ range, although no studies have been published to the author's knowledge. It may not be true for large but less costly projects. Krintizsky (1993a) discusses the cost of the LLNL regional PSHA study for the eastern U.S.:

> ". . . cost of the LLNL study from 1982 to 1989 was 1.2 million dollars. Allowing for inflation, the present cost would be at least two million dollars." "The LLNL expenditures are by no means ended. The Nuclear Regulatory Commission . . . SECY-92-122. . . an additional 2.3-2.8 million dollars will be allocated to resolve differences between the LLNL and EPRI studies."

Probabilistic methods are still undergoing rapid development and evolution. They have a limited track record in the hearing process. Deterministic methods have a long, but not illustrious, track record in the hearing process. It is possible that the deterministic method may be held partially responsible for the cessation of new nuclear power plant license applications in the U.S. during the past decade. However, it is also possible that the complexities of a license application, even at a deterministic level, are not fathomed by the public which then objects to the technology. It remains to be seen whether complex multivariate probability analyses will be the universal remedy that some of its supporters sincerely believe them to be. However, event and consequence probabilities are unquestionably useful information for making the ultimate expert judgement concerning the acceptability of major civil projects.

7 ABBREVIATIONS

ACNW	Advisory Committee on Nuclear Waste
ACRS	Advisory Committee on Reactor Safeguards
CNWRA	Center for Nuclear Waste Regulatory Analyses
CUS	central United States
DOD	Department of Defense
DOE	Department of Energy
DOI	Department of Interior
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
ESF	Exploratory Studies Facility
EUS	eastern United States
FD&SHA	Fault Displacement and Seismic Hazard Analysis
GPS	Global Positioning System
HLW	High Level Nuclear Waste
IA	Iterative Assessment
INEL	Idaho National Energy Laboratory
IPA	Iterative Performance Assessment
LLNL	Lawrence Livermore National Laboratory
MCE	Maximum Credible Earthquake
MCFD	Maximum Credible Fault Displacement
MDE	Maximum Design Earthquake
MLE	Maximum Likely Earthquake
MLFD	Maximum Likely Fault Displacement
MLM	Maximum Likely Magnitude
MPFD	Maximum Possible Fault Displacement
MPM	Maximum Possible Magnitude
NRC	Nuclear Regulatory Commission
NRR	NRC Office of Nuclear Reactor Regulation
NTS	Nevada Test Site
PA	Performance Assessment
PFD	Probabilistic Fault Displacement
SD	Standard Deviation
SHA	Seismic Hazard Analysis
SSE	Safe Shut Down Earthquake
STP	Staff Technical Position
USDOE	United States Department of Energy
USNRC	United States Nuclear Regulatory Commission
WUS	western United States

8 REFERENCES

Note this reference list includes citations both from the body of the report and from experts' reports in Appendix C.

Anagnos, T., and A.S. Kiremidjian. 1984. Stochastic time-predictable model for earthquake occurrences. *Bulletin of the Seismological Society of America (BSSA)* 74: 2593-26511.

Bernreuter, D.L, J.B. Savy, R.W. Mensing, and J.C. Chen. 1989. *Seismic Hazard Characterization of 69 Nuclear Power Plant Sites East of the Rocky Mountains.* NUREG/CR-5250. Washington D.C. U.S. Nuclear Regulatory Commission.

Bonano, E.J., S.C. Hora, R.L. Kenney, and D. von Winterfeldt. 1990. *Elicitation and Use of Expert Judgement in Performance Assessment for High-Level Radioactive Waste Repositories.* Albuquerque, NM: Sandia National Laboratories. SAND89-1821. NUREG/CR-5411.

Crouch, J. 1987. *Testimony on Diablo Canyon Rate Case,* Application 84-06-014, 85-08-025, Exhibit No. 11,345. San Francisco, CA. California Public Utilities Commission

DeWispelare, A.R., L.T. Herren, M.P. Miklas, and R.T. Cleman. 1993. *Expert Elicitation of Future Climate in the Yucca Mountain Vicinity.* CNWRA Report 93-016. San Antonio, Texas. Center for Nuclear Waste Regulatory Analyses.

Electric Power Research Institute (EPRI). 1989. Seismic Hazard Methodology for the Central and Center United States. EPRI NP-4726. Palo Alto, California.

Hofmann, R.B. 1991. *Probabilistic Fault Displacement and Seismic Hazard Analysis Literature Assessment.* CNWRA 91-013. revision 1 (February 1993) report to the U.S. Nuclear Regulatory Commission. San Antonio, Texas. Center for Nuclear Waste Regulatory Analyses.

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

Krinitzsky, E.L. 1993a. Earthquake probability in engineering - Part 1: Thee use and misuse of expert of expert opinion. The Third Richard H. Jahns Distinguished Lecture in Engineering Geology. *Engineering Geology* 33: 257-288.

Krinitzsky, E.L. 1993b. Earthquake probability in engineering - Part 2: Earthquake recurrence and limitations of Gutenberg-Richter b-values for the engineering of critical structures. The Third Richard H. Jahns Distinguished Lecture in Engineering Geology. *Engineering Geology* (in press).

Lawrence Livermore National Laboratory. 1989. *Seismic Hazard Characterization of 69 Nuclear Plant Sites East of the Rocky Mountains.* NUREG/CR5250: UCID-21517. Livermore, California.

McCann, M.W. Jr., R.K. McGuire, D. Veneziano, J. Van Dyck, G. Toro, R. Kulkarni, and C.A. Cornell. *Seismic Hazard Methodology for the Central and Eastern United States*. EPRI Report NP-4726-A, V1, Pt1. Palo Alto, CA. Electric Power Research Institute.

McConnell, K.I., M.E. Blackford, and A-K. Ibrahim. 1992. *Staff Technical Position on Investigations to Identify Fault Displacement Hazards and Seismic Hazards at a Geologic Repository*. NUREG-1451. Washington D.C. U.S. Nuclear Regulatory Commission.

McConnell, K.I.. and M.P. Lee. 1993. *Staff Technical Position on Consideration of Fault Displacement Hazards in Geologic Repository Design*. NUREG xxxx (in press). Washington D.C. U.S. Nuclear Regulatory Commission.

National Research Council. 1992. *Groundwater at Yucca Mountain, How High Can It Rise*. 231 pages. Washington DC. National Academy Press.

Nuclear Regulatory Commission. 1983a. *Staff Analysis of Public Comments on Proposed Rule 10 CFR Part 60*. NUREG 0804.

Nuclear Regulatory Commission. 1992. *Resolution of Differences Between Probabilistic Seismic Hazard Methodologies for the Eastern United States*. SECY-92-122. Washington D.C.: NRC

Nur, A.M., G.C. Beroza, and H. Ron. 1993. Nature of the Landers-Mojave earthquake line. *Science*, May 18th.

Pacific Gas and Electric Co. 1988. *Final Report of the Diablo Canyon Long Term Seismic Program*. Report to the U.S. Nuclear Regulatory Commission, Docket Numbers 50-275 and 50-233. San Francisco, CA. Pacific Gas and Electric Company.

Parsons, T., and G.A. Thompson. 1991. The role of magma overpressure in suppressing earthquakes and topography: worldwide examples. *Science* 253: 1399-1402.

Taylor, S.R., H.J. Porter and P.G. Richards. 1991. *Explosion Source Phenomenology*. AGU Monograph. Washington DC., American Geophysical Union.

Toksöz, M.N., and Kehrer. Tectonic strain release by underground nuclear explosions. *Geophysical Journal of the Royal Astronomical Society* 31:141-161.

U.S. Nuclear Regulatory Commission. 1993. *Staff Technical Position on Analyses of Fault Displacement Hazards and Seismic Hazards as They Relate to Design of a Geologic Repository, Internal Draft, February 1993*. Unpublished manuscript. Washington DC. U.S. Nuclear Regulatory Commission.

Wallace, R.E. 1985. *Variation in slip rates, migration and grouping of slip events on faults in the Great Basin Province*. Proceedings of Workshop XXVIII on the Borah Peak, Idaho Earthquake. R.S. Stein and R.A. Bucknam, eds. USGS OFR 85-290. Washington DC: Department of the Interior.

Wallace, R.E. 1987. Grouping and migration of surface faulting and variation in slip rates on faults in the Great Basin Province. *BSSA* 77: 301-314

APPENDIX A

May 17-18 1992 LIST OF ADVISORS, PREMEETING MATERIAL AND MEETING AGENDA

LIST OF ADVISORS

Advisors who participated in the Expert Group at the May 17-18 1992 FD&SHA Meeting at the Center for Nuclear Waste Regulatory Analyses (CNWRA) in San Antonio, Texas, are:

Professor C. Allin Cornell
P.O. Box 9260
Stanford, CA 94305
(415) 854-8053
(415) 854-8075 FAX

Professor Anne S. Kiremidjian
Co-Director, The John A. Blume
Earthquake Engineering Center
Civil Engineering Dept.
Stanford, University
Stanford, CA 94305-4020
(415) 723-4164
(415) 725-8662 FAX

Dr. Martin W. McCann Jr., President
Jack R. Benjamin & Associates, Inc.
Mountain Bay Plaza
444 Castro Street, Suite 501
Mountain View, CA 94041
(415) 969-8212
(415) 969-6671 FAX

Professor George A. Thompson
Geophysics Department
Stanford University
Stanford, CA 94305
(415) 723-3714
(415) 725-7344 FAX

Professor M. Nafi Toksöz
Director, Earth Resources Lab.
Mass. Inst. of Technology
42 Carleton Street
Cambridge, MA 02142
(617) 253-7852
(617) 253-6385 FAX

LIST OF PREMEETING MATERIAL PROVIDED TO THE ADVISORS

Bernero, R. 1992. Regulatory views on seismic and fault-displacement parameters needed for a geologic repository design. *Proceedings of the American Society of Civil Engineers (ASCE) Symposium on Dynamic Analysis and Design Considerations for Geologic Repositories, August 19-20, San Francisco, CA.*

Hofmann, R.B. 1991. *Probabilistic Fault Displacement and Seismic Hazard analysis Literature Assessment*. CNWRA Report 91-013 (rev. 1) to the U.S. Nuclear Regulatory Commission (NRC). San Antonio, Texas. Center for Nuclear Waste Regulatory Analyses, Southwest Research Institute.

McConnell, K.I., M.E. Blackford, and A-K Ibrahim. 1992. *Staff Technical Position on Investigations to Identify Fault Displacement Hazards and Seismic Hazards at a Geologic Repository*. NUREG-1451. Washington DC. U.S. Nuclear Regulatory Commission.

U.S. Nuclear Regulatory Commission. 1993. Staff Technical Position on Analyses of Fault Displacement Hazards and Seismic Hazards as They Relate to Design of a Geologic Repository - Internal Draft. U.S. Nuclear Regulatory Commission. Washington DC.

U.S. Nuclear Regulatory Commission. 1992. *Disposal of High-Level Radioactive Wastes in a Geologic Repository*. Code of Federal Regulations, Title 10, Part 60. Washington D.C. U.S. Government Printing Office.

MEETING OF CNWRA ADVISORS ON FAULT DISPLACEMENT HAZARDS AND SEISMIC HAZARDS ANALYSIS
AGENDA
May 17, 1993

9:00 – 9:15	Welcome to Center	Mackin
9:15 – 9:30	Introduction	McKague
9:30 – 9:45	Objectives and Overview of the STP Series	Ballard
9:45 – 10:15	Instructions to Chairman/Committee Caucus	McKague
10:15 – 10:30	BREAK	
	TOPICS OF DISCUSSION	
10:30 – 11:00	A. Outline of Investigations STP	McConnell
11:00 – 11:15	B. Outline of Avoidance STP	McConnell
11:15 – 12:00	C. Discussion of Analysis STP 1. Introduction to Analysis STP a. Objective b. Need c. Scope	McConnell
12:00 – 1:30	LUNCH BREAK	
1:30 – 2:30	2. Development of Fault Displacement Hazard Estimates a. Draft Positions b. Issues for Consideration – Deterministic and Probabalistic Approaches – Parameters Needed for the Analysis – Uncertainty in the Parameters – Output Required for Repository Design	Stirewalt
2:30 – 3:30	3. Development of Ground Motion Hazard Estimates a. Draft Position b. Issues for Consideration – Deterministic and Probabalistic Approaches – Parameters Needed for the Analysis – Uncertainty in the Parameters – Output Required for Repository Design	Ibrahim

MEETING OF CNWRA ADVISORS ON FAULT DISPLACEMENT HAZARDS AND SEISMIC HAZARDS ANALYSIS
AGENDA
May 17, 1993 (Cont'd)

3:30 — 4:30	D. Other Topics for Discussion 1. Use of Mean, Median, 95% 2. Sensitivity of Input Parameters 3. Data Extrapolation (Attenuation & Recurrence Relations) 4. Probability Distribution Functions 5. Expert Judgement and Its Implication For 10,000 Years	Hofmann
4:30 — 5:00	Questions/Clarifications	McKague

May 18, 1993

RECOMMENDATIONS FROM GROUP MEMBERS

9:00 — 10:00	Committee Discussions	Chairman
10:00 — 10:15	BREAK	
10:15 — ?	Initial Recommendations From Individual Expert Members (Lunch Break When Appropriate)	

(K\HLM\8)

APPENDIX B

MEETING PRESENTATIONS

PRESENTATION TO THE CNWRA ADVISORS ON FAULT DISPLACEMENT HAZARDS AND SEISMIC HAZARDS
May 17, 1993

Ronald L. Ballard, Branch Chief
Geology and Engineering Branch
Division of High-Level Waste Management

OBJECTIVES AND OVERVIEW OF STP SERIES

OBJECTIVES OF DHLWM GUIDANCE

PROVIDE ACCEPTABLE APPROACHES TO MEET REGULATORY REQUIREMENTS TO HELP ENSURE DOE'S PROGRAM WILL:

- IDENTIFY AND ADDRESS LICENSING ISSUES EARLY
- PROVIDE APPROPRIATE INPUT TO ASSESSMENTS
- PROVIDE BASELINE DATA
- DEVELOP COMPLETE LICENSE APPLICATION

STAFF GUIDANCE ON TECTONICS

- Investigations to Identify Fault Displacement Hazards and Seismic Hazards at a Geologic Repository ["Investigations" STP] (NUREG 1451)
- Consideration of Fault Displacement Hazards in Geologic Repository Design ["Avoidance" STP] (Submitted for Public Comment March 1993)
- Analysis of Fault Displacement Hazards and Seismic Hazards as they relate to Design of a Geologic Repository ["Analysis Methods" STP]
- Use of Tectonic Models
- Application of Fault Displacement Hazards and Seismic Hazards to Design ["Design" STP] (FY98)

APPLICABLE REGULATORY REQUIREMENTS

- 60.21(c)(1)(ii) requires a description and assessment of the site
- 60.122 requires the analyses to be adequate to assess the potentially adverse conditions related to fault displacement and seismicity
- 60.111 - Performance of the GROA
- 60.131(b)(1) requires structures... be designed so that natural phenomena...expected at the GROA will not interfere with necessary safety functions
- 60.112 - Overall system performance after closure
- 60.113 - Performance of particular barriers
- 60.133(h) requires the EBS be designed to assist the geologic setting in meeting the performance objectives

INPUT DESIRED ON TECTONICS GUIDANCE

- Provide council on proven approaches to address development of design bases for a geologic repository recognizing the unique features of the repository;
- Review and comment on strawman positions taken in the STP with respect to design basis for fault displacement hazards and seismic hazards;
  - Deterministic vs. Probabilistic methods
  - Use of expert judgment in determining the hazard
  - Comment on what level of conservatism in design for FDH and SH is sufficient to protect public health and safety.

PRESENTATION TO THE CNWRA ADVISORS ON FAULT DISPLACEMENT HAZARDS AND SEISMIC HAZARDS

MAY 17, 1993

Keith I. McConnell, Section Leader
Geology/Geophysics Section
Division of High-Level Waste Management

STAFF TECHNICAL POSITION ON INVESTIGATIONS TO IDENTIFY FAULT DISPLACEMENT HAZARDS AND SEISMIC HAZARDS AT A GEOLOGIC REPOSITORY

NEED FOR THE "INVESTIGATIONS" STP

- Staff site characterization analysis identified significant concerns with DOE's plans to investigate fault displacement hazards and seismic hazards (i.e., the ability to fulfill Part 60 requirements)
- Site characterization has begun at Yucca Mountain
- While the staff has no objection to DOE starting site characterization, staff concerns have not been resolved

CHRONOLOGY OF DEVELOPMENT

PUBLIC COMMENT DRAFT TP ISSUED	AUGUST 1989 (54 FR 35266)
DOE/NRC TECHNICAL EXCHANGE ON DRAFT TP ON METHODS OF EVALUATING SEISMIC HAZARD AT A GEOLOGIC REPOSITORY	DECEMBER 1989
DOE/NRC TECHNICAL EXCHANGE ON TECTONICALLY SIGNIFICANT FAULT	JUNE 1990
DOE/NRC TECHNICAL EXCHANGE ON STP	FEBRUARY 20, 1991
PUBLIC COMMENT DRAFT OF STP ISSUED	MAY 13, 1991 (56 FR 22020)
ACNW WORKING GROUP/FULL COMMITTEE MEETINGS ON FINAL DRAFT STP	DECEMBER 17-18, 1991
FINAL STP ISSUED	JULY 1992

PURPOSE AND OBJECTIVE OF "INVESTIGATIONS" STP

- PROVIDE AN ACCEPTABLE APPROACH TO THE COLLECTION OF SUFFICIENT DATA RELATED TO FAULT DISPLACEMENT HAZARD AND SEISMIC HAZARDS FOR INPUT TO BOTH PRECLOSURE AND POSTCLOSURE ASSESSMENTS OF DESIGN AND PERFORMANCE
  - Describe an acceptable approach to meet 10 CFR Part 60 requirements for investigation of fault displacement hazards and seismic hazards
  - Provide a path to resolution of SCA concerns with respect to fault displacement hazards and seismic hazards.

APPROACH ADOPTED IN THIS STAFF POSITION

- Benefits from past regulatory experience in using explicit criteria for identifying fault hazards (Does not adopt, in any form, Appendix A, 10 CFR Part 100)
- Uses deterministic criteria to determine which faults require detailed investigation, but recognizes the utility of probabilistic techniques for faults outside the controlled area
- Recognizes the need to perform iterative assessments of performance and that additional investigations to those noted in the STP may be identified by these assessments.

KEY PROVISIONS

- Identifies the entire Quaternary as the period of geologic time that should be considered (For the purposes of 10 CFR 60 the Quaternary = past 2 m.y.)
- Provides a methodology and criteria for identifying and investigating those faults that are of potential concern to the repository
- Specifies that faults or fault zones previously removed from further consideration may need to be reconsidered based on the results of site characterization
- Considers that it is better to err on the side of investigating some faults or fault zones which may be found to be of no concern to repository performance rather than risk overlooking a fault or fault zone that may be significant

FAULT TYPES DESCRIBED IN STAFF POSITION

- The process identified in the staff position describes three categories of faults:
  Type III Faults: Faults that do not need to be investigated in detail
  Type II Faults: Faults that are candidates for detailed investigation
  Type I Faults: Faults that should be investigated in detail

TYPE III FAULTS

- Type III Faults: Faults that do not need to be investigated in detail

---

1) Faults that are not subject to displacement; or
2) are located such that, or of a size (length) such that, they will not affect repository performance or will not provide significant input into models that will be used to assess repository performance

TYPE II FAULTS

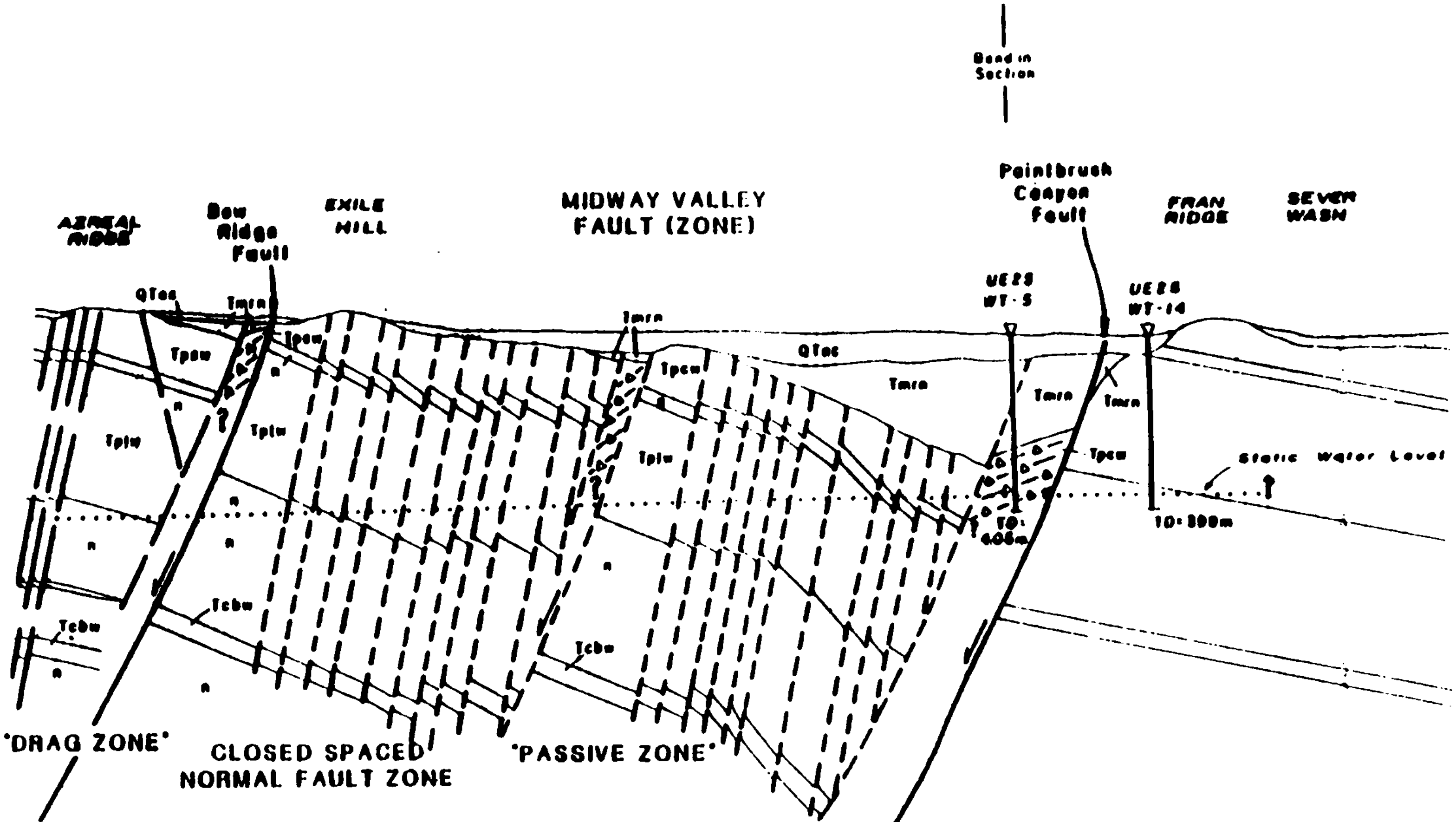
- Type II Faults: Faults that are candidates for detailed investigation

---

Faults inside the controlled area and those faults outside the controlled area that are determined to be located such that, and are of sufficient size (length) such that, they may potentially have an effect on repository performance or will provide significant input into models used to assess repository performance

CRITERIA DEFINING FAULT TYPE 1

- A Type 1 fault:
  1) is subject to displacement; and
  2) may affect the design or performance of structures, systems, and components important to safety, containment, or waste isolation; and/or
  3) may provide significant input to models used in assessments of design or performance of structures, systems, and components important to safety, containment, or waste isolation



QTac QUATERNARY/TERTIARY ALLUVIUM AND COLLUVIUM

Tmrn RAINIER MESA MEMBER OF TIMBER MOUNTAIN TUFF, NONWELDED

Tpcw TIVA CANYON MEMBER OF PAINTBRUSH TUFF, WELDED

n NONWELDED TUFF

Tptw TOPOPAH SPRING MEMBER OF PAINTBRUSH TUFF, WELDED

Tcbw BULLFROG MEMBER OF CRATER FLAT TUFF, WELDED

TD TOTAL DEPTH

3000 FT

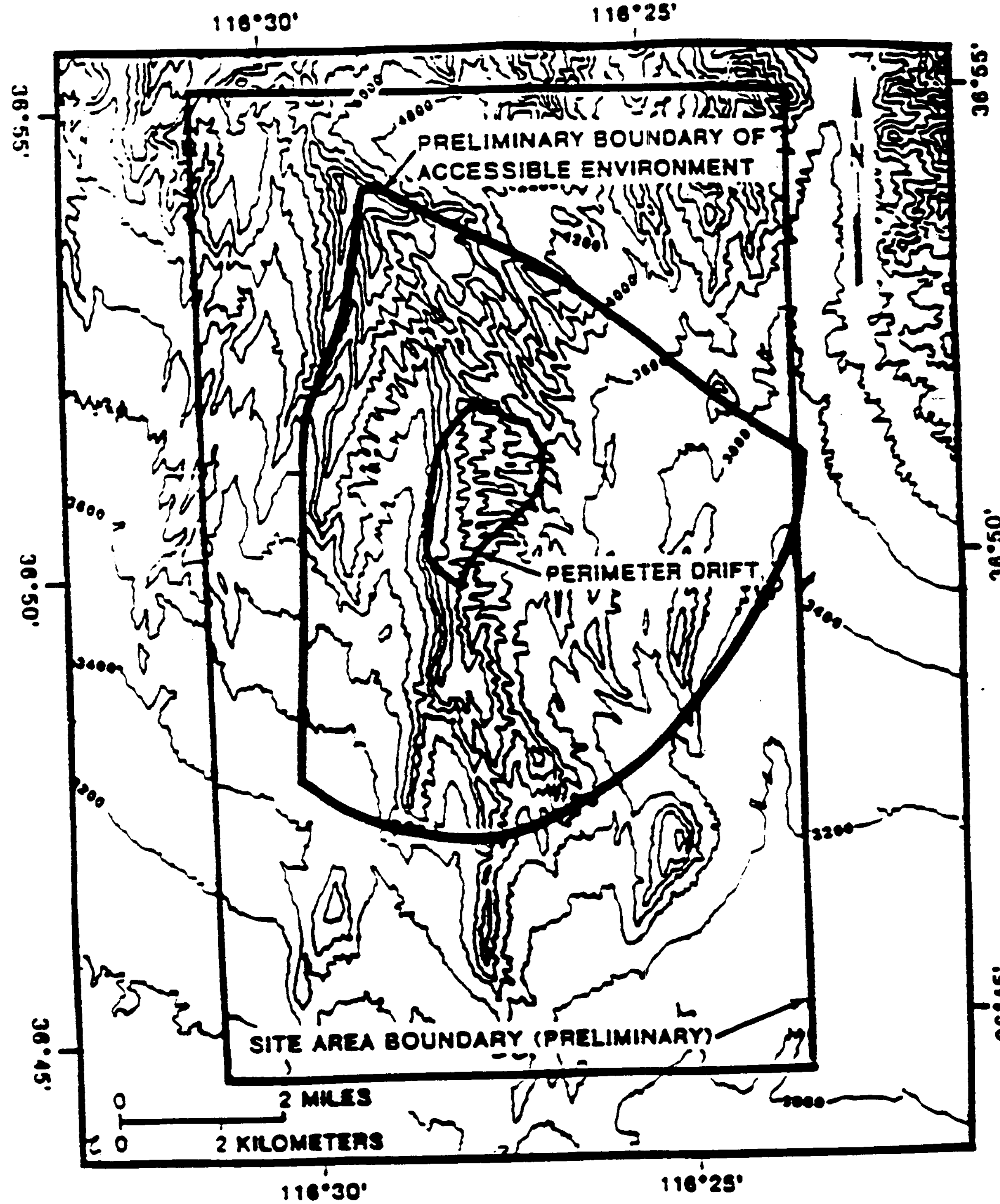
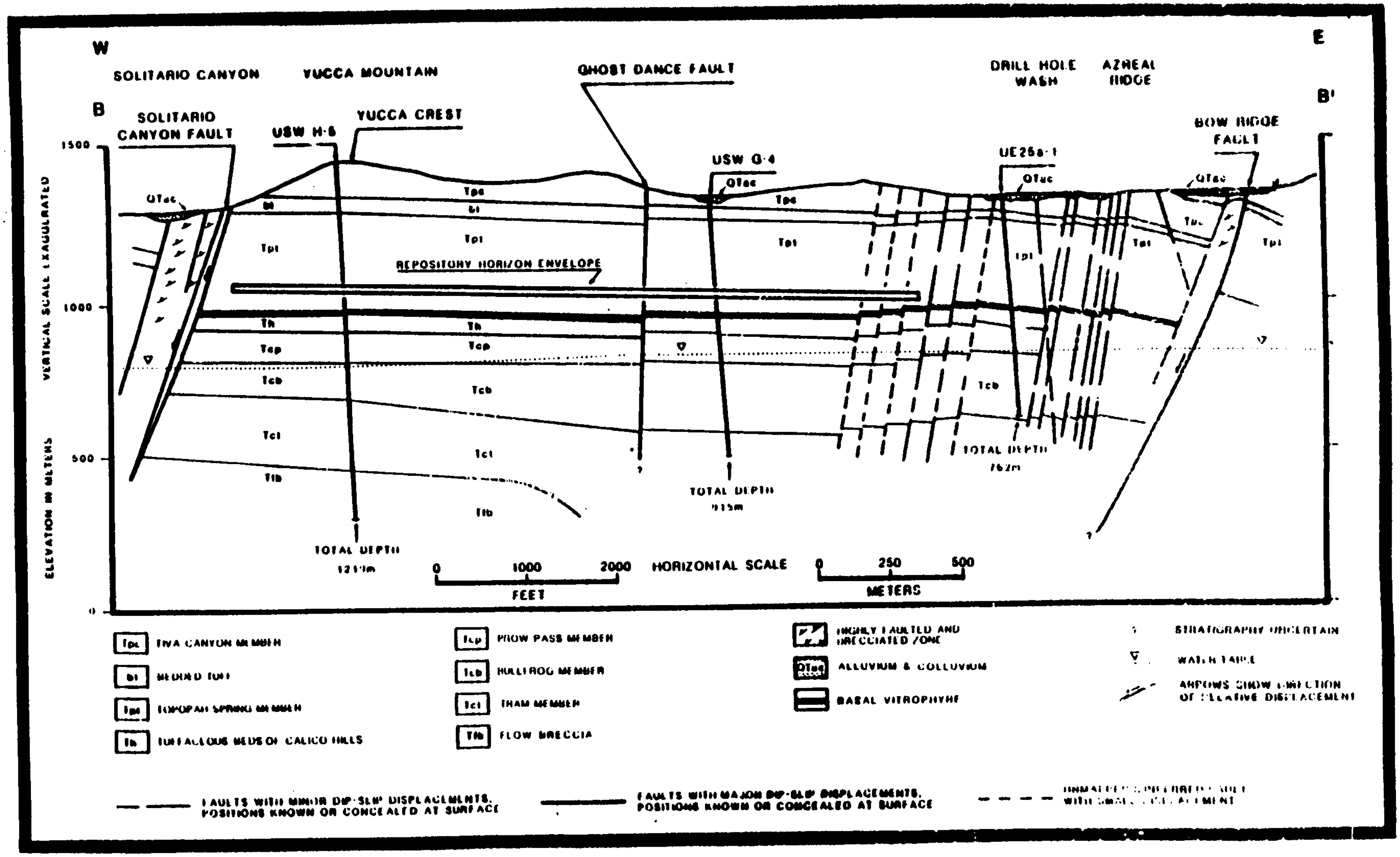


Figure 1-1. Areas of geologic investigation at Yucca Mountain.



W
E
SOLITARIO CANYON
YUCCA MOUNTAIN
GHOST DANCE FAULT
DRILL HOLE WASH
AZREAL RIDGE
B
B'
SOLITARIO CANYON FAULT
USW H-5
YUCCA CREST
USW G-4
UE25a-1
BOW RIDGE FAULT
QTac
Tpc
bt
Tpt
Th
Tcp
Tcb
Tct
Tfb
REPOSITORY HORIZON ENVELOPE
TOTAL DEPTH 1219m
TOTAL DEPTH 915m
TOTAL DEPTH 762m
1500
1000
500
0
VERTICAL SCALE EXAGGERATED
ELEVATION IN METERS
0 1000 2000
FEET
HORIZONTAL SCALE
0 250 500
METERS
TIVA CANYON MEMBER
BEDDED TUFF
TOPOPAH SPRING MEMBER
TUFFACEOUS BEDS OF CALICO HILLS
PROW PASS MEMBER
BULLFROG MEMBER
TRAM MEMBER
FLOW BRECCIA
HIGHLY FAULTED AND BRECCIATED ZONE
ALLUVIUM & COLLUVIUM
BASAL VITROPHYRE
STRATIGRAPHY UNCERTAIN
WATER TABLE
ARROWS SHOW DIRECTION OF RELATIVE DISPLACEMENT
FAULTS WITH MINOR DIP-SLIP DISPLACEMENTS, POSITIONS KNOWN OR CONCEALED AT SURFACE
FAULTS WITH MAJOR DIP-SLIP DISPLACEMENTS, POSITIONS KNOWN OR CONCEALED AT SURFACE

PRESENTATION TO THE CNWRA ADVISORS ON FAULT DISPLACEMENT HAZARDS SEISMIC HAZARDS
May 17, 1993

Keith I. McConnell, Section Leader
Geology/Geophysics Section
Division of High-Level Waste Management

DRAFT STAFF TECHNICAL POSITION ON CONSIDERATION OF FAULT DISPLACEMENT HAZARDS IN GEOLOGIC REPOSITORY DESIGN ["Avoidance" STP]

NEED FOR THE "AVOIDANCE" STP

- To Clarify Staff's Position on the Presence of Faults Within the Controlled Area.
- Development of Position was at the Request of the Advisory Committee on Nuclear Waste.

PURPOSE AND OBJECTIVES OF "AVOIDANCE" STP

OBJECTIVES:

- TO PROVIDE AN ACCEPTABLE APPROACH TO THE CONSIDERATION OF FAULT DISPLACEMENT HAZARD IN REPOSITORY DESIGN.
- TO IDENTIFY REGULATORY REQUIREMENTS THAT APPLY TO THE CONSIDERATION OF POTENTIALLY ADVERSE CONDITIONS (I.E., STRUCTURAL DEFORMATION) IN REPOSITORY DESIGN

SCOPE:

- STAFF TECHNICAL POSITION IS NARROWLY FOCUSED ON DESIGN CONSIDERATIONS AND DOES NOT SPECIFICALLY ADDRESS THE TREATMENT OF FAULT DISPLACEMENT HAZARDS IN REPOSITORY PERFORMANCE

CONSIDERATION OF FAULT DISPLACEMENT HAZARDS IN DESIGN

- Position 1:
  "The presence of 'Type I' faults...inside the controlled area of a geologic repository, does not, by itself, represent a 'disqualifying' feature of the candidate site for a geologic repository."

CONSIDERATION OF FAULT DISPLACEMENT HAZARDS IN DESIGN

- Position 2:
  When establishing specific locations for critical facilities, "...'Type I' faults should be avoided, where this can reasonably be achieved..."

CONSIDERATION OF FAULT DISPLACEMENT HAZARDS IN DESIGN

- Position 2a:
  If DOE chooses to locate critical facilities on or in the immediate vicinity of Type I faults, they "... should appreciate that reliance on engineering may be of limited value."

CONSIDERATION OF FAULT DISPLACEMENT HAZARDS IN DESIGN

- Position 2b:
  DOE must be able to demonstrate, with reasonable assurance, that any proposed repository facility designed to accommodate the effects of faulting meets 10 CFR Part 60 design criteria, and pre- and postclosure performance objectives.

TYPE III FAULTS

- Type III Faults: Faults that do not need to be investigated in detail

---

1) Faults that are not subject to displacement; or
2) are located such that, or of a size (length) such that, they will not affect repository performance or will not provide significant input into models that will be used to assess repository performance

TYPE II FAULTS

- Type II Faults: Faults that are candidates for detailed investigation

---

Faults inside the controlled area and those faults outside the controlled area that are determined to be located such that, and are of sufficient size (length) such that, they may potentially have an effect on repository performance or will provide significant input into models used to assess repository performance

CRITERIA DEFINING FAULT TYPE 1

- A Type 1 fault:
  1) is subject to displacement; and
  2) may affect the design or performance of structures, systems, and components important to safety, containment, or waste isolation; and/or
  3) may provide significant input to models used in assessments of design or performance of structures, systems, and components important to safety, containment, or waste isolation

PRESENTATION TO THE CNWRA ADVISORS ON
FAULT DISPLACEMENT AND SEISMIC HAZARDS

MAY 17, 1993

Keith I. McConnell, Section Leader
Geology/Geophysics Section
Division of High-Level Waste Management

DRAFT STAFF TECHNICAL POSITION ON ANALYSES OF FAULT DISPLACEMENT HAZARDS AND SEISMIC HAZARDS AS THEY RELATE TO DESIGN OF A GEOLOGIC REPOSITORY ["ANALYSIS"]

ADVISORS 06/17/93

NEED FOR THE "ANALYSIS" STP

- 10CFR60 is non-specific in what is required in the development of design bases for fault displacement hazards and seismic hazards
- Staff site characterization analysis comments identified significant concerns with DOE's plans to address fault displacement hazards and seismic hazards in repository design
- DOE design activities have begun

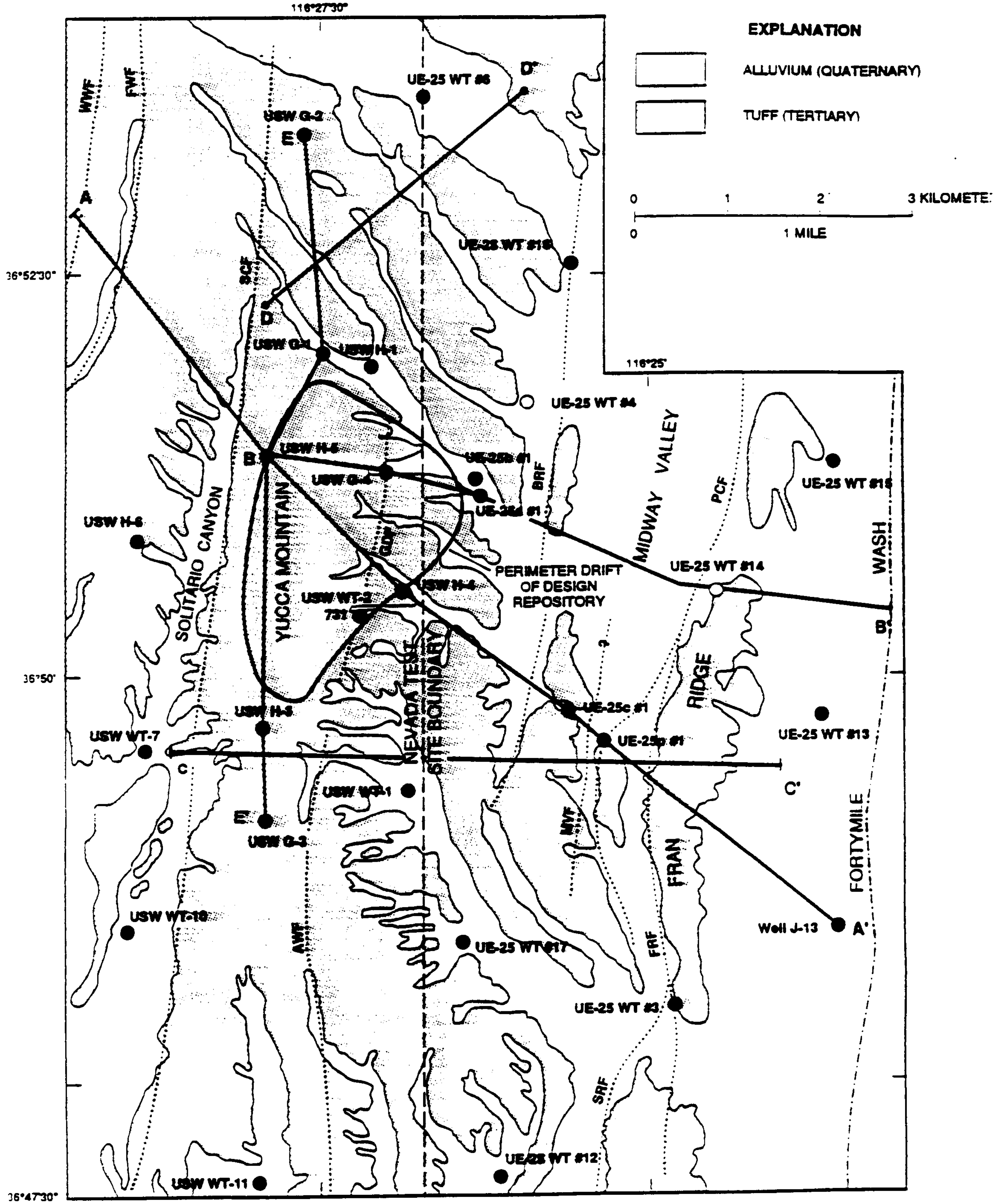
PURPOSE AND OBJECTIVES OF THE "ANALYSIS METHODS" STP

OBJECTIVES:

- TO PROVIDE AN ACCEPTABLE APPROACH TO THE ANALYSIS OF FAULT DISPLACEMENT HAZARDS AND SEISMIC HAZARDS FOR REPOSITORY DESIGN BASIS
- IDENTIFY REGULATORY REQUIREMENTS THAT APPLY TO THE ANALYSIS OF FAULT DISPLACEMENT HAZARDS AND SEISMIC HAZARDS IN RELATION TO REPOSITORY DESIGN

SCOPE:

- POSITION IS FOCUSED ON DESIGN CONSIDER-ATIONS AND DOES NOT ADDRESS OVERALL REPOSITORY PERFORMANCE


116°27'30"
EXPLANATION
ALLUVIUM (QUATERNARY)
TUFF (TERTIARY)
0
1
2
3 KILOMETE
0
1 MILE
116°25'
36°52'30"
36°50'
36°47'30"
WWF
FWF
SCF
A
A'
B
B'
C
C'
D
D'
E
E'
UE-25 WT #6
USW G-2
UE-25 WT #18
USW G-1
USW H-1
UE-25 WT #4
USW H-5
USW G-4
UE-25a #1
BRF
MIDWAY VALLEY
PCF
UE-25 WT #15
USW H-6
SOLITARIO CANYON
YUCCA MOUNTAIN
GDF
PERIMETER DRIFT
OF DESIGN
REPOSITORY
UE-25 WT #14
WASH
USW H-4
USW WT-2
731
NEVADA TEST SITE BOUNDARY
RIDGE
UE-25c #1
UE-25p #1
UE-25 WT #13
USW H-3
USW WT-7
USW WT-1
USW G-3
MWF
FRAN
FORTYMILE
USW WT-10
AWF
Well J-13
UE-25 WT #17
FRF
UE-25 WT #3
SRF
UE-25 WT #12
USW WT-11

PRESENTATION TO CNWRA ADVISORS ON FAULT DISPLACEMENT HAZARDS AND SEISMIC HAZARDS

May 17, 1993

Gerry L. Stirewalt, Principal Geoscientist
Center for Nuclear Waste Regulatory Analyses

DRAFT STAFF TECHNICAL POSITION ON ANALYSIS OF FAULT DISPLACEMENT HAZARDS AND SEISMIC HAZARDS AS THEY RELATE TO DESIGN OF A GEOLOGIC REPOSITORY

DEVELOPMENT OF FAULT DISPLACEMENT HAZARDS ESTIMATES

POSITION STATEMENTS FROM DRAFT STP — FAULT DISPLACEMENT HAZARDS

POSITION 1a (SUBSECTION 3.1.1)

- Deterministic Methods Primarily Used to Establish Design Basis for Fault Displacement Hazards
- Probabilistic Methods Used to Supplement Deterministic Methods in Assessment of Fault Displacement Hazards

POSITION 1b (SUBSECTION 3.1.1)

- Credible Alternative Fault Displacement (Tectonic) Models Used in Analysis of Fault Displacement Hazards

POSITION 1c (SUBSECTION 3.1.1.1)

- Maximum Credible Fault Displacement (MCFD) Along Type I Faults Provides Design Basis

POSITION STATEMENTS FROM DRAFT STP — FAULT DISPLACEMENT HAZARDS (Continued)

POSITION 2 (SUBSECTION 3.2)

- Elements of an Acceptable Analysis Include Consideration of:
  - Subsurface fault geometry, fault segmentation, distributive faulting, structural coupling between faults, association of faulting and volcanism for alternative tectonic models
  - Geometry and rates of regional strain
  - Temporal and spatial clustering of fault displacements
  - Quaternary slip rates, slip amounts, slip directions, recurrence intervals for faulting
  - MCFD for discrete slip events and cumulatively through Quaternary Period
  - Maximum Likely Fault Displacement (MLFD) with consideration of type of slip
  - Type I faults present but not detected
  - Regional and local stress fields, including in-situ stress and possible effects on in-situ stress from emplaced waste
  - Effects of MCFD on site hydrology

POSITION STATEMENTS FROM DRAFT STP — FAULT DISPLACEMENT HAZARDS (Continued)

POSITION 3 (SUBSECTION 3.4)

- Technical Uncertainties Exist in Data and Models
- Uncertainties Must Be Identified and Taken into Account in Analysis of Fault Displacement Hazards

ISSUES FOR CONSIDERATION — FAULT DISPLACEMENT HAZARDS

DETERMINISTIC versus PROBABILISTIC APPROACH (POSITION 1a)

- Tectonic Processes and Events Have the Potential to Disrupt Repository
- Complete Understanding of Tectonic Processes and Events Unlikely
- Difficult to Determine Contribution to Geologic Risk from Fault Displacement
- Deterministic Approaches Used in the Past in Design of Nuclear Facilities and Judged to Be Suitably Conservative

QUESTIONS ON ISSUES — FAULT DISPLACEMENT HAZARDS

DETERMINISTIC versus PROBABILISTIC APPROACH (POSITION 1a)

[1] • What is Understood by Application of "Primarily a Deterministic Approach" for Fault Displacement Hazards Analysis?

[2] • Is Deterministic Approach Both Reasonable and Possible?

[3] • Is Deterministic Approach Overly Conservative?

[4] • Should Uncertainties in Data and Models Be Treated Through Use of Supplementary Probabilistic Approach?

[5] • Can Probabilistic Assessments Be Done Without Formal Expert Judgment Elicitation?

ISSUES FOR CONSIDERATION — FAULT DISPLACEMENT HAZARDS (Continued)

ALTERNATIVE TECTONIC MODELS (POSITION 1b)

- Precise Tectonic Models and Simulations of Processes Related to Fault Displacement Generally Not Attainable

- Assessment of Alternative Tectonic Models Important for Understanding Tectonic Processes and Events and Selecting Credible Alternative Models for Use in Fault Displacement Hazard Analysis

QUESTIONS ON ISSUES — FAULT DISPLACEMENT HAZARDS

ALTERNATIVE TECTONIC MODELS (POSITION 1b)

[6] • Are Alternative Tectonic Models Essential Because of Complexities of Tectonic Setting at Yucca Mountain and Consequent Uncertainties in Characterization of Tectonic Hazards?

[7] • Is It Necessary to Identify All Possible Alternative Models, or Only "Bounding" Models?

ISSUES FOR CONSIDERATION — FAULT DISPLACEMENT HAZARDS (Continued)

ELEMENTS OF AN ACCEPTABLE ANALYSIS (POSITION 2)

- Fault Avoidance Thought Not Highly Likely at Yucca Mountain. Therefore, Consideration of Following Elements Are Part of the Analysis:

  - Subsurface fault geometry, fault segmentation, distributive faulting, structural coupling between faults, association of faulting and volcanism for alternative tectonic models

  - Geometry and rates of regional strain

  - Temporal and spatial clustering of fault displacements

  - Quaternary slip rates, slip amounts, slip directions, recurrence intervals for faulting

ISSUES FOR CONSIDERATION — FAULT DISPLACEMENT HAZARDS (Continued)

  - MCFD for discrete slip events and cumulatively through Quaternary Period

  - MLFD with consideration of type of slip

  - Type I faults present but not detected

  - Regional and local stress fields, including in-situ stress and possible effects on in-situ stress from emplaced waste

  - Effects of MCFD on site hydrology

QUESTIONS ON ISSUES — FAULT DISPLACEMENT HAZARDS

ELEMENTS OF AN ACCEPTABLE ANALYSIS (POSITION 2)

[8] • Are These Elements Necessary and Sufficient to Provide "Reasonable Assurance" Relative to Fault Displacement Hazards?

[9] • Should This List Be Modified by Inclusion of New Elements Or Exclusion of Existing Elements?

[10] • What Concerns Exist Related to Accuracy of Required Information (e.g., Subsurface Fault Geometry, Age of Faulting, Determination of Slip Amount) and Data Uncertainties?

ISSUES FOR CONSIDERATION — FAULT DISPLACEMENT HAZARDS (Continued)

ASSESSMENT OF TECHNICAL UNCERTAINTY (POSITION 3)

- Uncertainties Exist in Data and Models
- Uncertainties Must Be Identified and Taken into Account in Analysis of Fault Displacement Hazards
- Assume Uncertainties Reduced by Data Acquisition
- An Inherent Threshold Uncertainty Exists That Cannot Be Overcome Because of Unknown Subsurface Character of Faults
- Deterministic Approach Uses Conservative (Maximum) Value for Fault Displacement (i.e., MCFD) to Limit Uncertainty in This Parameter

QUESTIONS ON ISSUES — FAULT DISPLACEMENT HAZARDS

ASSESSMENT OF TECHNICAL UNCERTAINTIES (POSITION 3)

[11] • How Important Is Consideration of Data and Model Uncertainties in Analysis of Fault Displacement Hazards?

[12] • If Uncertainties Exist, Can They Be Quantified?

ISSUES FOR CONSIDERATION — FAULT DISPLACEMENT HAZARDS (Continued)

DETERMINATION OF REPOSITORY DESIGN BASIS (POSITION 1c)

- MCFD Along Type I Faults in the Site Area Provides Specific Design Basis

QUESTIONS ON ISSUES — FAULT DISPLACEMENT HAZARDS

DETERMINATION OF REPOSITORY DESIGN BASIS (POSITION 1c)

[13] • Is It Reasonable to Use the Quaternary Record in the Yucca Mountain Area to Establish MCFD for Faults at the Site?

[14] • Will MCFD Provide an Overly Conservative Design Basis for Fault Displacement Hazards?

[15] • Is It Reasonable to Consider "Analog" Faults Elsewhere in the Geologic Setting if MCFD Cannot Be Determined from Faults at the Site?

PRESENTATION TO THE CNWRA ADVISORS ON
FAULT DISPLACEMENT HAZARDS AND SEISMIC HAZARDS
MAY 17, 1993

ABOU-BAKR K. IBRAHIM
GEOLOGY AND ENGINEERING BRANCH
DIVISION OF HIGH-LEVEL WASTE MANAGEMENT

STAFF TECHNICAL POSITION ON
ANALYSIS OF FAULT DISPLACEMENT HAZARDS AND
SEISMIC HAZARDS AS THEY RELATE TO DESIGN
OF A GEOLOGIC REPOSITORY

DEVELOPMENT OF SEISMIC HAZARD ANALYSIS

STAFF POSITIONS (PRELIMINARY)

1a. BOTH DETERMINISTIC AND PROBABILISTIC METHODS SHOULD BE USED TO ESTABLISH DESIGN BASIS

1b. DESIGN BASIS SHOULD BE DEFINED AT THE FREE SURFACE IN TERMS OF SITE SPECIFIC ACCELERATION AND VELOCITY SPECTRA

STAFF POSITIONS (CONTINUED)

2. ELEMENTS OF AN ACCEPTABLE ANALYSIS OF SEISMIC HAZARDS WOULD INCLUDE

- o MAXIMUM MAGNITUDE EARTHQUAKE
- o IDENTIFICATION OF THE EARTHQUAKES TO BE CONSIDERED FOR DESIGN
- o PROVIDING MAGNITUDE-FREQUENCY RELATIONSHIPS
- o EXAMINING POISSON AND NON-POISSON DISTRIBUTION FUNCTIONS
- o ESTIMATION OF GROUND MOTION ATTENUATION
- o IDENTIFICATION OF CHARACTERISTIC EARTHQUAKE
- o EXAMINATION OF LOCAL SITE EFFECTS
- o EXAMINATION OF SURFACE AND SUBSURFACE VERTICAL AND HORIZONTAL ACCELERATIONS AND VELOCITIES
- o EXAMINATION OF CUMULATIVE EFFECTS OF SMALL EVENTS ON THE WASTE PACKAGE

ISSUES FOR CONSIDERATIONS, SEISMIC HAZARD ANALYSIS

DETERMINISTIC	PROBABILISTIC
ESTIMATE BASED ON AVAILABLE RECORDED DATA AND OBSERVATION IN THE FIELD	ESTIMATE BASED ON EXPERT ELICITATION AND PROBABILITY MODELING
FREQUENCY OF EARTHQUAKE OCCURRENCES ARE NOT FORMALLY TAKEN INTO ACCOUNT	FREQUENCY OF EARTHQUAKE OCCURRENCES ARE TAKEN INTO ACCOUNT
SINGLE ESTIMATE	MULTIPLE ESTIMATES, CONSIDER FULL RANGE OF POSSIBILITIES
ANALYSIS IS NORMALLY TRANSPARENT	LACK OF TRANSPARENCY. FUSE TOGETHER THE INPUT AND CAUSATIVE FACTORS CAN BE OBSCURED
DOES NOT INCORPORATE UNCERTAINTY	EXPLICITLY INCORPORATES UNCERTAINTY IN THE ANALYSIS
APPROACH NOW USED IN LICENSING NUCLEAR POWER PLANTS	APPROACH CONSIDERED IN THE REVISED PART 100 APPENDIX A (APPENDIX B)

(4)

SITE CHARACTERISTICS

- o YUCCA MOUNTAIN IS CHARACTERIZED BY COMPLEX TECTONIC FEATURES
- o THERE ARE WELL DEFINED QUATERNARY FAULTS IN THE REGION
- o EARTHQUAKE MAGNITUDE CAN BE ESTIMATED BASED ON LENGTH, AND RUPTURE AREA
- o CORRELATION OF EARTHQUAKES WITH TECTONIC FEATURES NOT WELL DEFINED

COMBINED DETERMINISTIC AND PROBABILISTIC APPROACH SHOULD BE CONSIDERED

[16] QUESTION: FROM YOUR EXPERIENCE IS THE COMBINED APPROACH (DETERMINISTIC AND PROBABILISTIC) APPROPRIATE FOR USE IN BOTH THE PRECLOSURE (100 YEARS) AND POSTCLOSURE (10,000 YEARS) PERIOD OF PERFORMANCE?

[17] IF NOT WHAT ARE THE ALTERNATIVES?

[18] QUESTION: DO YOU CONSIDER THE STAFF APPROACH ADEQUATE FOR IDENTIFYING THE DESIGN BASIS EARTHQUAKE?

[19] ARE THERE ANY OTHER APPROACHES THAT SHOULD BE CONSIDERED?

DEVELOPMENT OF SEISMIC HAZARDS ESTIMATES

PARAMETERS NEEDED FOR GROUND MOTION ANALYSIS

- o IDENTIFY SEISMIC SOURCES WITHIN THE SITE REGION
- o ESTIMATE EARTHQUAKE POTENTIAL FOR EACH SEISMIC SOURCE
- o IDENTIFY LOWER BOUND AND UPPER BOUND MAGNITUDE
- o ESTIMATE EARTHQUAKE OCCURRENCE RATE
- o ESTIMATE GROUND MOTION TRANSMISSION TO THE SITE
- o ESTIMATE SITE GEOTECHNICAL PROPERTIES
- o IDENTIFY EARTHQUAKES THAT COULD ADVERSELY AFFECT THE REPOSITORY DESIGN
- o ENVELOPE THE SPECTRA FROM THESE EARTHQUAKES

(8)

[20] QUESTION: ARE THERE ANY OTHER PARAMETERS NEEDED FOR CONSIDERATION IN THE GROUND MOTION ANALYSIS ?

DEVELOPMENT OF SEISMIC HAZARDS ANALYSIS

FACTORS CONTRIBUTING TO UNCERTAINTY IN THE GROUND MOTION ESTIMATES

- o SEISMIC SOURCE ZONE CONFIGURATION
- o THE "a" AND "b" VALUES IN THE RECURRENCE RELATION
- o LOWER BOUND MAGNITUDE
- o UPPER BOUND MAGNITUDE
- o THE GROUND MOTION ATTENUATION MODEL
- o THE UPPER BOUND PEAK ACCELERATION CUT OFF
- o INCLUDING OR NEGLECTING SITE EFFECTS ON THE HAZARD CALCULATIONS

(10)

[21] QUESTION: WOULD THE UNCERTAINTY ASSOCIATED WITH ANY OF THESE PARAMETERS HAVE A SIGNIFICANT EFFECT ON THE SEISMIC HAZARD ANALYSIS?

1

PRESENTATION TO THE CNWRA
FAULT DISPLACEMENT AND SEISMIC HAZARDS ADVISORS

MAY 17, 1993

Renner B. Hofmann
CNWRA

OTHER TOPICS FOR DISCUSSION

2

SUMMARY

MOST OF THE FOLLOWING ISSUES ARE NOT ADDRESSED IN THE STP.

Your advice is requested concerning their use in analysis of fault displacement and seismic design criteria.

- CRITERIA FOR DESIGN: MEAN, MEDIAN OR A STD. DEVIATION
- SENSITIVITY OF INPUT PARAMETERS
- DATA EXTRAPOLATION
- PROBABILITY DISTRIBUTION FUNCTIONS
- EXPERT JUDGEMENT APPLIED TO 10,000 YEAR PREDICTIONS

3

CRITERIA FOR SEISMIC DESIGN

- **Several measures have been proposed for hazard-curve peak-accelerations or spectral-band amplitudes, e.g.:**

  - **Mean**
  - **Median**
  - **One or more standard deviations**

- **LLNL studies show that the mean and median may greatly differ when expert opinions are used - unless it is constrained by, e.g.:**

  - **Limiting choices in response**
  - **Lengthy expert education and ground rules**

- **Standard deviations are used to encompass uncertainties and variability.**

[23] Which definitive criterion is preferred for design?

4 SENSITIVITY OF HAZARD CALCULATIONS TO INPUT PARAMETERS

- Source zones or faults
  - continuously planar at depth
  - listric
  - observed fault movements are controlled by unknown oblique master faults at depth?
- "a" and "b" values in the recurrence relation, and whether the recurrence relation can be described as a straight line for a 10,000 year period.
- Lower bound magnitude below which there is no design concern.
- Upper bound magnitude
- Upper bound peak acceleration cut-off
- Include site effects? To what level of sophistication?

SUBSTANTIAL UNCERTAINTIES ARE ANTICIPATED FOR THESE ITEMS

[24] Are any of these items more critical than others in the development of design input?

5

DATA EXTRAPOLATION

Considering the following, how should data extrapolation be addressed in analysis?

[25] • Recurrence extrapolation to large earthquakes or long periods of time.

[26] • Attenuation of Acceleration and velocity extrapolation, where data are inadequate,:

[27] - to short distances for large earthquakes

[28] - by fault type subset

[29] - by foundation material subset

5b

DATA EXTRAPOLATION (Continued)

- EXTRAPOLATION OF SURFACE GROUND MOTION AMPLITUDES TO REPOSITORY DEPTH

  Experience in mines suggests reduced shaking at depth

  Two fold amplification of body waves at the free surface from theory

  Borehole seismometers have produced variable results

  Interface wave theory predicts amplification at buried interfaces.

5c

DATA EXTRAPOLATION (Continued)

- FAULTS THROUGH OR ADJACENT TO A MINE ARE A SPECIAL CASE

How significant are the following points to design of a mined repository?

[30] - Mine is closer to fault slip area center than the surface

[31] - Guided waves along the fault interface may increase amplitudes

[32] - Energy directed along the fault plane may increase amplitudes

[33] - Recordings of large earthquakes on faults through mines are non-existent

6

PROBABILITY DISTRIBUTION FUNCTIONS

Considering the following, what do you recommend concerning probability distribution functions for a mined repository with a 10,000 year period of performance?

[34] • **Poisson - adequate for large data sets and long periods of time.**

[35] • **Time dependent - improves earthquake predictions for times past the median return period.**

[36] • **Truncated - represents earthquake data better than a Poisson distribution functions although seismic history is relatively short.**

7

EXPERT JUDGEMENT
IMPLICATIONS FOR REPOSITORY SEISMIC DESIGN

1. *Can the use of expert judgement to predict future seismic hazards be shown now to be better than in the past? In view of the following, can expert opinion be relied upon to establish quantifiable probabilities 10,000 years hence?*

- **10,000 years is longer than recorded history for known civilizations.**
- **California's seismic hazard was not publicly recognized in 1906. The recent Little Skull Mountain earthquake occurred in what was thought to be a seismically quiet zone.**
- **Management of expert judgement is a new science (art?)**
- **Futurist's predictions 100 years ago have proved to be of variable accuracy.**
- **Geologic record is a history of the past but its interpretation by experts to predict the future produces varied probabilities.**

7b

Expert Judgement (continued)

[37] 2. *Are there viable alternatives to expert judgement?*

[38] 3. *Is it adequate to rely only on the following three means of accommodating uncertainty:*

[39] - **Multiple barriers to accommodate data uncertainties**

[40] - **Use of the mean or median of available data and expert opinion to predict large earthquakes and fault movement 10,000 years into the future?**

[41] - **Will using expert judgement to obtain the full breadth of opinion drive engineering design to excessive levels?**

APPENDIX C

ADVISORS' REPORTS

Reports from the advisors are reproduced in their entirety without modification or changes in page numbers. There are five reports.

Fault Displacement and Seismic Hazard Analysis Report to

Center for Nuclear Waste Regulatory Analyses

by

Dr. C. Allin Cornell

June 25, 1993

These comments follow a reading of the material provided, and a two-day meeting (May 17 and 18) at CNWRA. They are organized in four parts*:

A. My opinion about MCFD and MCE.

B. My recommendations for what NRC should ask of DOE.

C. My suggestions as to parallel work by NRC and its contractors to prepare for their review effort.

D. A collection of comments on specific topics; these elaborate on issues in A, B, and C, and/or respond to specific CNWRA questions to our panel.

A. THE CASE AGAINST THE MCE AND THE MFD.

Under the circumstances, I do not think a traditional approach, namely one based on scientifically undefined concepts such as the Maximum Credible Fault Displacement (MCFD) and Maximum Credible Earthquake (MCE), can be defended any longer. These circumstances include:

(1) progress on many fronts away from the MCE (or its equivalent the "Minimum Incredible Earthquake," a Clarence Allen observation that reveals the weakness of the concept). These fronts include the expertise and experience in using a probability/frequency format for seismic assessments in many fields and for safety assessments and criteria-bases for many hazards, etc.

(2) the ultimate need (in order to meet EPA criteria) of a quantitative description of the randomness and uncertainty faced, e.g., for the IPA process. This description also provides the basis of probability-based criteria. (See B(6) below.)

*I also enclose as an appendix my May 14 post-reading notes, transmitted to CNWRA on May 17.

(3) the existence of alternative procedures that are consistent both with this ultimate need and with the evolving practice in seismic and other engineering fields. Examples: The latest NRC (reactor) and DOE criteria.

(4) the commendable incorporation already in the STP draft of the need for alternative models, and the admission already of major uncertainties in virtually every element of the FD and the SH problem.

(5) the need for incorporating systematically and consistently these two issues, i.e., alternative models and explicit uncertainty recognition into the evaluation and the criteria.

(6) the untested character of the MCE/MFD for this portion of the Basin and Range. Neither of the currently used MCE concepts (e.g., California practice and EUS/Appendix A practice) is obviously applicable. The Yucca Mountain region has a short history and low deformation rates. (See Item 10 in Part D.)

B. RECOMMENDATIONS FOR WHAT NRC SHOULD REQUEST OF THE APPLICANT (DOE).

1. Initial Deterministic Investigations

Do a "reasonable" site investigation per the previous STP. Support this with "reasonable" deterministic studies, interpretations, etc. (I find the current tunneling project admirable; expensive but informative.)

2. Information Management via Logic Trees and Event Trees

(a) Maintain in <u>logic tree format</u> (see, for example, applications at the Diablo Canyon NPP (1988) and elsewhere) the current information and alternative hypotheses. These trees can contain both alternative regional tectonic models and (further out on the branches) alternative interpretations of each known fault. The end nodes can contain states such as the maximum <u>possible</u> magnitude (MPM) and maximum <u>possible</u> fault displacement (MPFD) (per event and/or per specified time interval). The weights on the branches display the current evidence and judgments favoring alternative hypotheses. The trees should be updated as new information becomes available.

(b) Conventional event and logic trees should be expanded to include branches associated with potential multi-segment events (San Francisco 1906 and Landers 1992), and to include "potential undiscovered faults" (on and off-site). These are relatively new concepts and need more thought (see below). Note, in passing, that there is a (seldom explicitly recognized) difference between a logic tree (which describes possible alternatives in the "current state of nature", e.g., fault segment lengths) and an event tree (which describes events that might happen in the future, e.g., one segment or two segments fully rupture in the next earthquake on the fault). In a seismic hazard analysis, in effect, there is an event tree attached to each final node ("leaf") of a logic tree. The states of nature (mean slip rate, fault length, etc.) affect the values of the frequencies of future events. In practice the event tree is often not explicitly drawn; it is implicitly analyzed by, for example, standard probabilistic seismic hazard analysis software (EQ Risk, etc). In some cases, however, such an explicit tree is useful, especially for discrete possibilities such as either one or two segments rupture in the next event.

3. Analysis of Trees: MPM/MPFD Uncertainty, and More.

(a) The weights on the logic tree branches can be multiplied to produce uncertainty distributions on the MPM and MPFD for each fault. This uncertainty is "epistemic" uncertainty, i.e., it reflects "limited current knowledge" about the scientifically definable quantities maximum possible magnitude and displacement. These distributions will be used below.

(b) Do the same for maximum likely (mode or median) magnitudes and fault displacements (MLM, MLFD) and ground motions at surface and at depth, in several specified future windows (e.g., the next 10, 100, and 10,000 years) The MLM reflects "aleatory" randomness (e.g., how many, how often, when, how big, where, etc., will events occur in a given future time). As discussed above, these random future issues may be analyzed by formal (implicit) probabilistic analysis algorithms or by event trees. The logic trees will provide the degree of epistemic uncertainty in these measures of the aleatory/random behavior of nature. Examples are the uncertainty bands produced on seismic (aleatory) hazard curves in current SHA practice.

(c) Study and use the trees to suggest effective ways to reduce the uncertainty in the MPFD and in the MLFD, etc. Any proposed additional site investigation will presumably have as its purpose finding new information about known features or looking for potential, new features. The trees can be used to show the benefits of reducing uncertainty. It will reduce design values (see B(6) below).

(d) Supplementary analysis and judgments can be used to estimate the likelihood of, for example, finding a new fault given it exists ("likelihood functions"). Coupled with costs and benefits (see (c)), analyses would show the most cost-effective ways to reduce uncertainty and they would aid the decision as to when to stop site investigations. (Formally this is "preposterior" decision analysis.)

4. Analysis of Decisions.

Decisions to be made include (i) site investigation details and continuation (see 3(d) above), (ii) design decisions, and (iii) what to do if significant unidentified features are found only during construction, etc. The logic trees supplemented by decision trees and analysis can facilitate such decision making. In fact anticipating such decisions that might need to be made during construction (and their cost impacts) should be part of the decision as to when site investigations can stop.

5. Provide Input for Ongoing (Scenario-based) Performance Assessments at DOE and NRC.

This implies a closer coupling between the current NRC IPA (Integrated Performance Assessment) and the STP.

6. Criteria Evaluation.

As soon as NRC establishes its numerical criteria (see Part C(3), below), it can ask DOE to provide current design values. These will include design values for fault displacement, ground motion, etc. They may be in the form of percentiles (e.g., 84%) of the MPFD and/or of the MLFD, etc. (See Item c(3) below.) The results of the analyses in B(3) above will provide the numerical values.

C. RECOMMENDATIONS FOR RELATED NRC/CNWRA TASKS

Some topics that NRC/CNWRA should make efforts on directly or via contractors include:

1. NRC Logic Trees

Keep up-to-date NRC versions of the site description in the logic tree format described in part B. The discrepancies (and their implications with respect to MPFD, etc.) viz-a-viz the DOE reported trees (Section B(2)) will target areas for discussion and reconciliation (if important). These trees will provide ongoing NRC IPA input also.

2. Development Work

Conduct and/or commission background research and development with respect to:

(a) Elements of the logic tree and its analysis proposed above (see B2(b) and B3 and 4) with which the profession has less experience, e.g., branches for "undiscovered" faults, and analysis of the likelihood of finding them.

(b) Probabilistic fault displacement analysis.

(c) Probabilistic hazard analysis for long time windows.

(d) Criteria development issues in the Yucca Mountain Repository context, e.g., the role of the IPA, top-down criteria, long windows, etc.

(e) Expert opinion treatment in this context.

3. Develop the Basis for the Quantitative Criteria.

Issues include:

(a) Format and Level: for example, the 84% of the MPFD (i.e., epistemic uncertainty only) and/or the 84% of the MLFD in 10,000 years (i.e., aleatory and epistemic uncertainty). (Do they differ much? It depends on slip rate.) Should, instead, the MLFD basis be the displacement value associated with a <u>mean</u> frequency of occurrence of (less than), say, 10% in 10,000 years? (The <u>mean</u> covers the epistemic issue; the 10% covers the aleatory one. For this case, the more the epistemic uncertainty the larger this mean will be.) Other time windows are appropriate for pre-closure.

(b) Re-scaling time: It occurs to me that a basis for criteria could be established by re-scaling time (via relative slip rates) to use broader California experience as a guideline. Slip rates are 100 to 1000 times less; this implies that at Yucca Mountain 10,000 years "look like" 100 to 10 California years, or "typical" conventional engineering project window lengths in California.

(c) With the "re-scaled time" basis in (c) one would also have to look at the likelihood of a major/"sudden" change in the slip rates in the neighborhood in 10,000 years. This is a do-able problem. Think of the Wallace Basin and Range study. Think of analogies in space/time elsewhere.

(d) Transparency: there is a need to make logic-tree based seismic hazard analysis more "scrutable" by scientists (as opposed to analysts), without losing its complete integrating analysis benefits. There is some potential to do this, but it needs research.

D. A COLLECTION OF OBSERVATIONS WHILE READING AND LISTENING (IN NO PARTICULAR ORDER):

(1) The call for alternative models is good. There is no proposal for what to do with them, however. Is the MCFD the worst of the models anyone can conceive of? When is a model no longer credible? My recommendations cover this case.

(2) Defense in depth (Engineered and Natural Barriers). It should be said somewhere that the earthquake is a phenomenon that challenges both barriers simultaneously, reducing the effectiveness or dependability of this redundancy.

(3) There is nowhere a definition of the MCFD or MCE. Even its proponents, e.g., Bob Rothman at NRC, agree that it's not (in EUS Appendix A practice) the maximum possible event. Therefore it has been case dependent, i.e., dependent on failure consequence and lifetime duration of the facility, as well as on qualitative adjustments for frequency of occurrence, e.g., less than maximum possible magnitude at greater than zero distance in the EUS. This is why it is not a scientific concept; it is a disguised implicit engineering decision, i.e., one that reflects a cost/risk/benefit/frequency/uncertainty trade-off.

(4) What ground motion fractile (84th?) is to be used with the "maximum credible magnitude" in a deterministic criterion? Recall Appendix A and hence the Standard Review Plans do not necessarily apply. See Item 3.

(5) Over a 10,000 year life, a number of the details we worry about normally may not be necessary (e.g., possibly segmentation, characteristic magnitudes, non-Poissonian recurrence, etc.). Because, unless the slip rates are extremely small, multiple segment events are likely, the relative frequency of less the near-maximum events is secondary, and the exact timing of events is unimportant if there are going to be several in 10,000 years., etc. Ten thousand years can perhaps simplify some things. These "details" might have some impact in pre-permanent closure assessments. On the other hand, the slip rates are small!

(6) Section 4.2 is dense with words reflecting uncertainty and randomness, yet the only tool we have to deal with these concepts systematically and consistently is probability theory, which is then relegated to a secondary role in the draft proposal.

(7) The shopping list in Section 4.2 (e.g., interaction, coupling, stress increases induced by heat from the waste, spatial-temporal clustering, segmentation based on paleo-seismic studies, etc.) is a scientist's dream. But how much

is really do-able (e.g., all the excellent information about paleo-seismic events at Pallett Creek and Wrightwood seems to leave us more confused than ever about future event likelihoods and locations!) and/or verifiable (e.g., the implied geophysics of segment interactions and stress to cause failure, etc.). See also (5) above.

(8) At least when dealing with probabilistic models (what you call MLFD, MLE, etc.), it must be remembered that what is conservative with respect to MCFD and MCE is not necessarily conservative with respect to MLFD and MLE. For example, a smaller maximum possible magnitude implies more frequent events if the moment rate is known, and this may imply <u>increased</u> ground shaking hazard at a site.

(9) Is there enough regionally specific data to produce a Yucca Mountain specific ground motion model? Sub-surface motion prediction deserves more attention. Finite-length-source ground motion prediction models may be needed. Local site effects and SSI seem to be mixed together.

(10) The NRC staff must recognize that deterministic criteria (e.g., the MCE) are largely untested in this portion of the Basin and Range. With respect to the EUS the Basin and Range is different because it has identifiable active features and a shorter historic record of seismicity. With respect to California it is different because the deformation rates (and hence presumably the seismic "threat") is 100 to 1000 times smaller. Therefore, an MCE could be "doubly" conservative here.

(11) Focus on 10,000 year problem (the rest is more "familiar"). One approach is just to time re-scale California (see B(3) above). Another is systematic looks at issues such as:

> (a) What elements of familiar approach can be "left out"? (See item 5). What surely cannot?
>
> (b) What elements are new (e.g. is there potential for significant change in the current geological "steady state"?) How can they be addressed by science, logic, analogy, common sense, etc. "Address" includes: gain understanding, seek evidence about, assess likelihoods, develop engineering solutions to mitigate consequences of unlikely but uncertain events, provision with long-term robust (i.e., simple) monitoring.
>
> (c) How should criteria depend on the length of the window?

(12) This repository is a new situation. Let engineers be creative. Avoid criteria so rigid they tie designers' hands.

For example, design for rare/uncertain events is often best done by <u>super</u> hardening only a subset of the engineering safeguards, not "moderately-hardening" all. Permit alternatives if comparable or better performance can be demonstrated.

(13) Discussions suggested that the CNWRA/NRC staff may not themselves have thought in depth about MCE definition, especially in context of a range of options/opinions/evidence (i.e., implicitly or explicitly a suite of more and less plausible ("likely") values ranging from the maximum observed in the historic or the paleoseismic record to the "lunatic upper fringe").

(14) It appears that the technical interaction with DOE and its contractors is counter-productive. Is there no legal way to work together? (See for example Item 15.) This situation concerns me both as a professional and as a taxpayer.

(15) The NRC staff and its contractor, CNWRA do not as yet have the necessary experience, and background to address in depth the probabilistic dimensions of the fault displacement and ground motion problem. It is likely, unfortunately, that all the best sources of appropriate consulting support are already "compromised" by having worked for DOE or EPRI (see Item 14). The NRC should address this question immediately; it is crucial to effective development of probabilistic criteria, independent analysis of the site displacement and motion hazard, providing input to IPA, evaluating DOE submissions, etc. For example, I have seen a paper that suggests someone is doing probabilistic diffusion analysis for DOE. This could be supplemented, as George Thompson suggested, for potential seismic effects. Does NRC know about this work? Are they following it? Encouraging it? Prepared to contribute to or evaluate it?

(16) Because the facility is new, as are design for fault displacement and design for "leakage" vs. "breakage", a top-down, performance-goal-consistent design basis would appear to be desirable. Like the IPA itself this could lead to evolving criteria, which would make design difficult; practicality would suggest using the current (Summer '93) IPA as the basis for the 'design criteria' and then reminding the contractor to leave a margin for uncertainty in the evolution of information between now and the final performance assessment. Even with the current IPA, the derivation of top-down criteria would take time. Therefore, conventional bottom-up may be the best interim "guidance".

(17) On expert opinion. This letter report hardly permits a long response. In brief, our profession's experience in similar projects suggests that, with guidance and caution, it

can be very effective. It should be re-confirmed that it is not a substitute for hard data. We all agree "deterministic" site investigation is necessary (although knowing when to stop getting data is just as necessary.) Formal expert "opinion" assessment is simply (at any given time, given the data and information available at the site) the best way to process complex, conflicting evidence. It displays where there is consensus and where not, where there remains major uncertainty and where not, etc. The seismic area has (it is said in the literature) some of the most significant experience in the area of use of expert opinion in a highly technical context such as this. Some of the experience has been negative, but I believe we have learned from it. A current joint NRC/DOE/ EPRI project is working hard to improve the process. (But I suppose such a collaboration implies the product will be tarnished; see (14) above.) Given the situation at hand, the "answer" is going to rest on judgment in any case. It can only help to make sure that it is indeed expert judgment and that the <u>process</u> is of gathering and using and documenting it is the best available.

[wplet2.51\FD&SHA-r.cmt]

DR. C. ALLIN CORNELL

P. O. Box 9260
Stanford, CA 94305

110 Coquito Way
Portola Valley, CA 94028
Phone/Fax: (415) 854-8063

Preliminary Comments on

"FD & SHA ANALYSIS STP"
February, 1993

for
Center for Nuclear Waste Regulatory Analyses

C. Allin Cornell
14 May 1993

These are a few major and minor comments that come to the surface upon my reading of the subject document. They are not complete and they are not final; they are subject to clarification and completion after the Group's meeting on May 17 and 18.

A. My Major Reaction:

Under the circumstances, I do not think a traditional approach, namely one based on scientifically undefined concepts such as the MCFD and MCE, can be defended. These circumstances include

(1) progress on many fronts away from the MCE (or its equivalent the "Minimum Incredible Earthquake," a Clarence Allen observation that reveals the weakness of the concept).

Examples: The latest NRC (reactor) and DOE criteria.

(2) the ultimate need (for meeting EPA criteria) of a probabilistic description of the randomness and uncertainty faced.

(3) the existence of alternative procedures that are consistent both with this ultimate need and with the evolving practice.

(4) the acceptance already of the need for alternative models, and the admission already of major uncertainties in virtually every element of the FD and the SH problem.

(5) the need for incorporating systematically and consistently these two issues (in Item 4) into the criteria.

B. I recommend that you ask the applicant for:

(1) the management and presentation of the information available (including its limitations) through "logic trees" (or some equivalent scheme). Based on this, you can then ask for the "uncertainty distribution" on the maximum fault displacement (MFD) and the maximum earthquake (ME) (or at least the maximum magnitude (MM) on each fault, from which ground motions at the site can be estimated). The MFD and MM are scientifically defined. Yes, we are uncertain about what they are. This distribution is the information available (at any time). You can debate how much it can be "narrowed" by various tests, analyses, additional field work, etc. These trees are also the information and format needed for input into (EPA required) system performance models.

(2) Design bases can be established based on these displays of information. If appropriate, it could be: "Design for the MFD and the MM; one has 'reasonable assurance' he has done so if he uses the 84% fractile (or the mean or whatever) of the MFD and MM distributions." This is the "equivalent" of a deterministic or "worst scenario" approach except the information available is described in uncertainty/logic tree terms. Alternatively (preferably in my mind) one could use a "probabilistic" design basis, e.g., "use the FD that has a (mean or 84th percentile) probability of occurrence in 10,000 years of 10^{-1} or less." (This is a probabilistic criterion reflecting uncertainty.)

C. A Collection of Observations While Reading (In No Particular Order):

(1) The call for alternative models is good. There is no proposal for what to do with them, however. Is the MCFD the worst of the models anyone can conceive of? When is a model no longer credible? My recommendation covers this case.

(2) Defense in depth (Engineered and Natural Barriers). It should be said somewhere that the earthquake is a phenomenon that challenges both barriers simultaneously, reducing the effectiveness or dependability of this redundancy.

(3) There is nowhere a definition of the MCFD or MCE. Even its proponents, e.g., Bob Rothman, agree that it's not (in

Appendix A practice) the maximum possible event. Therefore it is case dependent, i.e., dependent on failure consequence and lifetime duration.

(4) What ground motion fractile (84th?) is to be used with the "maximum credible magnitude"? Recall Appendix A and hence the Standard Review Plans do not necessarily apply. See Item 3.

(5) Over a 10,000 year life, a number of the details we worry about normally may not be necessary (e.g., possibly segmentation, characteristic magnitudes, non-Poissonian recurrence, etc.) because multiple segment events are likely, relative frequency of less the near-maximum events is secondary, the exact timing of events is unimportant if there are going to be several in 10,000 years., etc. Ten thousand years can perhaps simplify some things.

(6) Section 4.2 is dense with words reflecting uncertainty and randomness, yet the only tool we have to deal with these concepts systematically and consistently is probability theory, which is then relegated to a secondary role in the draft proposal.

(7) The shopping list in Section 4.2 (e.g., interaction, coupling, stress increases induced by heat from the waste, spatial-temporal clustering, segmentation based on paleo-seismic studies, etc.) is a scientist's dream. But how much is really do-able (e.g., Pallett Creek and Wrightwood leave us more confused than ever!) and/or verifiable (e.g., the implied geophysics of segment interactions and stress to cause failure, etc.). See also (5) above.

(8) At least when dealing with probabilistic models (MLFD, MLE, etc.), it must be remembered that what is conservative with respect to MCFD and MCE is not necessarily conservative in a probabilistic context. For example, a smaller maximum magnitude implies more frequent events if the slip rate is known, and this may imply increased ground shaking hazard at a site.

(9) Is there enough regionally specific data to produce a Yucca Mountain specific ground motion model? Sub-surface motion prediction deserves more attention. Finite-length-source ground motion prediction models may be needed. Local site effects and SSI seem to be mixed together.

[wplet2.51\FD&SHA.com]

TO: *Dr. Renner Hofmann*
CNWRA-SwRI
6220 Culebra Road
San Antonio, TX 78284

FROM: *Dr. Anne S. Kiremidjian*
14210 Berry Hill Court
Los Altos Hills, CA 94022
(415) 941-8405 - H
(514) 723-4164 - O

SS # 053-42-5872

Date: June 21, 1993

Subject: Response to the Nuclear Regulatory Commission (NRC) Products Related to Fault Displacement and Seismic Hazard Analysis (FD&SHA) at a High Level Radioactive Waste (HLW) Repository

The objective of our review was to assess the adequacy of the Staff Technical Position (STP) on fault displacement and seismic hazard guidelines to be used for the design and licensing of a high level radioactive waste repository and to make appropriate recommendations for potential improvements of the STP. My recommendations are based on my experience in seismic hazard analysis with an emphasis on earthquake occurrence modeling and fault rupture risk analysis of underground structures, and on structural safety evaluations methods.

After a careful review of all written material sent to me prior to the meeting of May 17 and 18, 1993 and the presentations during that meeting, I interpret the NRC Staff position on fault rupture and seismic hazard assessment to consisting of the following key points:

• A deterministic approach is to be used for fault displacement and seismic site hazard assessment using the maximum credible criterion;

• Probabilistic analysis is to be used only as a supplement to the deterministic analysis;

• Alternative models are to be used to investigate variations in fault rupture assumptions and earthquake modeling as well as their short and long term effects on the repository;

• Two investigations are to be carried out: one for the preclosure and one for the postclosure period of the repository.

While the overall approach follows similar safety evaluation procedures such as these for nuclear power plants, there a number of important differences between siting and evaluation of high level radioactive waste disposal facility and other critical facilities. Of these, the most significant include the time frame over which safety needs to be insured (10,000 years), the potential for significant fault rupture over this long time period, the possibility for geologic changes that could not be hypothesized because of lack of information from the past 10,000 years, and the changes of the geo-hydrologic environment that may occur due to the high temperature of the radioactive material.

Deterministic Versus Probabilistic Models

The use of deterministic models can easily be justified in cases when little variations are observed, when there is good control over the experiment and its forces of influence, when the data are numerous and more than sufficient to conduct verification experiments or when the variations in the model, design and imposed forces have insignificant consequences. None of these criteria apply to the analysis of high level radioactive waste repositories. Perhaps I can accept the extreme value approach described in the STP Annotated Outline which indicates that a fault displacement hazard, for example, is to be evaluated for the "maximum credible earthquake". The following questions, however, come immediately to mind that would undoubtedly be raised during licensing:

(i) How was the maximum credible earthquake estimated?

(ii) Since the value selected was based on limited earthquake occurrence data and limited geologic exploration, how can we be sure that a larger event will not be possible?

(iii) How many of these events are likely during the next 100 years and the next 10,000 years?

(iv) What differential fault displacement and ground shaking levels will result from each of the hypothesized events? And so on.

The answers to these questions are most frequently educated guesses based on very limited and unreliable data. When attempting to model such highly uncertain phenomena, it appears only prudent that a probabilistic approach be considered. With a probabilistic approach the ranges of all possible values at each stage of the analysis can be included with corresponding likelihood weights (i.e. probabilities of observing these values). For example, consider the "maximum" differential fault displacements that can result from a magnitude 6.5 earthquake. If that maximum is assumed 20 cm, observations from throughout the world would point out that this is only an average (or a median value) of the possible maxima and the coefficient of variation of such estimates can be as high as 100%. A design based on 20 cm may be non-conservative. In contrast, a probabilistic approach allows for the potential occurrence of displacements larger than 20 cm with their likelihood of occurrence decreasing as the values move away from the mean (or median) value.

Another example is the number of earthquakes that can occur over the life of the repository. If we cannot determine how many events have occurred in the past 10,000 years even with the most sophisticated current geo-exploratory tools, can we predict with sufficient precision how many will occur in the next 10,000 years? A single value estimate will lead to suspicion and can be easily disputed by any opposition party. It is recalled that a probabilistic approach relies on summary statistics and uses parameters that typically represent all possible observable values.

Common to these examples is the question of how reliable are the single parameter estimates used in the deterministic model and how much in error can they be. The answer to these questions can be provided only through probabilistic analysis.

I would agree that a deterministic analysis provides for a simpler, more understandable or transparent approach and results in a single value that can be used when developing design criteria. This single value approach, however, is not defensible in the light of all the model, parameter and phenomenological uncertainties.

Alternative Models

The lack of complete knowledge and understanding of the geologic and hydrologic environment at the repository requires that alternative models be used to represent different possible scenarios. As new information is gathered and data are collected at the repository site new scenarios will become apparent for representing the behavior of faults and potential consequences of their movement. Thus, the consideration of alternative models should be essential part of the repository risk assessment methodology. Furthermore, for design purposes, alternative models can provide valuable information on the range of possible values and rational decisions can be made on that basis.

The logic tree approach as discussed by Cornell is widely used in risk assessment applications. That approach provides for a clear representation of different assumptions and for a systematic treatment of uncertainties as they propagate through the logic tree. Weighing of alternative models is greatly facilitated with the use of such a logic tree formulation. With respect to the question of who should provide the weights for the alternative models, it is my opinion that such weights should be provided by experts who are familiar with the geo-tectonic setting of the region and are knowledgeable in the intricacies of the various models used in the analysis. With appropriate questions biases can be identified and reduced. In no way am I implying that this is an easy or well understood process. However, the experience with the eastern United States seismicity studies conducted by DOE and EPRI should be utilized for this purpose.

I support the alternative modeling approach proposed in the STP outline with the recommendation that a logic tree approach be used for the systematic treatment of the different models. In addition care must be taken to identify highly unlikely scenarios and yet not to omit ones that are plausible.

Fault Displacement Modeling

Fault displacements at known faults depend on the size of the earthquake, the type and geometry of the fault, and the local geologic conditions. For the purposes of high level radioactive waste repository hazard assessment and design, it is important to estimate the potential displacement from individual earthquakes for the preclosure period and the cumulative displacement over the postclosure period.

There are a number of difficulties with this process. Even for the western United States, where fault locations and behavior are relatively better known, we seem to be surprised by the amount and type of differential fault displacements observed in recent earthquakes. For example, prior to the Loma Prieta earthquake of 1989, a common belief by some geologists was that the northern segment of the San Andreas fault is not capable of producing vertical displacements and all displacements are "strictly of the strike-slip" type. After the Loma Prieta earthquake a review of the geotectonic regime of the Santa Cruz Mountain region and instrumental observations from that earthquake showed that indeed significant vertical displacements took place at the location of fault rupture. Similar surprises appear to have occurred at the Landers earthquake only to come to the conclusion that indeed displacements of the size observed are possible and should not have been precluded a priori. In providing these examples, my objective is purely to demonstrate that seismology and for that matter earthquake engineering is still not a science but to a great extent an art.

The questions that can be raised when predicting the amount and type of differential fault displacement include:

- Can the general stress regime of the region be estimated to determine the direction of possible rupture (vertical, horizontal or combined)?

- Over the 10,000 year time frame, is it possible for new fissures or new faults to form in the vicinity of the repository or across the repository?

- Is the estimated total slip over the past 10,000 years the absolute maximum for the next 10,000 years? What precludes the occurrence of larger or smaller slip in the future?

- Is the estimated total slip from the quaternary the result of a single event or the cumulative slip of several events?

- If there is a potential for more than one seismic event over the life of the repository (primarily for the post-closure period), what displacement can each event produce (amount and type of differential displacement)?

- Are surface fault displacements representative of displacements at depths? And if not what is the difference?

- Can the variations in fault displacement along the rupture zone be quantified? Is this distribution triangular with a maximum at the midpoint of the rupture zone and decreasing towards the ends, or is it skewed? Were will the maximum displacement fall in relationship to the repository?

- Do we have sufficient information to correlate the displacements of the size of the hypothesized maximum earthquake (provided a MCE approach is considered)?

- If several en echelon segments of fault are present, is it possible for ruptures to extend across segments?

- Given a series of fault displacements over the postclosure life of the repository, what is the likelihood that water reaching the repository either through water table elevation changes or through rock dewatering?

- Given a fault displacement, what engineering measures can be taken to mitigate its effect on the repository?

A comprehensive fault displacement methodology should address each of these questions. Most of these questions cannot be answered with reliability because the information at present is not available. This points to two important issues: First, it is imperative that all possible geologic and seismologic data be gathered. Since the Yucca Flats area is already targeted as the possible repository sight it seems only prudent that a major effort be concentrated on the accumulation of needed data and information. Second, the reliability of predicted fault displacements to be used in design should be assessed through a probabilistic analysis. In fact, the selection of appropriate differential fault displacement design levels should be for a specified reliability level. The selection of a reliability level is best done if the analysis is carried all the way through the risk assessment stage. Under such approach the likelihood of failure of different engineered design alternative for various displacements can be determined. This analysis will enable the selection of an optimal engineered design.

Ground Motion Hazard

Assessment of the ground motion hazard is important for both the preclosure and the postclosure periods. For the preclosure period, surface ground motions are critical. For the postclosure period, ground motions at depth are needed. I agree with the view that subsurface ground shaking has caused little if any damage to underground structures. Ground shaking hazard, however, becomes important in the more global picture of the hydrogeologic regime of the repository. Of particular concern are potential crack initiation or expansion in the host rock providing pathways for ground water or rock water to reach the repository through a dewatering process as pointed out by Thompson during our meeting. There is sufficient evidence from past earthquakes that such dewatering of rock has taken place. The level of shaking at which such dewatering or crack propagation and widening can occur is not well understood. Laboratory experimentation may prove useful in determining critical parameters and in developing an understanding the mechanism of these processes. Assessment of potential ground shaking from nearby and distant faults is also required for more reliable characterization of ground motions at the repository site. Partial information may be available from recordings of past nuclear explosion. It is my opinion that these data are tractable and can prove to be valuable if for nothing else at least for estimating the general attenuation characteristics of the region. In addition, the site should be instrumented to capture ground motions from faults in the southeastern California region.

Poissonian or Non-Poissonian Earthquake Occurrence Models

The choice of Poissonian or time-dependent models for earthquake occurrences is dictated by the relationship between the average interarrival time of events, the forecast time and the estimated time of the last major event. Non-Poissonian models are appropriate when the average interarrival time between events is of the same order of magnitude as the forecast time. If, in addition, the sum of the time since the last occurrence and the forecast time approaches the average interarrival time of events, then a Poisson model has been shown to be non conservative (see Kiremidjian and Anagnos, 1984 and Anagnos and Kiremidjian, 1984). For faults in the Yucca Mountain region, the average interarrival time of events is of the order of 10,000 years according to my understanding from the presentations during our May meeting. For such long interarrival times, the probability of occurrence of at least one event in the next 10,000 years if estimated from a time dependent model is likely to be considerably higher than the estimates that would be obtained from a Poisson model. Thus, it is recommended that the selection of occurrence model be done with care and understanding of the tectonic mechanism. It appears that the use of a simple time-dependent model may be more appropriate for the Yucca Mountain faults than a Poisson model.

With respect to consideration of segmentation, spatially dependent events, and characteristic events, models are available to include these characteristics. A main advantage of looking at these types of model is that often they identify the type of data needed for better representation of the seismicity of a region. The detail of information needed for these models, however, is not likely to be available for the Yucca Mountain site. It is my recommendation that these models be considered only if sufficient data can be obtained. The added accuracy with these more sophisticated models is likely to be lost if the appropriate data are not available.

Summary of Recommendations

It is my opinion that NRC should ask for the following information and procedure to be followed for high level radioactive repositories licensing and design:

- A detailed geo-hydrologic exploration and data gathering should be conducted. The only constrain would be economic feasibility of certain types of exploration. However, I strongly believe considerable amount of additional exploration and testing can be performed to better understand the geo-hydrologic regime and the potential for fault displacement and ground shaking.

- A deterministic approach will not be defensible in the light of all the uncertainties and the inherent randomness of earthquake phenomenon. A probabilistic approach should be considered for assessing both the fault displacement and ground shaking hazard.

- It is important that all methods and analysis techniques are transparent, reproducible and the results verifiable.

- A logic tree approach should be used to represent the alternative models and to assess the relative weights of various models.

- The repository hazard and risk evaluation should include consequence scenarios to assess the overall risk of release.

- Design parameters and methodologies can be best selected on the basis of minimal risk of failure of alternative mitigating solutions. This will require that there is direct communication and integration of information between the user, engineer and the assessor of the potential risks.

Review Comments

on

U.S. Nuclear Regulatory Commission Staff Technical Position On Fault Displacement Hazards and Seismic Hazards As They Relate To Design of a Geologic Repository

Prepared By

Martin W. McCann, Jr.
Jack R. Benjamin and Associates, Inc

June 28, 1993

EXECUTIVE SUMMARY

This report provides review comments on the U.S. Nuclear Regulatory Commission (USNRC) outline of a Staff Technical Position (STP) on 'Analyses of Fault Displacement Hazards and Seismic Hazards As They Relate to Design of a Geologic Repository.' The comments are based on the Internal Draft outline of the STP (dated February 1993) and the briefing provided by members of the USNRC Staff and the staff of the Center for Nuclear Waste Regulatory Analysis (CNWRA) at a meeting held May 4-5 in San Antonio.

In summary, the following general comments on the STP are offered:

1. The Staff has taken a big step in calling for the explicit consideration of "credible alternative models." This reflects a clear recognition of the uncertainties associated with the interpretation of earth science data. The recognition of the need to account for these uncertainties may be the most difficult step, from a philosophical perspective.

2. The dual deterministic-probabilistic approach for assessing fault displacement and seismic hazards is not well defined in the STP. The idea of a dual approach is inconsistent with the concept of having a stable (e.g., technically defensible) licensing process that is workable by both the applicant and the USNRC Staff.

3. The deterministic assessments perceived by the Staff seem to be generally based on experience derived from the application of 10 CFR Part 100 Appendix A to power reactor sites in the central and eastern U.S. (EUS). Due to differences between the tectonics in the EUS and the Yucca Mountain site for the geologic repository and current technology, the Appendix A experience is not directly transferable.

4. The assumption that the Appendix A approach could be used again since it worked before may be erroneous. It is arguable as to whether it has worked. It is not clear if one were to apply Appendix A today at existing power plant sites, that the same answer in terms of the estimate of maximum magnitude earthquake and the SSE ground motion would be determined. I don't think the Appendix A process would work in the context of today's regulatory, intervenor, financial environment.

5. Given the general movement away from the use of deterministic methods in safety assessments and the development of design levels, the dual approach in the STP is out of sync.

6. The STP does not address the role of experts in the fault displacement and seismic hazard analysis (FD & SHA). Assuming experts are used in the

development of alternative models, experience suggests that the process to elicit their input can be as critical as other technical aspects of the assessment.

Based on the review of the STP, the following primary recommendations are made:

1. Eliminate the dual deterministic - probabilistic approach. Use only a probabilistic FD & SHA.

2. Establish a design approach, based on the Environmental Protection Agency (EPA) risk goals that utilizes the probabilistic assessment of fault displacement and seismic hazards.

3. Establish specific documentation requirements for the FD & SHA that will provide reasonable assurance of the technical integrity and transparency of the analysis results.

4. The Staff should develop a mechanism to have a technical capability in a number of critical areas. These areas include experts in the use of experts in FD & SHA, probabilistic seismic hazard assessment, Yucca Mountain geology, seismology, etc. Those involved should have a hands-on role.

TABLE OF CONTENTS

1.0 INTRODUCTION

1.1 Background

This report provides review comments on the U.S. Nuclear Regulatory Commission (USNRC) outline of a Staff Technical Position (STP) on 'Analyses of Fault Displacement Hazards and Seismic Hazards As They Relate to Design of a Geologic Repository.' The comments are based on the Internal Draft outline of the STP (dated February 1993) and the briefing provided by members of the USNRC Staff and the staff of the Center for Nuclear Waste Regulatory Analysis (CNWRA) at a meeting held May 4-5 in San Antonio, Texas.

As brought out at the meeting with the Staff, the subject STP is part of the overall regulatory framework. While other USNRC activities related to the waste repository were discussed, it is not clear what the overall approach is. As illustration, a number of issues come to mind:

- How does the evaluation of and the design for fault displacement and seismic hazards fit within the context of the EPA safety standards?
- How are issues such as the relationship between seismicity and hydrology and vulcanism being addressed?

The Staff has attempted to modularize the elements of a complex problem. Having said this, some of the comments and recommendations that are made may extend beyond the scope of the STP. However, they are believed to be sufficiently related to objectives of the STP that the comments are offered.

In preparing the draft outline of the STP, the Staff has recognized the uncertainties associated with modeling geologic and potentially seismogenic structures. Further, the Staff recognizes the uncertainties involved in performing a fault displacement and seismic hazards analysis (FD & SHA) and has taken the position (at least in the Internal Draft of the STP) that an applicant should formally identify and consider the implications of alternative interpretations of available earth science data. This is an important step forward. There is however no guidance provided as to how this should be done. As subsequent comments will indicate, the next logical step should be taken in terms of characterizing the fault displacement and seismic hazard. That is, a formal assessment of the alternatives (e.g., uncertainty) should be provided in the context of a probabilistic assessment of the randomness of future events and what we can say about their likelihood.

1.2 Organization

In the following section specific comments are provided on the draft STP. This is followed in Section 3.0 by an overview of some of the lessons that have been learned regarding the use of experts in the interpretation of available data and the development of input to probabilistic seismic hazard assessments.

In the final section recommendations for the Staff and for the final development of the STP are provided.

2.0 COMMENTS ON THE STP

In this section comments are provided on the position presented in the draft STP. Recognizing the document submitted for review is not complete (it was advertised as a draft outline), the remarks provided are intended to provide guidance in the preparation of the final STP.

2.1 Overview

This subsection provides some comments on the STP. Comments are provided on the following subjects:

- dual probabilistic-deterministic approach
- relying on 10 CFR Part 100 Appendix A experience
- uncertainties in FD & SHA
- assessment of alternative models
- level of detail

1. Dual Probabilistic-Deterministic Approach - Recommending that the applicant perform a deterministic and a probabilistic assessment is inconsistent with current efforts to develop and apply probabilistic methods in the evaluation of natural hazards.

2. Relying on 10 CFR Part 100 Appendix A Experience - In proposing that a deterministic assessment be performed to evaluate fault displacement and ground motion hazards, the Staff seems to be relying on the experience from applying 10 CFR Part 100 Appendix A. This is ill-advised for a number of reasons. Although plants have been licensed using Appendix A, arguably the process did not work very well. If the Appendix A process were re-applied to sites in the EUS, it is fairly clear that the same results would not be obtained. Simply the issue of how to determine the maximum magnitude has changed enough to produce major differences.

3. Uncertainties in FD & SHA - As part of the STP there is a direct recognition of the technical uncertainties associated with the assessment of natural hazards. Thus, the STP calls for the evaluation of alternative models in the FD & SHA. This is a positive and important part of the STP.

4. Assessment of Alternative Models - The STP is silent on the issue of how to develop alternative models. Must a group of experts be used or can a single expert or

contractor develop the alternative models?

5. Level of Detail - In the draft, the STP provides a considerable amount of detail on the technical considerations of modeling fault displacements and ground motion hazards. On the other hand very little is said regarding the considerations in performing a probabilistic FD & SHA, the assessment of alternative models, etc.

2.2 Probabilistic Versus Deterministic

In the draft STP the Staff has taken the position that a dual probabilistic-deterministic approach should be used. The STP states that the probabilistic assessment should be used to supplement the deterministic method. Recommending this approach puts the Staff and the applicant in an inherently untenable and confrontational situation.

Consider the implications of promoting a dual approach. On the one hand, a deterministic assessment implies that an estimate of the hazard (fault displacement or ground motion) can be made on a unique (single-valued) characterization. (Note, in practice a deterministic assessment does consider the implications of different modeling assumptions, data, etc. However, in the final analysis a single-valued characterization of the hazard is put forth.)

On the other hand, a probabilistic assessment is based on the fact that fault displacement and ground motion hazards are random events whose time and location of occurrence are not known. Furthermore, due to limitations in the available data and our understanding of the physical processes being modeled there are uncertainties associated with modeling these events. These uncertainties lead to multiple, scientifically credible (are consistent with current understanding) models (assessments).

As a result of conducting these types of assessments in parallel, a probabilistic assessment identifies and enumerates the randomness and uncertainties in the problem whereas the deterministic approach in effect denies that they are part of the problem. Which is correct?

In an adversarial process, the dual approach would seem to provide a system that leads to disagreement rather than resolution and decision-making.

Contemplating the implementation of the approach proposed in the STP, one can consider a number of questions that at one point or another would have to be addressed:

1. How is the probabilistic assessment used to supplement a deterministic analysis?

   In the STP an algorithm to reconcile, combine, etc. the deterministic and probabilistic assessments is not provided. Since the probabilistic assessment embraces the deterministic analysis (i.e., a single deterministic assessment will be included in the probabilistic analysis), it is difficult to argue that a combination of the results of the two approaches is reasonable.

2. How are "credible alternatives" considered in the probabilistic assessment? In the deterministic assessment?

   It is not clear in the STP, nor was it clear in the discussion at our meeting with the Staff how credible alternatives are developed. The statement that they be considered and developed seems too open ended.

3. How should the "credible alternatives" be developed? Can/should/must earth science experts be used?

   There is no mention of the use of experts in the STP. While it would seem obvious that experts should be used, the STP doesn't seem to take a position on this. This is a drawback that gives the applicant the flexibility to avoid using a group of experts.

4. What basis is there to expect that the procedure recommended in the STP will satisfy the EPA safety goals? Is the design likely to be overly conservative? unconservative?

   Given the fact that a deterministic approach seems to be driving the assessment of the design basis, the Staff seems to have a technical position that is not well defined with respect to the ultimate decision criterion (e.g., the EPA safety goal).

Having taken the position of recognizing uncertainties in the FD & SHA, the STP should focus on how to provide information (an assessment of the hazards) that provides a basis to logically incorporate them in the decision-making process (i.e., determination of the design basis).

2.3 Satisfying EPA Safety Goals

Ultimately the design of the waste repository must meet the EPA safety goals. It is not clear that the approach for evaluating fault displacement and seismic hazards is consistent with the EPA goals. For example, if the deterministic assessment drives the final determination of the seismic design basis, it is not clear whether this will be overly conservative relative to the EPA goals (and thus unnecessarily more costly).

3.0 ELICITATION OF EXPERT INPUT

3.1 Background

Recent experience in performing seismic hazard assessments where a comprehensive measure of uncertainty is required clearly indicates the need to utilize earth scientists to interpret available information and to provide parameter estimates. This need is equally as great in the assessment of fault displacement and seismic hazards at a geologic repository.

3.2 Lessons Learned

The EPRI and LLNL seismic hazard assessments performed for the eastern U.S. (1,2), the Diablo Canyon seismic hazard study (3) and recent studies in the Pacific Northwest are examples where extensive use has been made of expert interpretations. There are a number of lessons from these studies that can be learned. Some of which are discussed below.

The earth scientists that are enlisted to participate in a probabilistic FD & SHA are being asked three things:

- to provide their professional interpretation of available data,
- develop alternative models based on their scientific interpretation and understanding of tectonics processes, etc. to estimate the temporal and spatial rate of future earthquake occurrences and the size of those events, and
- assign a measure of credibility to each model representing the degree to which they are believed to represent the hazard.

The capabilities of the experts is, for the most part, limited to their particular area of expertise in the earth sciences. Experience suggests that within the context of having to identify and quantitatively assess the uncertainty in data and more importantly in models they develop, the earth scientist is not well versed. Furthermore, it also seems clear that even in the context of developing basic models that the expert is familiar with (i.e., development of recurrence relationship for a single seismic source), the process becomes difficult to carry-out when the uncertainty in models or model parameters must be assessed.

The lesson from all of this seems to be that in order to utilize the experience and interpretive and modeling capabilities of the experts, an elicitation process must have at least the following attributes:

- there must be formal organization of all phases of the process pertaining to the expert assessment, including formal treatment of data, training of experts, facilitation of expert evaluations and interpretations, etc.,

- use of model building methods that fit within the experience and capabilities of the experts,

- use of facilitation methods that assist the experts to evaluate and assess the implication of modeling alternatives,

- guidance regarding the assessment/interpretation of model and parameter uncertainty, and

- requirements for formal documentation of the scientific basis for interpretations and models that are development.

3.3 Individuals Versus Teams

The LLNL study used a group of individual earth science experts whereas the EPRI study used a group of teams. Based on the experience of these two studies, it is generally recognized that an individual expert (i.e., a seismologist, geologist or geophysicists) is not fully qualified to interpret and evaluate the multi-disciplinary information that must be considered as part of the assessment. The EPRI study used groups of experts in an attempt to overcome this problem.

The question arises as to whether individuals or teams of experts should be used. In either case a suitable facilitation and elicitation process must be used.

If individuals are used, it generally recognized that some level of facilitation/education is needed to provide a reasonable assurance that the expert is working from a complete understanding of the data, its representation and its implication. On the other hand, if teams are used, the concern has been raised that the uncertainty expressed by individual members of a team may be suppressed as a result of the group's dynamics.

Based on the LLNL and EPRI experience it is clear that at some level, both teams and individuals require information, tools, guidance and facilitation. For example, the use and interpretation of probability and statistics is an area where the earth scientist requires assistance. Somewhat surprisingly, the basic task of estimating the a- and b-values and their uncertainty in a recurrence relationship is a part of the hazard, where, beforehand it was believed the experts were familiar with this process. In retrospect this was not the case. The individual experts had difficulty in assessing and understanding the implications of their uncertainty assessments. This seems to be as much or more a function of the process that they went through than the experts themselves.

4.0 RECOMMENDATIONS

In this section recommendations are provided for the USNRC Staff and for the STP. The purpose is to provide the Staff with specific guidance that can be used in the preparation of the final STP and to address the issues that were raised.

4.1 USNRC Staff

This subsection provides specific recommendations for the Staff that would not necessarily show up in the STP, but play a role in the technical position taken by the Staff. For example, the STP states that the analyses described coupled with the data obtained from the site investigation 'will provide the information necessary to establish the design bases ...' The purpose of the STP is not to develop the design basis for the repository required. However, the procedure that will be used to determine the design basis is clearly related to the specific results that should be provided by the FD & SHA.

In this subsection recommendations for the Staff are made in the following areas:

- Staff Approach
- Design Basis Strategy
- Establish a Seismic Hazard Design Probability Level
- Seismic and Other Hazards
- Ongoing Seismic Hazard Developments

Staff Approach - In order to have a reasonable assurance that the applicant submits a FD & SHA that satisfies the need to be technically adequate and the needs of reviewers (USNRC Staff, licensing boards, etc.) and users (USNRC, designers, etc.) it is my recommendation that the Staff take a strong position with regard to the framework of what is considered an acceptable FD & SHA and the results that are provided as part of these assessments. The framework should be well defined such that deviations would be unexpected and should be well supported. At the same time the applicant should have the flexibility to select different methods to perform specific evaluations.

At the same time, a clear list of specific results that must be provided as part of the analysis results should be defined. The purpose is to provide information on the inputs to the assessment and intermediate and final results that make the assessment more scrutable.

If an STP is issued that fails to take a strong position on these issues, it is possible that an applicant may conduct an assessment that was not performed to the level of depth and detail that is appropriate.

Design Basis Strategy - Develop an approach to determine the design basis for fault displacement and ground motion that is based specifically on the EPA risk criteria. To do this, the Staff will require a:

- global risk model for the repository, including its response to fault displacement and ground motion, and the
- measure of the capability to provide margin in the repository design for fault displacement and ground motion.

The Staff should develop a design strategy for fault displacement and ground motion that satisfies the EPA criteria and provides a practical design.

Establish a Seismic Hazard Design Probability Level - Based on the development of an overall design strategy, the Staff should develop a position regarding the procedure for determining the design basis for the waste repository. As part of this process a design probability level for fault displacement and ground motion must be determined.

Seismic and Other Hazards - The relationship of this STP to others that deal with geologic investigations and vulcanism and seismic-hydrologic issues etc. should be identified. Specific correlations that should be addressed by the applicant should be identified.

Ongoing Seismic Hazard Developments - The Staff should make every effort to remain up-to-date regarding the status of changes taking place in SHA. In particular, they should remain up-to-date with respect to the proceedings of the ongoing DOE/EPRI/USNRC seismic hazard resolution project. While the results of this effort may not be available for a year or more, there may be elements that are advanced to a degree such that they can be utilized in the development of the STP. In particular the developments in the area of eliciting input from experts should be helpful.

4.2 Staff Technical Position

This subsection provides specific recommendations for the STP. As stated in the draft, the STP is intended to provide the applicant with information regarding the Staff's position on an acceptable approach to evaluate fault displacement and seismic hazards. The STP should provide a clear definitive framework for evaluating and reporting fault displacement and seismic hazards. The framework must provide the applicant with the flexibility to use new methods and data and alternative interpretations of regional and local tectonics, while at the same time insuring computational and reporting requirements are satisfied.

Recommendations are provided in the following areas:

- Terminology
- Deterministic Analysis
- Elicitation of Expert Input
- Applicant Submittals
- Transparency of FD & SHA Results

Terminology - Eliminate the use of adjectives and terms such as: maximum credible fault displacement, maximum likely fault displacement, precise, sufficiently credible, etc. These terms are ambiguous and could lead to problems down the road.

Deterministic Analysis - For the reasons discussed above, it is recommended that the deterministic part of the FD & SHA assessment be eliminated from the STP.

Applicant Submittal - If possible, it might be useful to incorporate in the STP reporting milestones for the preliminary submittal (for information purposes) by the applicant of detailed program plans to deal with critical issues. The issue of site investigation appears to be handled in this way.

Extending this concept to the FD & SHA, the applicant could be requested to report on the approach to elicit expert input. The plan should be detailed enough such that an experienced reviewer would be able to identify the positive and negative attributes of the approach and provide comments accordingly.

Transparency of FD & SHA Results - One of the difficulties posed by multi-variate probabilistic assessments that involve a dual probabilistic characterization of random variables (in terms of their randomness and uncertainty components) is the fact that the physical characteristics of the problem can often remain obscure. In contrast, a benefit of deterministic assessments is the fact that they are more transparent and easily understood.

In a SHA the relative contribution of individual seismic sources to the hazard and the relative contribution of near-by moderate size events to large, more distant earthquakes is not apparent. At times even the experienced seismic hazard analyst cannot easily identify the dominant contributors to the seismic hazard. As a result a seismic hazard information base is required to fully examine in detail the physical and probabilistic attributes of the site hazard.

It is recommended that the STP provide definitive guidance regarding the development of a seismic hazard information base. This includes presentation of intermediate and final results as well as post-processing. It is important that a probabilistic FD & SHA be equally transparent to the earth scientist (non-probabilist) and to the seismic hazard analyst (probabilist) alike. The objective is to insure that a minimum level of information is computed and reported as part of a seismic hazard assessment which facilitates both the analysts and the Staffs review and interpretation of the results.

In reporting the results of a SHA, the following should be provided, as a minimum, as part of a seismic hazard information base:

1. Seismic hazard results for the total hazard and for specified magnitude-distance pairs.

2. Fraction contribution of each magnitude-distance pair to the total hazard (probability of exceedance) for each ground motion level.

3. Fraction contribution of each seismic source to the total hazard for each ground motion level.

4. Fraction contribution of the input provided by individual experts to the total hazard, including the contribution of the expert source combinations and ground motion models.

5. Analysis of variance of the primary components (experts) and parameters in the seismic hazard assessment.

Elicitation of Expert Input - The use of experts is a critical part of the FD & SHA. As a result, the STP should provide explicit guidance regarding acceptable methods and procedures for the use of experts. Unfortunately, the EPRI and LLNL seismic hazard experience in the EUS indicates that when it comes to the use of experts, general guidance is not adequate. Both EPRI and LLNL started with the same general guidance, however the approaches they used and the results they obtained were dramatically different.

Guidance in the use of experts for the FD & SHA should address issues such as:

1. Establish rules (if possible) or guidance regarding the development of alternative models.

2. Development of a framework for the following areas:

    - training and education of experts

    - development of communication tools/methods to facilitate the expert assessments

- addressing extreme outlier opinions or parameter assessments

2. Documentation of the process that was used to acquaint the experts with the data, including the facilitation of their understanding of data and its alternative interpretation.

3. Documentation requirements for expert interpretations and models that document the evaluations performed, the role of alternative data sources in the assessment, relationship of alternative models.

4. Aggregation of multiple expert inputs

5.0 REFERENCES

1. Electric Power Research Institute, "Seismic Hazard Methodology for the Central and Eastern United States," EPRI NP-4726, Palo Alto, California, 1989.

2. Lawrence Livermore National Laboratory, "Seismic Hazard Characterization of 69 Nuclear Plant Sites East of the Rocky Mountains," NUREG/CR-5250, UCID-21517, Livermore, California, 1989.

3. Pacific Gas and Electric Company, "Final Report of the Diablo Canyon Long Term Seismic Program," Docket Nos. 50-275 and 50-323, July 1988.

COMMENTS ON THE DRAFT OF

"STAFF TECHNICAL POSITION ON ANALYSES OF FAULT DISPLACEMENT HAZARDS AND SEISMIC HAZARDS AS THEY RELATE TO DESIGN OF A GEOLOGIC REPOSITORY"

and

THE MEETING OF CNWRA ADVISORS ON FAULT DISPLACEMENT HAZARDS AND SEISMIC HAZARDS ANALYSIS

by

M. Nafi Toksöz

Earth Resources Laboratory
Massachusetts Institute of Technology
Cambridge, MA

I. INTRODUCTION

The primary role of the Advisory Committee on "Fault Displacement and Seismic Hazard Analysis at a High-Level Radioactive Waste (HLW) Repository" was to review the Staff Technical Position (STP) report draft and to make appropriate comments and recommendations for improvements. The two major components of the STP are the evaluation of hazards due to fault displacement(s) at or very near the repository, and seismic hazard (i.e., ground shaking) due to local and regional earthquakes. Furthermore, the Committee has been asked to evaluate the relative merits of the "deterministic" or "probabilistic" approaches to fault displacement and seismic hazard analysis.

I have been involved in earthquake hazard studies in the eastern United States for more than twenty years. In addition to academic research I have participated in three major studies conducted by Lawrence Livermore National Laboratory (LLNL) and two by the Electric Power Research Institute (EPRI). These studies have helped me understand the relative merits of the deterministic and probabilistic approaches, the utilization of "expert" opinions, the assignment of uncertainties, aggregation of the results for hazards estimation, and sensitivity analysis and validation studies. In the next section I will give some general comments and, in sections II and IV,
I will provide specific recommendations to the STP.

II. GENERAL COMMENTS

Most earthquake hazards studies that have been carried out in the past two decades have employed a probabilistic approach. The preference of probabilistic methods over deterministic methods is due to the fact that the probabilistic approach can accommodate input data with uncertainties, alternate hypotheses, and logic tree frameworks, as well as input from a wide variety of sources (experts) by assigning proper weights. Hazard estimation, although computationally intensive, generally follows a well-developed methodology. The computed hazard curve provides the mean value and the confidence intervals. Having these numbers is very useful for the designers, management, and the general public.

There are some pitfalls to this approach. These result not because the methodology is unsound, but because of the poor quality of the input data and implementation. (Note: R. B. Hofmann's report "Probabilistic fault displacement and seismic hazard analysis literature assessment," February 1993, is an excellent document on this subject.) It is like having a puréed vegetable soup at a French restaurant. It tastes OK to everyone but no one can identify the ingredients.

In probabilistic analysis, there is a general tendency to be less discriminating and more tolerant than in the deterministic approach. This applies both to experts providing input and to integrators making the calculations. An expert may feel that if he/she is not quite accurate, other experts will provide the correct input. Thus, there is no pressure to dig into the matter as one would be forced to if one were providing a single deterministic input. Extensive education and discussions and even confrontation between experts may increase awareness. On the other hand, this approach has been criticized by some for interfering with the process of obtaining "unbiased" input from the experts. Based on my experience, assisting the experts by providing them with all the information that may be available is useful, since each expert may not be able to undertake a comprehensive study on his/her own.

Most experts who provide input to probabilistic hazard studies do not carry out a "sensitivity" analysis. Even if such studies are carried out, they are done late in the process of hazards calculations. It is important to evaluate carefully those features that contribute most to the hazard. In this respect a comparison of "deterministic" and "probabilistic" approaches may help. The probabilistic approach can identify a set of significant features based on sensitivity analysis. Then the deterministic approach can be used to evaluate the hazard from the most obvious individual features. The comparison of two sets of results provides reassurance and gives an indication of the effects of using an alternate hypothesis.

The most important factor affecting the reliability of fault displacement and seismic hazards estimates is the availability of good input data. Yucca Mountain, the Nevada Test Site, and surrounding areas have been studied extensively for the past forty years because of the underground nuclear testing program, the Yucca Mountain Repository studies, and general scientific studies that are being undertaken to enhance the understanding of geology, tectonics, and seismicity of the Nevada-California region. For example, for seismicity alone, vast amounts of data were collected by the LRSM network in the 1960s and 1970s. Specialized seismic networks have also been run in the region by the University of California at Berkeley and by Lawrence Livermore National Laboratory. A dedicated network for the repository was established and run by the U.S. Geological Survey and is being continued by the University of Nevada. All of these have provided not only seismicity data, but also attenuation and three-dimensional crust-upper mantle structure based on tomographic inversions.

Tectonic strain release associated with underground nuclear explosions has shown the properties of the r onal stress field (see Taylor *et al.* (eds.), *Explosion Source Phenomenology*, AGU Monograph, 1991; Toksöz and Kehrer, "Tectonic strain release by underground nuclear explosions," *Geophys. J. Roy. Astr. Soc.*, *31*, 141–161, 1972). Recent earthquakes in the Mojave and Owens Valley (Landers earthquake, 1992; Bishop earthquake, 1993) have added new information for the evaluation of the seismic potential, and have given rise to an alternate tectonic model (Nur *et al.*, 1993).

Much more relevant data from the data bases and archives of DOE, DOD, DOI, their contractors, and the national laboratories should be used in the evaluation of fault displacement and seismic hazards. The STP, while discussing the methodology, assumes that all relevant data will be used. However, based on past experiences we are aware that retrieval, evaluation, and presentation of such data in a usable format is a more formidable task than hazard calculation. I urge, therefore, that the importance of the data collection effort be conveyed either as part of the STP or as a separate memorandum.

III. SPECIFIC COMMENTS ON FAULT DISPLACEMENT

Estimating fault displacement is probably more difficult than seismic hazard analysis. In this area there are mapped faults and also there may be faults without known surface expressions. There are uncertainties about the time intervals at which faults may rupture, sense (mechanism) of fault displacement, magnitude of displacement, changes of fault dislocation, and coupling or interaction between faults. Fault trenching and other analysis may provide some data on recent geological movements of these faults. Given the geologic experience from other parts of the world, there will be large uncertainties associated with these data.

To accommodate these uncertainties, alternate tectonic models and questions such as whether if one fault moves this would preclude motion of another fault, or the opposite, that it would facilitate the motion of the other fault, require careful analysis. The most straightforward approach to study this problem would be the probabilistic approach. However, given how much *a priori* geologic and tectonic knowledge needs to be incorporated, a deterministic approach could provide meaningful and defensible results. Let me give an example. The regional stress regime is determined from general tectonics, earthquake, and nuclear explosion source mechanisms, in-situ stress measurements, and geodetic deformations. Given the orientation (strike dip) of a fault, the sense of motion could be predicted. If such displacement occurs on this fault, then it is possible to calculate whether this would "load" another fault and increase the probability of its rupture, or would "unload" it and decrease the likelihood of rupture. Such detailed specific analysis could provide how one establishes scenarios. These in turn could be used as tectonic input models for probabilistic calculations.

The draft STP (Section 3.2, pp. 5–6) contains the most relevant items that should be considered on fault displacement hazards. A few items need to be added or clarified. Tectonic deformations could change over a period of 10,000 years. Large earthquakes occurring on the Mojave Plate, and some increased rate of seismic activity in Mammoth and Owens Valley, may signal a change. Magma upwelling, doming, and other processes could occur that may result in uplift and a changed state of stress. Some faults that would have remained locked could become unlocked and move. These possibilities need to be built into the fault displacement model.

The term "fault segmentation" is used in the STP. Fault segmentation generally implies that the length of a "segment" determines the maximum moment of the earthquake and hence the maximum displacement. Several recent examples (including the Landers earthquake) showed that fault rupture occurred over several segments, and surface fault displacements were much larger than those predicted from the segmentation models. In considering maximum credible earthquake or maximum credible fault displacements, it would be prudent to consider the total length of all segments and larger displacements than one might anticipate from a single, straight segment fault. Even in the case of straight faults there could be large displacements at asperities, as was the case in the 1979 Imperial Valley earthquake and others.

The secondary effects of faulting on ground water are not emphasized in the STP. It is important that this aspect of fault displacement be thoroughly covered between the hydrology STP and fault hazards.

IV. SEISMIC HAZARD ANALYSIS

Section 3.3 of the STP provides good coverage of the elements that should be included in the seismic hazard analysis. I would like to re-emphasize some important aspects and add a few additional items for consideration.

- The probabilistic method is the proper approach for seismic hazard analysis.

- Large earthquakes on the Mojave block and a possible change in the tectonic regime of eastern California and western Nevada should be included in seismic sources.
- The effects of crustal structure on geometric spreading of seismic energy at regional distances (especially in the Δ = 100–200 km range) should be included.
- Three-dimensional structural effects should be considered.
- Attenuation is highly variable in the region. All data, including laboratory measurements being made from cores, should be used. Generally, it is appealing to go with a generic California attenuation model. This project deserves more detailed and specific study.
- It is implied in the STP that ground motion at depth is smaller than the surface value. This is not always true. A highly attenuating, thick near-surface layer could decrease the ground motion at the surface.
- Ground motion modeling should include 3-D structural effects near the repository. Lateral heterogeneities are such that peak ground motion could vary by a factor of ten over relatively short distances.
- Since there are other experts on the applicability of the Poisson model, I will not comment on it at this time. Personally, I do not believe that the seismicity rate will remain stationary over a 10,000-year period and I would choose input parameters to represent this uncertainty.