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INPUT ON PROBABILISTIC METHODS FOR A STAFF TECHNICAL POSITION ON FAULT DISPLACEMENT ANALYSIS AND SEISMIC HAZARD ANALYSIS

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PREVIOUS REPORTS IN SERIES

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—	Identification of Pertinent Regulatory Requirements for Systematic Regulatory Analysis of Issues Related to Probabilistic Fault Displacement and Seismic Hazard Analysis in 10 CFR Part 60	February 1991
CNWRA 91-013	Probabilistic Fault Displacement and Seismic Hazard Analysis Literature Review	November 1991
CNWRA Letter Report	Assessment of Requirements for Exercising the SEISM Code on Computer Systems Available to the CNWRA	May 1992
CNWRA Letter Report	Selection of Alternate Acceleration Attenuation Functions for the Basin and Range	August 1992
CNWRA Letter Report	SEISM 1 Code Modifications and Applications: Assessment of Needed Effort	August 1992
CNWRA Letter Report	Regulatory History and Intent for Probabilistic Fault Displacement and Seismic Hazard Analysis (PFD&SHA)	September 1992
CNWRA 91-013, Rev 1	Probabilistic Fault Displacement and Seismic Hazard Analysis Literature Assessment	February 1993
CNWRA Letter Report	SEISM 1 Code: Adaptations for Use in the Western U.S.	May 1993
CNWRA Letter Report	Summary of the May 17-18, 1993, CNWRA Advisors Meeting and Reports on Fault Displacement and Seismic Hazard Analysis	July 1993
CNWRA 94-014	SEISM 1.1 Test Analysis	August 1994
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ABSTRACT

The Center for Nuclear Waste Regulatory Analyses (CNWRA) reports concerning probabilistic seismic or fault displacement analysis were reviewed to extract material relevant to a potential Staff Technical Position (STP) on Analysis of Fault Displacement Hazards and Seismic Hazards as they Relate to Design of a Geologic Repository. A draft potential STP was prepared for review by a CNWRA Fault Displacement Hazards and Seismic Hazards Advisory Group in May, 1993. The Advisors' comments on the STP were considered by Nuclear Regulatory Commission (NRC) staff, with other material reviewed including presentations at the Advisors' meeting. A tentative revision to the draft STP, which includes suggested items concerning probabilistic methods, was prepared as a part of this report. The U.S. Department of Energy's (DOE) first seismic Topical Report which describes Probabilistic Seismic Hazard Analysis methodology and its interface with earthquake resistant design, and DOE-STD-1020 for natural phenomena hazards design which is included by reference, were considered in preparation of the revised draft STP. Changes and additions include:

- The elimination of terms such as maximum credible earthquake or maximum credible fault displacement
- Confirmation of the requirement for a parallel deterministic analysis with additional details concerning its comparison with probabilistic results
- Requirement for supportive single-expert analyses with extensive rationales, which bound the input parameters of the multivariate probabilistic analysis
- Acceptable practices
- Input parameters, which if used, are subject to expert opinion

This report is prepared to assist the NRC in developing text regarding inclusion of probabilistic analysis in a STP. If DOE Topical Reports in preparation include material encompassing the proposals in this report or proposals by NRC staff, in addition to or in lieu of those in this report, there may not be a need for STP addressing probabilistic analysis aspects of fault displacement and seismic hazards. Such a determination may or may not await completion of the three DOE Topical Reports.

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QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: No CNWRA-generated original data is contained in this report. Sources for other data should be consulted for determining the level of quality for those data.

ANALYSES AND CODES: The SEISM 1.1 computer code was used for analyses referenced in this report. However, the code has not been sufficiently developed to be placed under the CNWRA Configuration Management system.

1 INTRODUCTION

1.1 BACKGROUND

A fault displacement and seismic hazard analysis (FD&SHA) for a high-level nuclear waste (HLW) repository is to be primarily deterministic but supported by probabilistic analyses. Technical criteria for FD&SHA are currently being formulated by Nuclear Regulatory Commission (NRC) staff. This report reviews the Center for Nuclear Waste Regulatory Analyses (CNWRA) suggestions for such criteria that resulted from technical support efforts for NRC/Nuclear Material Safety and Safeguards (NMSS) over the past four years. The author of this report takes cognizance of NRC (1995) Design Basis Event (DBE) rulemaking, in which Subpart E of 10 CFR Part 72 is included by reference for natural events less frequent than 10^{-2}/yr. Subpart E of 10 CFR Part 72 requires use of 10 CFR Part 100, Appendix A for nuclear power reactors with regard to earthquake design bases. A proposed revision of 10 CFR 100, Appendix A, recommends a 10^{-5}/yr hazard level for probabilistic earthquake design of nuclear power reactors. These proposed regulatory changes make suggestions presented here tentative.

Probabilistic methods of determining seismic input to nuclear facility design has evolved through several NRC programs to reevaluate design margins in existing nuclear power plants (NPPs) after changes in perceived seismic risk had occurred. Early efforts in this regard are summarized by Bernreuter and Minichino (1982). Later developments, for example, Bernreuter et al. (1987) outlined the development of two probabilistic seismic risk computer codes that used expert opinions as input in addition to numerical data. The SEISM computer code (also known as SHC) developed by Lawrence Livermore National Laboratories (LLNL) for the NRC was one of them. EQHAZARD, developed by the Electric Power Research Institute (EPRI) for the Seismic Owners Group (SOG) of NPPs in the eastern United States, was the other. As a consequence of evaluation of design margins, the NRC is considering a revision of 10 CFR Part 100 to include probabilistic methods of defining Safe Shutdown Earthquakes (SSEs) for NPP design. This is a significant departure from the NRC past regulatory philosophy which embraced only deterministic methods for setting initial seismic design criteria.

Because of broad interest in probabilistic seismic hazard methods, a Panel on Seismic Hazard Analysis organized under the Committee on Seismology of the National Research Council, prepared a review of these methods (National Research Council, 1988). The panel was charged with the assessment of capabilities, limitations, and future trends in probabilistic seismic hazard analysis (PSHA) in the context of alternatives. The study and report were funded by the NRC, the U.S. Department of Energy (DOE), the U.S. Geological Survey (USGS), the Air Force Offices of Scientific Research (AFOSR), the Federal Emergency Management Agency (FEMA) and the Defence Advanced Research Projects Agency (DARPA).

The NRC Office of NMSS, Division of Waste Management (DWM) initiated efforts at the CNWRA to assess PSHA methodologies for potential application to a HLW repository with a 10,000 yr period of performance, which contrasts with a nominal 40 yr life expectancy for NPPs and most other civil structures. Part of the CNWRA program was to acquire one or both of the seismic risk computer codes and implement them on their computers. The NRC/LLNL code was acquired and modified to perform PSHA at western U.S. sites. A hazard calculation was made using published expert opinions, and a probabilistic fault displacement analysis (PFDA) capability was implemented in the code and tested (Hofmann, 1994).

Both before and during the period of CNWRA investigation of PSHA, it became clear that the DOE intended to use probabilistic methods to develop seismic hazard inputs to various categories of HLW repository structures. Consequently, attempts were made to formulate a Staff Technical Position (STP) on probabilistic fault displacement and seismic hazard analysis (PFD&SHA) which was also to include deterministic analyses. Initial attempts at preparation of a PFD&SHA STP were abandoned because of a rapidly changing technology. However, to keep pace with the DOE activities at Yucca Mountain (YM), two STPs were prepared: McConnell et al. (1992) regarding the identification of fault displacement hazards and seismic hazards at a geologic repository, and McConnell and Lee (1994) on consideration of fault displacement hazards in geologic repository design.

A board of FD&SHA advisors was convened at CNWRA to review efforts at developing an STP on the analysis portion of the originally envisioned STP and to respond to questions posed by NRC and CNWRA staff. The potential STP provided for the advisor's review is labeled the "draft STP" throughout this report. The advisors' responses were not uniform but generally they all supported the use of probabilistic methods. The board was divided on whether or not to also require a deterministic analysis.

The DOE has proposed preparation of three seismic related Topical Reports. The first on PFD&SHA methodology, also outlined the interface with design and stated that methods described in DOE-STD-1020 (U.S. Department of Energy, 1992) would be used. Initially the report was rejected by the NRC because it did not include a parallel deterministic evaluation of the seismic hazard as well as a probabilistic one. It was later accepted for NRC review after a commitment to include a requirement for a parallel deterministic analysis was provided by the DOE. An annotated outline of the second Topical Report on seismic design methodology was reviewed and critiqued. The DOE agreed to add a section discussing the rationale for various factors used to asses the probabilistic or deterministic seismic hazard before it is used in design calculations for specific structures. A third Topical Report is to provide the calculations and results of PFD&SHA for the YM HLW repository.

The annotated outline of the DOE second Topical Report appears to follow DOE-STD-1020 and concentrates on calibrating the probabilistic hazard methodology with the risk levels proposed by building codes for uncritical or less critical structures. For critical structures, acceptable hazard levels are calibrated to average hazards derived from deterministic SSE design accelerations for existing NPPs (except that a median ground motion is recommended rather than the 85th percentile ground motion used for NPPs). The DOE "calibration" of hazard (inverse of return period) level results in lower design criteria for earthquakes than for other natural hazards. The opposite position was taken for tornadoes in DOE-STD-1020, resulting in a lower hazard level and more stringent design criteria rather than the reduced design criteria for earthquakes. Therefore, the "calibrated" hazard level for two of the four natural hazards considered are exceptions to the DOE uniform natural phenomena hazard concept. The DOE justifies the reduction of accelerations or spectra on the basis that they intend to use elastic design methods which do not consider the energy absorbed by the structure during its degradation when ground motion exceeds elastic design parameters (U.S. Department of Energy, 1994b). The process of structural degradation is termed "ductility" by the DOE. NRC regulations and Standard Review Plans for NPPs currently require that a nonreduced deterministic seismic hazard and an elastic design be used. Designing elastically for less than a reasonably expected level of ground motion is justified by the DOE because there is no active fission reaction taking place in a repository as there is in a NPP. Therefore, they argue that the immediate risk to the public is much less than for an NPP and some structural degradation short of failure should be permissible.

There are concerns that the DOE combined ground motion determination and design philosophy may not be adequately conservative to ensure that the public will not be exposed to undue risk, because the amount of radioactive material planned for the repository is orders of magnitude larger than contained in a single NPP, the repository's period of retrievability may be several times as long as an expected NPP time of service, and the repository's planned performance period is about 200 times as long. Although the first of the series of three DOE seismic related Topical Reports has been prepared, all details of seismic design philosophy and the results of that philosophy are not final.

1.2 OBJECTIVES

The objective of this report, pending more complete information regarding the DOE seismic input determination and proposed ground motion reduction before use in design calculations, is to summarize DWM PFD&SHA efforts germane to the development of an analysis STP. Suggested probabilistic input to an internal draft analysis STP, from DWM/CNWRA PFD&SHA efforts, is in Appendix A of this report. Further STP development, however, will depend on whether details in the DOE Topical Reports, taken together, are in reasonable agreement with NRC staff concerns. Because of the limited 3 yr time allotted NRC for review of the DOE License Application (LA), the NRC must be in a position to develop an analysis STP for ground motion and fault displacement should it become apparent that DOE and NRC staff are in significant disagreement over planned levels of conservatism in ground motion or fault displacement. An objective of this report is to document basis for staff concerns and provide input to a draft STP which incorporates these concerns.

1.3 STAFF TECHNICAL POSITIONS AS TECHNICAL GUIDANCE

The STPs are issued to describe and make available to the public methods acceptable to the NRC staff for implementing specific parts of the Commission's regulations, and to provide regulatory guidance to the DOE. The STPs are not substitutes for regulations, and compliance with them is not required. Methods and solutions differing from those set out in the STP will be acceptable if they provide a basis for the findings requisite to the issuance of a permit or license by the Commission.

Published STPs will be revised, as appropriate, to accommodate comments and to reflect new information and experience.

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2 DOCUMENT REVIEW

Several documents prepared as a part of the NRC DWM PFD&SHA efforts and allied efforts include elements relevant to the development of an analysis STP:

- PFD&SHA Literature Assessment, CNWRA 91-013, 1991 (Revision 1, 1993)
- Summary Report of the May 17-18, 1993 CNWRA Advisors Meeting and Reports on FD&SHA, CNWRA Letter Report of July, 1993
- SEISM 1.1 Test Analysis, CNWRA 94-014, 1994
- Testing of SEISM 1.1: Sensitivity Analysis, CNWRA Letter Report of January 1995
- Background Report on the Use and Elicitation of Expert Judgement, CNWRA 94-019, 1994
- Input to the Draft STP on Elicitation of Expert Judgement, CNWRA 95-006, 1995
- Text and Illustrations of Presentations made at the DOE/USGS Ground Motion Data Needs Workshop 20-21 April, 1995 in Salt Lake City, Utah
- NRC Internal Draft STP on Analyses of Fault Displacement Hazards and Seismic Hazards as they Relate to Design of a Geologic Repository, an Annotated Outline, February 1993

These documents are reviewed for materials that may be addressed in an analysis STP. Other NRC, DOE, or CNWRA documents may also be referenced in the process of these reviews.

2.1 SUMMARY OF THE PROBABILISTIC FAULT DISPLACEMENT AND SEISMIC HAZARD ANALYSIS LITERATURE ASSESSMENT (CNWRA 91-013, REVISION FEBRUARY 1993)

Several topics were reviewed briefly in CNWRA 91-013 (Hofmann, 1993). They included:

- The EPRI PSHA method
- The NRC/LLNL PSHA method
- A draft of the American Society of Civil Engineers'(ASCE) procedure which emphasized use of theoretical attenuation functions
- Probability of deterministic ground motion
- The direct PFDA method
- PFDA using earthquake recurrence relationships and seismic moment

- Characteristic slip, earthquakes, and segmentation
- Distribution of fault slip with branching faults near the surface
- Fault mechanics including chaotic characteristics
- Ground motion attenuation formulae
- Probability distribution functions including chaos considerations
- Theoretical near-field ground-motion modeling formulae
- The Delphi method and the use of expert-opinion in PFD&SHA

Other topics are also addressed. Section 2.1.7 and Chapter 4, Conclusions and Recommendations of CNWRA 91-013, contain suggestions for STP topics as perceived at the time of the report's preparation. In view of increasing acceptance (and controversy) over PFD&SHA methods since that time, not all of those topics now appear to be as appropriate. Subsequently, other concerns have arisen. The topics for inclusion in a STP may be consolidated under several themes or categories:

- Expert opinion
- Near-field
- Benchmarking or calibration
- Stress drop
- Effects on groundwater or hydrologic flow
- Other effects, for example, fault-slip area size, slip on subsidiary faults (coseismic faulting), generation of new faults, slip sensitivity to stress fields, extension of PSHA from short to long lived facilities, recurrence on individual fault planes, and determination of maximum magnitudes

2.1.1 Expert Opinion Related Topics

Note that general characteristics of expert opinion and a draft expert opinion STP are reviewed later in this report. Suggested concerns related to this topic from the PFD&SHA Literature Assessment report follow:

- Variables which can be directly determined from data should not be determined by expert opinion.
- Expert opinion should not be substituted for reasonably obtainable data.

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- A complete rationale should accompany each expert opinion. The rationale's should be developed to the extent that they have or could be subject to peer review. The rationale's will be reviewed by NRC technical staff and rejected if found to have insufficient or erroneous bases.

- Requests for expert opinion for which no rationale can be given, should be avoided.

- If constraints are placed on expert opinion, for example, multiple choice entries are provided, a fully justified rationale for the constraints should be provided.

- Basis for choice of experts should be provided.

These items are included in Section 3.6 of Appendix A of this report.

2.1.2 Near-Field Related Topics

Ground motion in the near-field of fault slip is not well recorded nor is there consensus regarding the extent of such effects or whether they have an impact on structural response. Fifteen km is the nominal depth from the surface to the elastic-plastic interface as defined by the occurrence of aftershocks in the Basin and Range Tectonic Province (i.e., University of Nevada at Reno and the U.S. Geological Survey, 1992). Therefore, near-field is defined here as any point within 15 km of the slipping portion of a fault (Bernreuter et al., 1987b).

- If a fault cannot be eliminated as a potential earthquake source and it is within 15 km of underground workings or surface facilities, near field effects on earthquake induced ground motion should be investigated.

- Sites within 15 km of a fault plane and which lie with 10 arc degrees of any point on a potential slip surface within that fault must be considered to lie within a zone of enhanced seismic ground motion and this potential effect should be taken into account when determining ground motion at the site.

- Theoretical methods of determining near-field ground motion must be shown to be compatible with the limited set of near-field strong motion records and their probability distributions.

- Ground motion spectral attenuation will consider the effect and probabilities of the breaking of asperities or barriers in the near-field as well as long period effects attributable to the throw of the fault.

- If near-field ground motion is specified using computer modeling techniques, several such techniques should be used and results treated as expert opinions in PSHA.

- Published attenuation curves, theoretical or empirical, have a limited basis for near-field values. Available data should be plotted with the attenuation curves used and a rationale provided for their extrapolation or adjustment in the near-field distance range.

These elements are broadly considered in Section 3.3 of Appendix A of this report.

2.1.3 Benchmarking or Calibration Related Topics

There are three themes within this group: (i) benchmarking; (ii) comparison of complex methods for PSHA, PFDA, and age dating techniques; and (iii) comparison with analogs. Some suggestions under this heading were given in slightly different form in the prior section. Therefore, only those suggestions not previously listed will appear here.

- PSHA is known to have some level of instability (National Research Council, 1988). That is, PSHA for the same site by two different groups of experts or by the same group of experts at different times will not produce the same answer (Bernreuter et al., 1987). The level of instability may be site specific. Therefore, an estimate of instability should accompany each PSHA. This may be accomplished by making two or more PSHA and comparing results.

- "Testing the validity of PSHA results is difficult." According to the National Research Council (1988), therefore, alternative methods are required for comparison, for example, deterministic.

- PSHA methods should be benchmarked against historic and paleo seismicity which are used as inputs to the process. PSHA should accurately predict what has happened; if it does not, a rationale is required.

- Proposed PFDA or PSHA methods should be compared to published methods. Serious differences should be reconciled with an extensive well supported rationale.

These suggestions are considered in Section 3.1.1 of Appendix A of this report.

2.1.4 Stress Drop Related Suggestions

Stress drop, fault-slip area, amount of offset, and rigidity at depth are part of one of the equations describing seismic moment or moment magnitude. Therefore, although stress drop will not influence the determination of magnitude from seismic records, it will play an important role in translating paleo-offsets into magnitudes for paleo-earthquakes.

- Normal faults are thought to be less energetic than strike slip or thrust faults (McGarr, 1984). Establishment of stress by several means is recommended, for example, by aftershock area and instrumental magnitude with well supported assumptions of offset and rigidity, as well as from corner frequencies of teleseismic spectra.

- Analog earthquakes from other extensional areas of the world should be used to augment limited data from the Basin and Range tectonic province and the YM area in particular, for determination of stress drops associated with dip slip earthquakes.

- Dynamic fault modeling should be employed with empirical support for a best estimate stress drop in order to estimate magnitudes of paleo-earthquakes. Such modeling should be performed by several experts using various published techniques with which they are familiar.

These suggestions are broadly considered in Section 3.3 of Appendix A of this report.

2.1.5 Earthquake Effects on Groundwater

Two of the CNWRA FD&SHA experts strongly advised that effects on groundwater should be considered along with requirements for estimation of fault displacement or seismic hazards. Draining of perched water tables during the 1989 Loma Prieta, California, earthquake and increases in groundwater level and flow during the 1983 Borah Peak, Idaho and 1959 Yellowstone Park, Wyoming, earthquakes were cited. Therefore, suggestions regarding this topic are included for consideration in a PFD&SHA STP.

- PFD analyses must show relevance to the mechanisms by which fault displacement and groundwater changes will affect repository performance. Principal mechanisms to be addressed are: (i) opening of fractures which increase hydrologic flow, (ii) creation of fault gouge which could divert hydrologic flow, (iii) canister rupture or degradation which could result in increased corrosion rates, and (iv) reduction in porosity which could squeeze interstitial water into the repository. These effects should be considered for both pre- and post-closure.

- Establish mechanisms for groundwater elevation changes associated with earthquakes. If modeling is used, the methodology should be benchmarked against observed occurrences.

- Document analog situations to aid in the evaluation of groundwater changes that have accompanied earthquakes and that may accompany earthquakes at YM.

- Develop the conditions and their probabilities for increasing or decreasing permeability along fault planes as a consequence of fault movement accompanying earthquakes. Ideally this information should be obtained from Basin and Range tectonic province earthquakes and geology.

These suggestions are broadly considered in Section 3.3 of Appendix A of this report.

2.1.6 Recurrence of Earthquakes or Fault Offsets

The recurrence of earthquakes in source regions or on particular faults appear to have a strong influence on the interpretation of paleo-offsets on faults which may be used to predict strain rates, paleo-earthquake recurrence or paleo-offset recurrence and consequently on development of probabilistic hazards. Although, there are some differences of opinion, many investigators (Abercrombie and Brune,

1994) are convinced that for regions where there is a statistically significant sample of earthquake data, a Gutenberg and Richter type of recurrence (Gutenberg and Richter, 1954) will apply and the slope of the recurrence will be near 1.0 if magnitudes are expressed as Richter magnitudes. Richter magnitudes are defined as the Richter local magnitude, M_L, for magnitudes less than 6.5 and 20 second surface wave magnitude, and M_S, for magnitudes of 6.5 and greater. Recent changes to the Richter magnitude definition require the use of moment magnitude, M_W, for magnitudes greater than 8.0. Use of M_W for all magnitudes may not indicate a recurrence slope of near 1.0.

A concern, however, is that earthquake recurrence for individual faults often declared as earthquake sources for a PSHA within a region, have not and cannot be determined (Krinitzsky, 1993). This concern must be resolved if PFD&SHA is to be considered a viable methodology for application to an HLW repository with a 10,000 yr time of performance concern. These concerns must be resolved for shorter term hazard assessment as well. Factors and recommendations relevant to these concerns are:

- An annual exceedance probability hazard curve should be developed for offsets on particular faults that may affect repository performance.

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

- The theory that barriers or asperities eventually break (Davidson and Scholz, 1985), suggests that the characteristic earthquake concept may not define faulting recurrence over long periods of time. An HLW repository must function over a long period of time. Therefore, assignment of characteristic earthquakes to a YM HLW repository for the postclosure time period may not be valid.

- If time dependent models are used, they should include chaotic or fractal models which suggest clustering of seismic activity in time and space. These, in turn, suggest that the current relatively low seismicity at YM may be a temporary condition. Wallace (1985, 1987) and Ryall and Van Wormer (1980), for example, support this concept with geological evidence from the Basin and Range tectonic province.

- Scoping calculations for recurrence over different periods of time should be performed to determine the stability of earthquake recurrence geographically and with time. For example, Rogers et al. (1987) depict contours of seismic energy release for the historical record near YM, and Shedlock et al. (1980) derive slip amounts from seismic energy release. The inverse of this process would yield seismic energy from paleo-fault offset measurements. Current slip across the Basin and Range tectonic province derived from Global Positioning System (GPS) and past geodetic measurements could be randomly distributed over faults to estimate potential seismicity over long time periods. These calculations may provide an estimate of uncertainty in recurrence evaluation.

- Wesnowsky et al. (1982) found a best fit to individual fault recurrence in western Honshu to be repetitions of the maximum magnitude possible for a given fault length, with aftershocks. Wesnowsky (1994) found best fits to splays of the San Andreas fault to be a characteristic recurrence or a Gutenberg-Richter recurrence. The entire San Andreas fault system was best fit by a Gutenberg-Richter recurrence. Few faults are sufficiently active or sufficiently monitored that a definitive recurrence for them can be established. There appears to be a range of possible recurrences on individual faults which must be accommodated in some way, within the regions enclosing them. This is a large uncertainty which according to Wesnowsky et al. (1982) may change hazard results by a factor of two. This difference may be larger when the implications for variations in background seismicity required to maintain a regional Gutenberg-Richter recurrence are also considered.

These topics are broadly considered in Section 3.2 and 3.3 of Appendix A of this report.

2.1.7 Other Topics

Recommendations for other STP topics that were not easily categorized are included in this section.

- If fault segments are identified, the maximum earthquake should be determined from the sum of the length of each segment plus the width of the barrier or barriers.

- The maximum magnitude earthquake that could be caused by mining the repository should be estimated using the formulae of McGarr (1976, 1991).

- Computer codes for PFDA and PSHA and other analysis methods used (including logic trees) should be flow diagrammed in sufficient detail that their function may be reproduced and tested. If logic tree detail is left to the "expert," complete examples should be provided in the methodology flow diagrams and the entire logic tree used by each expert should be presented in the final evaluation of hazard.

- Published Type IV PSHA methodologies (National Research Council, 1988) are only for short lived facilities (25–50 yr). There is not a consensus regarding the level of uncertainty in these analyses (Bernreuter et al., 1987). Therefore, high uncertainties may render these or longer time span hazard estimates too unreliable for use in regulating a HLW repository. Uncertainty estimates in long term probability assessments must be defensible and the methodology used to obtain these estimates must be justified in the light of other methodologies which may indicate higher uncertainties.

- Donath and Cranwell (1981) offer a probabilistic approach to generation of new faults and the probability of recurring displacements on existing faults. Orientation of faults to stress may increase the probability of movement of one fault versus another, (McConnell et al., 1992). These techniques should be implemented in the mathematical framework of fault displacement probability (Morris et al., 1995).

- The probability of offsets on smaller faults parallel to main faults or their splay faults should be calculated using, for example, Bonilla and Lienkamper (1984), Slemmons (1977), or similar relationships developed using data from the most recent earthquakes in addition to those analyzed by these publications.

These items are addressed in Sections 3.1, 3.2, 3.3, and 4.1 of Appendix A of this report.

2.2 SUMMARY OF THE MAY 17-18, 1993, CENTER FOR NUCLEAR WASTE REGULATORY ANALYSES ADVISORS MEETING AND REPORTS ON FAULT DISPLACEMENT AND SEISMIC HAZARD ANALYSIS

NRC and CNWRA staff made presentations at this meeting and posed questions to the FD&SHA advisors. The advisors had been sent an internal draft of an analysis STP. All responded with recommendations prior to the meeting. Two advisors revised their recommendations following the meeting. There is considerable detail in the individual reports. Major categories of recommendations are summarized here:

- Terminology
- Use of Deterministic Analysis
- Setting NRC Probabilistic Analyses Requirements
- Elicitation of Expert Opinion
- Credibility and Weighting of Expert Opinion
- Alternative Tectonic Models
- Stability of the Tectonic Regime
- Uncertainties
- Data Collection
- Relationship of PFD&SHA to Groundwater and Iterative Performance Assessment (IPA)
- Transparency of PFD&SHA
- Attenuation with Depth
- Costs

These items are addressed in various sections of Appendix A of this report.

2.2.1 Terminology

Two experts were strongly opposed to the use of terminology such as maximum credible earthquake (MCE), maximum credible fault displacement (MCFD), and such words as "precise" or "sufficiently credible." Three experts did not comment on this topic.

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2.2.2 Use of Deterministic Analyses

Opinion was divided on this issue. An advisor stated that deterministic analysis are needed to establish basic data, distinguish among hypotheses, test models, and provide "reality checks," but complete data and physical models are never achievable so probabilistic analysis is important and necessary. Another expert stated that the deterministic approach can be used to evaluate the hazard from the most obvious individual features and that given how much *a priori* geologic and tectonic knowledge needs to be incorporated, a deterministic approach could provide meaningful and defensible results. This expert also pointed out that because of the poor quality of the input data and implementation there are pitfalls to the probabilistic method. Speaking of the complexity of the process, he stated "It is like having pureed vegetable soup at a French restaurant. It tastes OK to everyone but no one can identify the ingredients."

The other side of the argument was taken by three of the experts with two being somewhat ambivalent and one adamant. The latter stated that the idea of a dual approach is inconsistent with the concept of a stable, for example, technically defensible licensing process that is workable by both the applicant and the NRC staff. "Eliminate the dual deterministic - probabilistic approach. Use only a probabilistic FD&SHA." One expert stated that the ultimate need, in order to meet the Environmental Protection Agency (EPA) criteria, of a quantitative description of randomness and uncertainty provides the basis for probability-based criteria. Also stated was that a site investigation should be supported with a deterministic analysis. In support of a probabilistic procedure, another advisor suggested that several questions would have to be answered implying that only a probabilistic approach could do so. Questions posed were "(i) how was the MCE 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 yr and the next 10,000 yr; and (iv) what differential fault displacements and ground shaking levels will result from each of the hypothesized events? and so on." This advisor also states that a single value estimate will lead to suspicion, can be easily disputed by any opposition party and that a deterministic analysis provides for a simpler, more understandable or transparent approach, however the single value is not defensible in the light of all the model, parameter and phenomenological uncertainties. This advisor concludes that a deterministic approach will not be defensible in the light of all the uncertainties and the inherent randomness of earthquake phenomena.

This topic is addressed in Sections 3.3 and 4.3 of Appendix A.

2.2.3 Setting Nuclear Regulatory Commission Probabilistic Analysis Requirements

The DOE is expected to develop its seismic design using probabilistic accelerations or spectra. The NRC needs to develop HLW repository seismic acceptance criteria. Currently, an acceleration or spectra which recurs once every 100,000 yr is recommended by the NRC as acceptance criteria for NPPs in a proposed revision to 10 CFR Part 100. Two of the FD&SHA advisors included the setting of such criteria by the NRC as an item that should appear in the analysis STP.

> "As soon as NRC establishes its numerical criteria [See Part C(3), below], it can ask DOE to provide current design values."

With regard to setting fault displacement probabilistic criteria:

> C(3) "(a) Format and Level: for example, the 84 percent of the maximum probable fault displacement[1] (MPFD) (i.e., epistemic uncertainty only) and/or the 84 percent of the maximum likely fault displacement[1] (MLFD) in 10,000 yr (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 mean frequency of occurrence of (less than), say, 10 percent in 10,000 yr? (The mean covers the epistemic issue: the 10 percent 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."

With regard to setting ground motion probabilistic criteria:

> C(3) "(b) Re-scaling time: It occurs to me that a basis for criteria could be established by rescaling 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 YM 10,000 yr 'look like' 100 to 10 California yr, or 'typical' conventional engineering project window lengths in California."
>
> C(3) "(c) With the 're-scaled time' basis in (c) one would also have to look at the likelihood of a major/'sudden' change in slip rates in the neighborhood in 10,000 yr. This is a do-able problem. Think of the Wallace Basin and Range study. Think of analogies in space/time elsewhere."

Another expert wrote:

> "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 identified."

Proposed positions of this topic are in Sections 3.2 and 3.3, and are discussed in Sections 4.2 and 4.3 of Appendix A of this report.

2.2.4 Elicitation of Expert Opinion

More than one advisor pointed out that there were no expert elicitation criteria in the draft STP and implied that there should be. Some advisors provided specific advice.

One expert stated that guidance should be provided in the use of experts for issues such as:

- Establish rules (if possible) or guidelines regarding the development of alternative models
- Develop a framework for the following areas:

[1]Definition added by CNWRA.

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- — Training and education of experts

- — Development of communication tools/methods to facilitate the expert assessments

- — Addressing extreme outlier opinions or parameter assessments

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

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

- Aggregation of multiple expert inputs

Another advisor stated:

"The preference of probabilistic methods over deterministic methods is due to the fact that the probabilistic approach can accommodate input data with uncertainties, as well as input from a wide variety of sources (experts) by assigning proper weights." "In probabilistic analysis, there is a tendency to be less discriminating than in the deterministic approach. This applies to both 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 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 of his/her own." "Most experts who provide input to probabilistic hazard studies do not carry out 'sensitivity' analysis." 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."

A third opinion was:

"On expert opinion. This letter 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 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 there is not, where there remains major uncertainty and where not, etc. "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 process is of gathering and using and documenting it is the best available."

These topics are broadly addressed in Sections 3.6 and 4.6 of Appendix A of this report.

2.2.5 Credibility and Weighting of Expert Opinion

This theme was discussed by several of the FD&SHA advisors.

"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 intense 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."

"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 the experts who are familiar with the geo-tectonic setting of the region and 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 the DOE and EPRI should be utilized for this purpose."

"The STP does not address the roles of experts in the 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 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, PSHA, YM geology, seismology, etc. Those involved should have a hands-on role."

Proposed statements in Appendix A are that expert opinions must be well documented and technically supported. Further, that experts chosen by peer nomination do not require weighting because these differences of opinion are a measure of uncertainty based on information available at the time of elicitation.

2.2.6 Alternative Tectonic Models

The advisors related this topic to expert opinion and were, in general, pleased that the draft STP addressed the topic of alternative tectonic models. The implication is that if alternative models are to be considered, they should be weighted and their probability quantified in PFD&SHA.

2.2.7 Stability of the Tectonic Regime

This topic is related to alternative tectonic models and expert opinion. Several advisors stated that this was an important topic which should be considered in PFD&SHA at YM. Several advisors commented that they thought that there was a good possibility that the tectonic regime could change significantly over a 10,000 yr period. One expert cited papers by Wallace which identified paleo-seismic activity changes on about 1,000 yr intervals in the Basin and Range tectonic province. Another expressed concern over the effects observed after the 1992 Landers earthquake which resulted in the $M = 5.6$ Little Skull Mountain earthquake near YM. This FD&SHA expert believes that stress fields should be known and analyzed to determine the likely consequences on faults near the HLW repository, of major movements on large California faults.

This topic is discussed in Sections 3.2, 3.3, 4.2, and 4.3 of Appendix A of this report.

2.2.8 Uncertainties

The advisors agreed that uncertainties in models and interpretations of data could only be estimated by expert judgement. 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, virtually all pertinent data is interpreted by experts to some degree. Both geologic and engineered barriers are simultaneously challenged by an earthquake, thereby reducing the effectiveness of this redundancy. Therefore uncertainties must be reduced by other means such as using a higher than 50th percentile ground motion or fault offset and through conservative designs.

This topic is addressed in Appendix A by the proposed requirement for 84th percentile measures of fault offset or ground motion values in design if they are higher than deterministic values.

2.2.9 Data Collection

Data and data needs were at times addressed by the advisors. In regard to a critique of the draft analysis STP outline of 1992, FD&SHA experts wrote:

> "Is there enough regionally specific data to produce a YM specific ground motion model?" The shopping list in Section 4.2 (e.g., interaction, coupling, stress increases induced by heat from the waste, spacio-temporal clustering, segmentation based on paleo-seismic studies, etc.) is a scientists dream. But how much is really do-able (e.g., all the excellent information about paleoseismic 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 failures, etc.)
>
> ". . . the gathering of facts and data that is usually motivated along deterministic lines is absolutely essential. The basic data base needs to be incorporated as transparently as possible into probabilistic analyses." ". . . deterministic studies are needed to establish basic data, distinguish among hypotheses, test models, and provide 'reality checks'."
>
> ". . . it is imperative that all possible geologic and seismologic data be gathered."
>
> "The most important factor affecting the reliability of fault displacement and seismic hazards estimates is the availability of good input data. YM, the Nevada Test Site (NTS), and surrounding areas have been studies extensively for the past forty yr because of the underground nuclear testing program, the YM 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 Long Range Seismic Monitoring Program (LRSM) network in the 1960s and 1970s. Specialized networks have also been run in the region by the University of California at

Berkeley and by the LLNL. A dedicated network was established and run by the USGS and is being continued by the University of Nevada. All these have provided not only seismicity data, but also attenuation and three-dimensional crust-upper mantle structure based on tomographic inversions."

The latter expert also relates that contributions to understanding of the stress field of the area have resulted from the testing program and recent earthquakes have added understanding of the region's seismicity. He concludes:

"Much more relevant data from the data bases and archives of DOE, U.S. Department of Defense (DOD), U.S. Department of the Interior (DOI) and their contractors, and the national laboratories should be used in the evaluation of fault displacement and seismic hazards. The STP, while discussing 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 useable format is a more formidable task than hazard calculation. I urge, therefore, that the importance of the data collection effort be conveyed either as a part of the STP or as a separate memorandum."

The CNWRA is in the process of identifying the DARPA LRSM data and other NTS related seismic monitoring. Analogue LRSM data tapes being abandoned on the closure of the Teledyne-Geotech operated office of the Air Force Technical Applications Center in Alexandria, Virginia, were collected by Dr. Phinney of Princeton University, and Dr. Alexander of Pennsylvania State University. Dr. Helmberger at the California Institute of Technology is reputed to have a complete set of LRSM data in its original analogue tape form (Tajima and Hofmann, 1995).

That relevant data gathering and research are required is stated or strongly implied in various sections of Appendix A of this report.

2.2.10 Relationship of Probabilistic Fault Displacement and Seismic Hazard Analysis to Groundwater and Iterative Performance Assessment

Four of five FD&SHA experts commented that the STP should discuss or provide limits to groundwater changes and IPA:

". . . 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 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 (PA). Even with the current IPA, the derivation of top-down criteria would take time. Therefore, conventional bottom-up may be the best interim guidance."

". . . two non-traditional aspects of seismic-coupled hazard, hydrology and volcanism, deserve special attention, because the proposed repository site at YM is unique both in its location hundreds of meters above the water table and also its location near small basaltic volcanoes, one of which is Quaternary in age."

This expert pointed out that, like Loma Prieta, there are many perched water tables in the YM area. During the Loma Prieta earthquake many of these perched water bodies drained because of earthquake induced permeability increase in faults or fractures. He also points out that where volcanism is present, seismicity is low—a condition that is also seen at YM. Other FD&SHA experts stated:

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

This topic is addressed in Sections 4.1 and 4.6 of Appendix A of this report.

2.2.11 Transparency

The advisors agreed that PFD&SHA procedures tend to obscure the rationale being used. Multivariate expert-opinion-based PFD&SHA obfuscates the reasoning that is being applied to obtain the probabilistic estimate of hazard. This tendency has been called lack of transparency. Deterministic methods are much more transparent. There was at least one recommendation that transparency of PSHA be achieved through disaggregation which identifies the magnitude-distance pairs from which hazard statistics are being developed. A large number of certain magnitude-distance pairs generated within the PSHA computer code identifies those pairs as principal contributors to seismic hazard. Strong motion records which match these magnitudes and distances, may then be located and used in finite element analyses, or a number of them may be analyzed to produce spectral envelopes, with standard deviations, for pseudostatic structural analysis.

Such a process improves understanding the output of PSHA, but does not contribute greatly to understanding the rationale behind inputs to the analysis. Research was recommended to improve transparency. One advisor was a staunch advocate of the use of logic trees with final leaves being event trees. Others agreed that some sort of bookkeeping method to track alternative tectonic models and parameters was a good idea. Logic trees may have a disadvantage in that they can be perceived to include many trivial models or parameter differences which dilute the effects of consequential differences of opinion among experts. They may also constitute deviations from accepted analysis procedures. This further adds to lack of transparency and may detract from PFD&SHA acceptance by hearing boards.

This topic is addressed in Sections 3.2 and 3.3, and discussed in Sections 4.2 and 4.3 of Appendix A.

2.2.12 Attenuation with Depth

The advisors acknowledged that generally, ground motions were observed to be less with depth and that the theoretical maximum reduction at depth, of ground motions measured at the surface, was 50 percent. However, one of the advisors added warnings regarding taking these generalizations as generally applicable rules:

> "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 three-dimensional (3D) structural effects near the repository. Lateral heterogeneities are such that peak ground motion could vary by a factor of ten over relatively short distances."

The advisor verbally related several examples of exceptions to the rule of diminishment of ground motion at depth, during discussions at the advisors meeting. It may be important to note that the maximum 50 percent reduction of ground motion is a function of wavelength. Therefore, the reduction is dependant on frequency of vibration of ground motion, the velocity profile beneath the site and the depth of the facility.

This topic is broadly addressed in Section 3.3 of Appendix A of this report.

2.2.13 Costs

Costs were not considered by the FD&SHA panel; however, costs of multivariate expert opinion based PSHA were discussed by Krinitzsky (1993):

> ". . . 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." "...an additional 2.3-2.8 million dollars will be allocated to resolve differences between the LLNL and EPRI studies."

Advocates of multivariate expert opinion based PSHA believe that the orders of magnitude increased cost over deterministic analyses is justified because of increased stability of design values after construction has begun. The argument is based on the logic that discovery of a new larger or closer fault to a facility may have little impact if earthquake recurrence on the new fault is shown to be low. Even if the fault cannot be proved to have a low recurrence, the addition of one expert opinion, indicating a significant recurrence, to expert opinions in the original analysis, will not change the probabilistic hazard very much. However, if the new opinion is well supported and accepted, a re-elicitation could result in revisions in some or all previously given opinions. It remains to be seen how well this logic plays out in licensing hearings for new facilities.

Costs are of particular interest when designers propose to reduce the seismic input given to them before engaging in design calculations for individual structure. When large reductions are to be applied, the resulting input may be so low as to be inconsequential. In this circumstance, justification of the much higher expense of probabilistic methods is difficult.

Because of the HLW repository requirement for PA over longer time periods than are documented by human experience, and the large size and potential long term secondary hazard posed by the repository, the use of supportive probabilistic analyses are necessary. The high cost of multivariate probabilistic analyses using expert opinion is recognized. Means of implementing these methods that reduce costs are recommended. For example, keep management of experts to a minimum, use expert elicitation only where data cannot be reasonably obtained, and accept elicited opinions without repeated group interaction to move toward consensus.

2.3 SUMMARY OF THE SEISM 1.1 TEST ANALYSIS, CNWRA REPORT 94-014

This report (Hofmann, 1994) documents modification to and a calculation made with, the LLNL/NRC multivariate expert opinion-based PSHA code SEISM 1. The code is also known as SHC. The CNWRA revision of the code to extend its capabilities to western United States sites and to calculate probabilistic fault displacement hazards is called SEISM 1.1. As a consequence of exercising the code, using published expert opinions regarding which faults near YM or the NTS should be considered, the maximum magnitude each can generate, and their seismic activity rates, some items applicable to an STP are noted.

- Five items that contribute to uncertainty are:

  — Only the largest magnitude earthquakes that occur in the Basin and Range tectonic province produce visible surface offset

  — Fault ruptures, associated with earthquakes taper, in their offset from a maximum in the center of the offset to zero at the ends—therefore, a trench is likely to intercept a less than maximum portion of offset

  — Graphs of maximum fault offset indicate that for each succeedingly smaller magnitude, displacement is reduced by a half an order of magnitude—therefore, it is likely that only offsets from the largest magnitudes of paleo-earthquakes will be readily recognizable in trenches

  — Maximum fault offset, for predominantly dip-slip earthquakes in the Basin and Range tectonic province, will occur at depth near the center of the slip surface—therefore, for any magnitude less than one which fills the entire down-dip extent of the fault (about 15 km) may not have a maximum offset at the surface

  — Near the surface, large normal faults often branch into several parallel faults over which displacement may be irregularly distributed

- Earthquake recurrence for broad regions with a statistically significant sample of seismicity, produce *b*-values of about 1.0 for Richter magnitudes. Use of other magnitudes or excessive editing of earthquakes thought to be aftershocks may not produce *b*-values of about 1.0. Therefore, significant deviations from 1.0 for a regional *b*-value suggests that data are too limited or magnitude differences may not have been taken into account.

- Quasi-theoretical attenuation formulae based upon Hanks and McGuire (1981) must be verified by comparison with empirical data including near field data to be accepted for use in probabilistic analyses

These detailed recommendations generally do not appear in Appendix A but are broadly addressed in Appendix A, Sections 4.2 and 4.3, pages A-14 and A-17 respectively.

2.4 SUMMARY OF THE TESTING OF SEISM 1.1 SENSITIVITY ANALYSIS, CNWRA REPORT - MAY 1995

The sensitivity of hazard results were tested for several background zone configurations (Hofmann, 1995). Activity rates for background zones were set by using the sum of activity rates for enclosed faults assuming that lower magnitudes were distributed randomly over the background zone. The exercise indicated that it is not possible for individual faults to produce earthquakes according to a Gutenberg and Richter (e.g., 1954) recurrence and maintain the observed regional recurrence. This observation suggests that faults produce more earthquakes near the maximum possible on a fault than a Gutenberg and Richter recurrence indicates. Studies by Wesnowsky et al. (1982), Wesnousky (1994), and by Schwartz and Coppersmith (1984) indicate that recurrence for individual faults may differ from a Gutenberg and Richter recurrence. Few, if any, individual faults have produced enough earthquakes to derive a recurrence function for them. Wesnousky (1994) investigated three segments or splays of the San Andreas system and found a characteristic earthquake recurrence (Schwartz and Coppersmith, 1984; Youngs and Coppersmith, 1985) to be a better fit for two of them. A Gutenberg and Richter recurrence was a better fit for one splay fault and for the entire San Andreas fault system. However, earthquakes were chosen from a 20 km band on either side of the faults which could include a significant number of smaller ancillary faults. Krinitzsky (1993) has an excellent reference list and points out many of the difficulties in establishing a recurrence for individual faults. A consequence of the background zone sensitivity exercise are three specific items that may be included in an analysis STP:

- The sum of earthquake recurrences on individual faults within a region should be tested against the observation that regional recurrence is of a Gutenberg and Richter type.

- Use of historic seismicity to establish background zone seismicity may be acceptable for short lived surface facilities, but not for calculation of postclosure hazards.

- Large earthquakes should not be postulated to occur randomly in a background zone because Basin and Range historic earthquakes infrequently produce surface rupture. Most large Basin and Range earthquakes are clearly associated with faults or fault trends even though they may not have produced surface rupture.

These items are broadly addressed in Sections 3.3 and 4.3 of Appendix A of this report.

2.5 SUMMARY OF THE EXPERT ELICITATION REPORTS

A series of reports have been prepared at CNWRA regarding the general use of expert elicitation and on expert elicitations conducted for specific purposes. The reports are:

Tschoepe, E., and L.R. Abrahamson. 1992. *Substantially Complete Containment (SCC) Elicitation Report*. CNWRA 92-016. San Antonio, TX: Center for Nuclear Waste Regulatory Analyses.

Winkler, R.L., S.T. Hora, and R.G. Baca. 1992. *The Quality of Expert's Probabilities Obtained through Formal Elicitation Techniques*. CNWRA Report of September 1992. San Antonio, TX: Center for Nuclear Waste Regulatory Analyses.

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

DeWispelare, A.R., and E.J. Bonano. 1995. *Input to the Draft Staff Technical Position on Elicitation of Expert Judgment*. CNWRA 95-006. San Antonio, TX: Center for Nuclear Waste Regulatory Analyses.

DeWispelare, A.R. 1995. *Characterization of Elicited Data Distributions Concerning Future Climate in the Yucca Mountain Vicinity*. CNWRA Letter Report of August 1995. San Antonio, TX: Center for Nuclear Waste Regulatory Analyses.

Presentation to the Commission, June 22, 1995, by NRC Staff regarding a proposed "expert elicitation" Staff Technical Position.

Because a separate STP is being prepared by NRC staff on the subject of expert elicitation, this subject is not extensively reviewed here. Several items of potential importance to an FD&SHA analysis STP, however are:

- Selection of experts may be effectively accomplished by peer nomination
- Experts should be identified by peer nomination, without regard to potential conflict of interest; however, conflicts if any, should be identified
- Appropriate documentation of the expert's rationale for his responses
- Detailed documentation of procedures for aggregation of expert opinion
- Taping of elicitation sessions to provide a means of referring back to the interview particularly to obtain the context in which responses were received
- Pre-elicitation training to aid experts in the identification of bias and for practice in providing quantitative judgments
- Both normative and subject matter experts should be involved in any formal elicitation process
- Experts should be given feedback concerning the consequences of their opinions
- A site visit by subject-matter experts is valuable to calibrate the interpretation of data and research performed by them in preparation for the elicitation

These items are addressed in Section 3.6 of Appendix A of this report.

2.6 SUMMARY OF THE TEXT AND ILLUSTRATIONS OF PRESENTATIONS GIVEN AT THE U.S. GEOLOGICAL SURVEY/DEPARTMENT OF ENERGY GROUND MOTION DATA NEEDS WORKSHOP OF APRIL 20-21, 1995, IN SALT LAKE CITY, UTAH

The expert elicitation process described in this meeting appears to go beyond those described in CNWRA reports. The DOE process involves considerable group interaction. For example, according to a presentation by J. Savy (1995) of LLNL, each expert will describe his opinions regarding PSHA to the other experts, who will then write their own interpretation of what a particular expert expressed. These combined descriptions will all be given equal weight, apparently in some sort of aggregation process. Although not succinctly stated, it appears that each expert is to use his preferred method to derive a ground motion estimates and perhaps a seismic hazard curve for YM. These results will then be modeled by G. Toro, of Risk Engineering, using a single process. Presumably, the experts will be elicited for the variables to be used in Toro's analysis. The process was not clearly defined at the meeting. Perhaps the participants had experience in previous elicitations for other DOE facilities and no need was seen for reiterating the process.

N. Abrahamson discussed the process for removal of an expert from the panel for failure to perform. This concern apparently stems from the eastern United States seismic hazard characterization project (which continued for a longer period of time than anticipated) and similar projects for the DOE nuclear facilities, e.g., the new production reactor in Idaho. The problem appears to be that the elicitation process can be lengthy, perhaps indeterminate in length, and as practiced by the DOE, involves much group interaction. This situation interferes with other activities of the experts and to some it may be distasteful. Consequently, all experts may not find it in their interest to continue with the process to the bitter end. Reasons for dismissal include failure to prepare for workshops, failure to meet established schedules for deliverables or being uncooperative and disruptive. Obviously the DOE process goes beyond mere elicitation of expert opinion. This process suggests that some pressure is being applied to the experts to agree or at least minimize disagreement. This topic was also touched upon by J. Savy who identified a phase in the process whereby disagreement is minimized.

A handout at the meeting describes the organization to conduct the elicitation and analysis. There are seven ground motion experts. There are 18 seismic source characterization and fault displacement experts. Formal expert elicitation appears not to have been made of the 18 source characterization experts. They were divided into four teams at an earlier meeting in Denver and asked to devise five fault scenarios. The common results of the teams were accepted for the five scenarios.

Three of the four teams also agreed upon another fault scenario that was added to those to be considered. A "scattered" earthquake in the Walker Lane seismogenic zone was rejected. It is not clear from the paper by Schneider and Hanks (1995) whether a background zone with maximum earthquakes in 6.2 to 6.4 range was accepted. Their conclusion, however, was that it would probably not add much to the hazard. The view is contrary to that of Quittmeyer et al. (1994) who found that a background zone earthquake controlled hazard at most levels. Individual experts were allowed to make a case for other scenarios, but they were not accepted. The process was one of consensus. These experts may be elicited at future workshops to provide input to a final hazard calculation by G. Toro.

These faults or fault combination descriptions were provided to the ground motion experts to use in their initial calculations. A total of about 50 individuals provide expert opinions, manage, facilitate, provide oversight advice, or perform independent calculations. Some of these individuals serve more than one function. Even if the 17 source characterization experts are not counted, the total number of staff, in addition to the seven ground motion experts to be elicited, seems large compared to the elicitations conducted by CNWRA (DeWispelare et al., 1993; Tschoepe et al., 1992). The extensive oversight, management, and facilitation functions suggests that a certain level of control is to be exercised. This is a concept that may work to limit real uncertainty present among the experts regarding their opinions. The paper by Schneider and Hanks (1995) described extensive discussions on what was meant by "realistic earthquakes" and "representative ground motion" to be developed by the experts. Elicitation of expert opinion should follow normative guidelines.

F.H. Swan (1995) raised several issues related to seismic source characterization which ought to be considered while developing the STP.

- There is an absence of Quaternary cover for many YM faults of concern. Although not specifically pointed out by Swan, age dating of gouge as an alternative is not always satisfactory. If the last movement of a fault cannot be proved to be pre-Quaternary, must it be assumed to be active? In an area of active tectonism, albeit at a low rate, is it reasonable to ask experts what the probability is that a fault is "active" and use that probability in PFD&SHA?

- What is maximum earthquake magnitude? Is it the maximum expected earthquake or the MCE (or possibly the maximum likely earthquake)? This question assumes that these terms can be defined. Should maximum magnitude be defined on the basis of historical seismicity, fault length or potential rupture area and type of faulting? Should it be defined on the basis of maximum displacement or average displacement empirical relationships?

- How is fault slip (offset/displacement) per event defined? Is it net slip or apparent slip? Should the observed displacement be somehow converted to the maximum displacement or the average displacement along the strike (and/or width?) of the fault? An example of the 1995 Kobe Japan earthquake suggests a 1.3 meter average net offset, a maximum of about 2.2 m and nearly zero offset at one location between points of observation of larger offsets. Vertical and horizontal components of net slip at any one point were variable (Somerville, 1995).

- What criteria should be used to identify segment boundaries? Should the simultaneous rupture of segment boundaries be considered? How permanent are segment boundaries? One of the CNWRA FD&SHA experts (see Section 2.2 of this report) believed that time dependent recurrence should be employed in analysis of YM hazards because slip rates are low but the time of concern is long. However, one CNWRA advisor suggested that time dependent recurrence should not be considered, apparently because the time of repository performance concern was long, and paleo-age dating is problematical.

- What earthquake recurrence models should be considered for individual faults? exponential, characteristic, or maximum magnitude? The latter was not explained but may be in reference to Wesnowsky et al. (1982), in which it was determined that a long history of fault ruptures in western Honshu, Japan, was best explained by assuming that the faults only ruptured at near their maximum potential magnitude.

- Should tectonic behavior be considered uniform or should clustering effects be considered?
- Faulting in the Basin and Range is often distributed among subparallel faults at the surface. How should this distribution for potential future earthquakes be defined?
- How should uncertainty in the down dip geometry of faults be incorporated in PFD&SHA?

Arabasz (1995) listed concerns about the importance of:

- Volcanic related earthquakes including seismogenic cavity collapse.
- Distance limit for fault consideration in PSHA.
- Affect on recurrence of remote triggering of earthquakes by large distant mainshocks. This concern is apparently based on the correlation of the Little Skull Mountain, Nevada, earthquake with immediately preceding the Landers, California, earthquake.
- Complexity of PFD&SHA compared to the need for simplification to meet time pressures for completion.
- The need for a common magnitude measure. Moment magnitude has achieved increased popularity because it is presumed to be more linearly related to energy and possesses reduced saturation compared to the broadly defined Richter magnitude - M_L to $M=6.5$ and M_S for larger magnitudes. However, published studies of behavior of *a* and *b* values for a Gutenberg and Richter recurrence are based on the Richter magnitude.
- Removal of dependent events—foreshocks and after-shocks. These events contribute to hazard and their removal is largely a heuristic endeavor. Therefore, this author questions the wisdom of removing them unless aftershocks of only one dominating maximum event in the historical record clearly result in an inaccurate regional *b*-value.

There were many presentations at the USGS/DOE meeting in Salt Lake City, Utah. The presentations served to define the tasks and problems ahead in the definition of PFD&SHA. Many concerns were expressed. Principle ones are reiterated in this report section. A definition of postclosure PFD&SHA remains to be fully expressed by the DOE. The elicitation and hazard calculation being made as a consequence of the series of USGS/DOE meetings on this subject will form a basis for all hazard calculations, preclosure and postclosure.

Postclosure design criteria are apparently to be tied to PA which will be derived from various scenarios which include earthquake and faulting. The DOE MPC first-line-of-defense engineered barrier has been stated to greatly minimize earthquake and faulting concerns for the postclosure time period.

Definition of minimum or *de minimis*, postclosure design criteria appears appropriate to reduce potential redesign and reconstruction costs resulting from possible changed perceptions of hazards at the site in the future. The *de minimis* criteria may also provide potential conservatism in the event that PA derived engineering criteria are argued to be small or negligible. Initial added conservatism would have greatly reduced the cost of redesign and reconstruction of several nuclear power plants as perceptions of earthquake hazards changed during the course of their construction or operation. This lesson should be incorporated in the STP. Cost-effectiveness has not proved to be a minimal initial cost for the nuclear industry. Safety, however, not cost, is the principal driving concern for NRC activities.

Such criteria are suggested in Appendix A of this report.

2.7 INTERNAL DRAFT, STAFF TECHNICAL POSITION ON ANALYSIS OF FAULT DISPLACEMENT HAZARDS AND SEISMIC HAZARDS AS THEY RELATE TO DESIGN OF A GEOLOGIC REPOSITORY, FEBRUARY, 1993

The draft STP was prepared in February 1993 for review by the CNWRA panel of FD&SHA advisors at the meeting described in Section 2.2 of this report. This draft is sometimes referenced as an annotated outline. Both fault displacement hazard analysis and seismic hazard analysis are discussed. The draft STP does not discuss scenario development or a relationship with PA. Some of the advisors thought that it should have discussed theses topics. The draft STP was specifically prepared for sites west of the Rocky Mountain front.

The draft STP describes the regulatory framework which is set forth in 10 CFR Part 60, particularly 60.21(c), 60.122, and 60.131. These sections require: (i) a description and assessment of the site sufficient for the analysis of structures; (ii) a description and assessment of potentially adverse conditions such as structural deformation; and (iii) require that structures systems and components be designed to withstand natural phenomena, respectively. These matters are discussed more thoroughly in a later section of this report.

The draft STP called for deterministic fault displacement analyses as the primary methodology for fault displacement hazard analysis. It recommended that both probabilistic and deterministic analyses be used to establish seismic design bases. Incorporation of credible alternative models of fault displacement in the analyses was recommended.

A MCFD is the fault displacement hazards design basis and a MCE is the seismic hazard design basis. These bases are to be augmented with MLFD and maximum likely earthquakes (MLE) for 100, 1,000, and 10,000 yr periods.

Elements of acceptable fault displacement hazard analyses and acceptable seismic hazard analyses, included in the draft STP, are summarized here.

Elements of an Acceptable Fault Displacement Hazard Analysis

- Alternative tectonic models which include:
  - — subsurface fault geometry and changes with depth
  - — changes in fault characteristics or behavior along strike
  - — distributed faulting, i.e., secondary and branch faults
  - — structural (mechanical) coupling between faults

- Geometry and rates of tectonic strain at the site and regionally
- Temporal and spatial clustering of fault displacements
- Quaternary fault slip rates, amounts, directions and recurrences
- Estimates of the MCFD from discrete measurements and from cumulative displacements
- Estimates of the MLFD, including strike and slip direction for 100, 1,000, and 10,000 yr
- Locations and characteristics of Type 1 faults that may be present and undetected
- Regional and local stress fields, both ambient and thermally induced from nuclear waste
- Effect of discrete MCFD events on site hydrology

Elements of an Acceptable Analysis of Seismic Hazards

- Estimate of the maximum magnitude earthquake (MME)
- Design basis earthquakes
- Earthquake recurrence relationships
- Sensitivity of hazard to poisson and non-poisson distributions of parameters
- Characteristic earthquakes
- Site effects
- Surface and subsurface vertical and horizontal velocities and accelerations
- Effects of repeated small events on canisters

Uncertainties receive special consideration in Sections 3.4 and 4.4 of the draft analysis STP.

The draft analysis STP points out that the relatively short period of historical seismicity and even shorter period of instrumental recording of earthquakes in the United States, is a cause of many technical uncertainties. Because of the slow pace of earthquake occurrence in the Basin and Range tectonic province, these uncertainties cannot all be resolved but may be reduced by earthquake observations before construction of the proposed HLW repository at YM. Geologic investigations, including paleo-fault offset studies may also reduce uncertainties.

The draft analysis STP states that uncertainties should be identified. The draft analysis STP suggests two methods. One is through the use of logic trees as recommended by the National Research Council (1988). Fault trees were implemented by EPRI in their eastern United States Seismic Characterization Study. The other proposed method of documenting uncertainties is to place confidence bounds on calculated values, for example, Bernreuter et al. 1989.

The division of uncertainty into two categories, data variation or randomness, and systematic or modeling uncertainty (Reiter, 1990) is mentioned in Section 3.4 of the draft internal analysis STP. It also identifies a third category which is that related to the wide variation in conceivable future conditions. Some argue that data variation is caused by an incomplete model and therefore there is no distinction between the first two types of uncertainty. Randomness in a particular parameter may be established with empirical observations of available data. Systematic and future-condition uncertainties, however, are usually not identifiable from available data and are a topics of expert opinion. Methods to derive uncertainties in parameters, which ultimately result in confidence bounds, are not discussed in the draft internal analysis STP.

The draft STP broadly addressed many of the concerns raised in the preceding sections of this report. This STP is the basis for Appendix A to which additional technical positions are tentatively proposed regarding probabilistic analyses and to accommodate comments of CNWRA FD&SHA advisors.

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3 REGULATORY FRAMEWORK FOR A FAULT DISPLACEMENT AND SEISMIC HAZARD ANALYSIS STAFF TECHNICAL POSITION

This section is derived from Section 2 of the draft STP, CNWRA February 7, 1991, Letter Report: Identification of Pertinent Regulatory Requirements for Systematic Regulatory Analyses of Issues Related to PFD&SHA in 10 CFR Part 60 (Hofmann, 1991); and the CNWRA 1992 Letter Report, Regulatory History and Intent for PFD&SHA (Hofmann, 1992). Proposed changes to 10 CFR Part 60 (NRC, 1995), regarding DBE and to 10 CFR Part 100, which would be included by reference, are not discussed here. These potential actions, however, may impact the regulatory framework for an analysis STP directed toward implementation of 10 CFR Part 60 requirements of FD&SHA.

3.1 PROBABILITY

Part 60 does not mention probability directly, although such methods have been proposed to satisfy fault and earthquake investigation requirements of Part 60. The EPA regulation is a part of Part 60 by reference as required by the Nuclear Waste Policy Act (NWPA). The first EPA regulation promulgated (41 CFR Part 191), but currently remanded by a Federal Court, posed requirements for radionuclide migration to the biosphere on a probabilistic basis. Proposed revisions of this regulation also will likely be in probabilistic terms. Because there are numerous references in Part 60 to requirements for investigating earthquakes and faulting which could influence the performance of an HLW repository site, and performance is measured in the EPA regulation in probabilistic terms, it follows that a FD&SHA would require probabilistic elements.

Part 60 also addresses uncertainty which may be quantified by probabilistic methods, thereby implying that such methods would be a part of an analysis to determine if a site and repository system meet the requirements of 10 CFR Part 60. Considerable discussion of the rationale leading to 10 CFR Part 60 are in staff responses to comments (NRC, 1983) on publication of this rule. Uncertainty is recognized, as is the fact that to a large degree it will be estimated from judgements. A distinction is made between the standards for performance and the quality of the evidence used to support a finding that the standard of performance has been met. The staff states "treatment of uncertainties will rely heavily on expert judgement both for selection of an appropriate method and for application of that technique." The staff goes on to state that uncertainties are considered to be compensated by the defense-in-depth principle, with both engineered barriers and the geologic repository sharing responsibility for waste containment and isolation.

3.2 SITING REQUIREMENTS

10 CFR 60.122 lists adverse conditions relating to earthquakes and faulting. Demonstration that the effect of these adverse conditions be adequately evaluated using analyses sensitive to the conditions is required. The analyses must show that the adverse condition does not affect significantly the ability of the geologic repository to meet performance objectives for the isolation of waste.

3.3 SAFETY REQUIREMENTS

In 10 CFR Part 60, NRC requirements related to siting, design criteria, and performance, establish bases for investigations related to fault displacement hazards and to seismic hazards. These requirements apply to both preclosure and postclosure time periods. For example, during the preclosure time period, according to 10 CFR 60.111, the geologic repository operation are (GROA) is to be designed to provide protection against radiation exposures and releases of radioactive material, in accordance with standards set forth in 10 CFR Part 20 (See Code of Federal Regulations, Title 10, "Energy"). Section 131(b)(1) states that structures, systems and components important to safety must be designed so that natural phenomena and environmental conditions expected at the GROA will not interfere with necessary safety functions.

3.4 RETRIEVABILITY

10 CFR 60.111 requires that the GROA be designed so that the option to retrieve emplaced radioactive waste is preserved. Safety requirements of Part 20 apply during this period. 60.131(b)(1) requires that structures, systems and components important to safety must be designed so that natural phenomena and environmental conditions expected at the GROA will not interfere with necessary safety functions.

3.5 PERFORMANCE OBJECTIVES

The procedures and technical criteria set forth in 10 CFR Part 60 are designed to support the concept of multiple barriers, which entails the combination of engineered barriers (e.g., the design of repository facilities) and favorable characteristics of the natural barriers to provide reasonable assurance that the performance objectives can be met. Criteria set forth in 60.21(c)(1)(ii) require a description and assessment of the site at which the proposed GROA is to be located, with appropriate attention to faults and earthquakes that might affect GROA design and repository performance. The assessment called for in 10 CFR 60.21(c)(1)(i-ii) must be of sufficient depth to support the assessment of the effectiveness of engineered and natural barriers called for in 60.21(c)(1)(ii)(D), as well as the analysis of design and performance requirements for structures, systems, and components important to safety called for in 10 CFR 60.21(c)(3). Furthermore, the analyses performed to address the requirement must be adequate to assess any potentially adverse condition under 10 CFR 60.122 (e.g., structural deformation). Elsewhere in 10 CFR Part 60, NRC requirements related to siting, design, and performance establish additional considerations for hazard analysis. According to 10 CFR 60.111, the GROA is to be designed to provide protection against radiation exposures and releases of radioactive material, in accordance with standards set forth in 10 CFR Part 20.

For the postclosure period, the total system performance criteria of Section 60.112 require that the geologic setting be selected and the engineered barrier system (EBS) be designed to assure that releases of radioactive materials to the accessible environment following permanent closure conform to applicable environmental standards established by the EPA. Moreover, the subsystem performance criteria of 10 CFR Part 60.113 require that the EBS be designed so that assuming anticipated processes and events that containment of HLW will be substantially complete during the containment period and that any release from the EBS should be a gradual process which results in small fractional releases to the geologic setting over long times. Finally, 10 CFR 60.133(h) requires that engineered barriers be designed

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to assist the geologic setting in meeting the above noted performance objectives for the period following permanent closure.

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APPENDIX A

DRAFT STAFF TECHNICAL POSITION WITH CNWRA SUGGESTIONS REGARDING PROBABILISTIC ASPECTS OF FAULT DISPLACEMENT AND SEISMIC HAZARD ANALYSIS

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ABSTRACT

The Nuclear Regulatory Commission (NRC) regulations for the disposal of spent nuclear fuel and high-level radioactive waste (HLW) in a geologic repository recognize that fault displacement and seismic activity are potentially adverse conditions (10 CFR 60.122(c)(11), 60.122(c)(12), 60.122(c)(13), 60.122(14), and 60.122(c)(20). The staff recognizes the acceptability of designing the geologic repository to take into account the attendant effects of potential fault movements and consequent earthquake shaking. This Staff Technical Position (STP) outlines characteristics of fault displacement hazard and seismic hazard analyses that are acceptable to the staff.

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CONTENTS

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1 INTRODUCTION

The Nuclear Regulatory Commission (NRC) Staff Technical Position (STP) on "Investigations to Identify Fault Displacement Hazards and Seismic Hazards at a Geologic Repository," NUREG-1451 (McConnell et al., 1992) describes an acceptable approach to identify and investigate faults (or fault zones) of possible regulatory concern to the geologic repository. The STP on "Consideration of Fault Displacement Hazards in Geologic Repository Design," NUREG-1494, (McConnell and Lee, 1994) addresses those faults of regulatory concern (designated as "Type I" faults in NUREG-1451) that exist or are assumed to exist at the locations of systems, structures or components important to safety or important to waste isolation[1]. This STP addresses the of fault displacement and seismic hazards analysis (FD&SHA) as they apply to the design of systems, structures, and components important to safety or important to waste isolation. This STP recognizes the importance of taking fault displacement and seismic ground motion parameters into account in the design of the repository with consideration that conservative criteria may compensate for uncertainty in future states. This STP defines separate strategies and criteria for FD&SHA for preclosure and postclosure time periods, in each case with care to include redundancy in analyses to provide conservatism and accommodate uncertainties. Definitions and guidance provided in the prior STPs of this series, NUREG-1451 and NUREG-1494 are to be considered together with this STP.

1.1 BACKGROUND

The analysis procedures described in this STP are to provide fault displacement hazards and earthquake hazards estimates that are conservative and will adequately encompass the range of uncertainty present in the analyses, their input parameters, and future states, such that design of the geologic repository will permit a judgement that issuance of a license to operate the geologic repository will not constitute an unreasonable risk to the health and safety of the public. (See 10 CFR Part 60.41). The analyses should be derived from the data collected under the guidance provided by NUREG-1451 and augmented by NUREG 1494.

This STP draws on the experience gained in applying the concepts in Appendix A of 10 CFR Part 100 (Code of Federal Regulations, Title 10, "Energy"), to establish appropriate analysis methods for providing fault displacement hazard and earthquake ground motion hazard input to the design of geologic-repository structures, systems and components important to safety. This STP, however, does not adopt Appendix A of 10 CFR Part 100 for guidance in hazard analyses. A more thorough discussion of the relationship between STPs applicable to a geologic repository and Appendix A of 10 CFR Part 100 is provided in Appendix A of NUREG-1451.

Despite recent advances in the treatment of fault displacement hazards (Coppersmith and Youngs, 1990) and seismic hazards [Electric Power Research Institute, (EPRI) 1988; and Bernreuter et al., 1989], uncertainties remain in characterization of these hazards (Sobel, 1993). Because of these uncertainties it has been difficult to place the contribution of geologic risk into proper perspective in the

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[1]10 CFR Part 60 is structured around the multiple-barrier concept and the NRC principles of defense-in-depth, and primarily focuses on repository performance. The applicant [the U.S. Department of Energy (DOE)] must demonstrate compliance with performance objectives of Subpart E of 10 CFR Part 60 in order to have a potential geologic repository licensed. To ensure that such compliance can be demonstrated, 10 CFR Part 60 sets out a number of specific siting and design criteria. Performance issues are, therefore, closely linked with siting and design issues, and the staff position set out herein must be understood in that context.

development of individual nuclear facility designs, thus typically leading to the assumption of conservative design bases (NRC, 1979). The NRC regulations for the disposal of spent nuclear fuel and high-level radioactive waste (HLW) in a geologic repository, 10 CFR Part 60 (Code of Federal Regulations, Title 10 "Energy"), recognize that fault displacement and earthquake ground motion can be potentially adverse conditions [10 CFR 60.122(c)(11), 60.122(c)(12), 60.122(c)(13), 60.122(c)(14), and 60.122(c)(20)]. Given the differences in function and performance between geologic repositories and other nuclear facilities, the staff has developed this STP to express its views on an acceptable approach to the treatment of probabilistic fault displacement and hazard analysis (PFD&HA) and probabilistic seismic hazard analysis (PSHA) in the design and operation of a geologic repository.

1.2 SCOPE

The guidance presented in this STP is considered most applicable for candidate sites west of the Rocky Mountain Front, approximately 104° west longitude. Seismic activity can, in general, be better correlated with tectonic structures and seismic source zones in areas west of the Rocky Mountain Front, than can similar activity in areas east of the Rocky Mountain Front, where surface expression of tectonic structures is more obscure.

1.3 STAFF TECHNICAL POSITIONS AS TECHNICAL GUIDANCE

STPs are issued to describe, and make available to the public, methods acceptable to the NRC staff, for implementing specific parts of the NRC regulations, and to provide regulatory guidance to the DOE. STPs are not substitutes for regulations, and compliance with them is not required. Methods and solutions differing from those set out in the STP will be acceptable if they provide a basis for the findings requisite to the issuance of a permit or license by the NRC. Published STPs will be revised, as appropriate, to accommodate comments and to reflect new information and experience.

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2 REGULATORY FRAMEWORK

The NRC exercises licensing and regulatory authority with respect to HLW disposal facilities. In 10 CFR Part 60, the NRC has set out procedures and technical criteria applicable to licensing a mined geologic repository. These procedures and technical criteria are designed to support the concept of multiple barriers, which entails the combination of the engineered barriers (design of repository facilities) and favorable characteristics of the natural barriers to provide reasonable assurance that the repository will meet required performance objectives. As such, the design bases of facilities important to safety, containment, and waste isolation need be considered in the context of providing this reasonable assurance that the performance objectives can be met. The performance objectives and design criteria described in 10 CFR Part 60 establish the basis for considering fault displacement hazards and seismic hazards in this context are discussed below.

Criteria set forth in 60.21(c)(1)(ii) require a description and assessment of the site at which the proposed geologic repository operation area (GROA) is to be located, with appropriate attention to faults and earthquakes that might affect GROA design and repository performance. The assessment called for in 10 CFR 60.21(c)(1)(i-ii) must be of sufficient depth to support the assessment of the effectiveness of engineered and natural barriers called for in 60.21(c)(1)(ii)(D), as well as the analysis of design and performance requirements for structures, systems, and components important to safety called for in 10 CFR 60.21(c)(3). Furthermore, the analyses performed to address the requirement must be adequate to assess any potentially adverse condition under 10 CFR 60.122 (structural deformation). Elsewhere in 10 CFR Part 60, the NRC requirements related to siting, design, and performance establish additional considerations for hazard analysis. According to 10 CFR 60.111, the GROA is to be designed to provide protection against radiation exposures and releases of radioactive material, in accordance with standards set forth in 10 CFR Part 20. During the preclosure period, 10 CFR 60.111 requires that the GROA be designed so that the option to retrieve the emplaced radioactive waste is preserved. The design criteria of Section 60.131(b)(1) require that structures, systems, and components important to safety must be designed so that natural phenomena and environmental conditions expected at the GROA will not interfere with necessary safety functions.

For the postclosure period, the total system performance criteria of Section 60.112 require that the geologic setting be selected and the engineered barrier system (EBS) be designed to assure that releases of radioactive materials to the accessible environment following permanent closure conform to applicable environmental standards established by the Environmental Protection Agency (EPA). Moreover, the subsystem performance criteria of 10 CFR Part 60.113 require that the EBS be designed so that assuming anticipated processes and events, containment of HLW will be substantially complete during the containment period and that any release from the EBS should be a gradual process which results in small fractional releases to the geologic setting over long times. Finally, 10 CFR 60.133(h) requires that engineered barriers be designed to assist the geologic setting in meeting the above noted performance objectives for the period following permanent closure.

It is expected that much of the information needed to support the fault displacement hazards and seismic hazards evaluation required by 10 CFR 60.111 and 60.131(b)(1), for the preclosure period, can also be used to support fault displacement hazards and seismic hazards evaluation for the period after permanent closure, with due consideration given to the uncertainties associated with the much longer period of postclosure performance. Accordingly, the analyses performed to address the requirements of 10 CFR 60.131(b)(1) should be conducted to also address postclosure performance. These include evaluations of performance under 10 CFR 60.112 and 60.113, as well as evaluations of potentially adverse conditions under 10 CFR 60.122—especially the conditions addressed under 10 CFR 60.122(c)(3), 60.122(c)(4), 60.122(c)(11), 60.122(c)(13), and 60.122(c)(14).

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3 STAFF TECHNICAL POSITIONS

It is the position of the NRC staff that the approach to analyses described in this STP, in combination with the guidance in NUREG-1451 on "Investigations to Identify Fault Displacement Hazards and Seismic Hazards at a Geologic Repository" (McConnell et al., 1992) and NUREG 1494 on "Consideration of Fault Displacement Hazards in Geologic Repository Design" (McConnell and Lee, 1994) will provide the information necessary to establish design bases for structures, systems, and components important to safety, containment, and waste isolation.

3.1 ANALYSIS CONSIDERATIONS

This section provides guidance on acceptable approaches for analyses of fault displacement and seismic hazards for both pre-closure and postclosure design. Acceptable analyses of fault displacement hazards and seismic hazards should establish design bases, including mitigating factors, for structures, systems, and components of a geologic HLW repository which are important to safety, containment and waste isolation. PSHA, and by inference probabilistic fault displacement analysis (PFDA), are known to lack stability (National Research Council, 1988). This instability may be site specific and may need to be quantified. Instability is defined as producing different results when different experts are elicited or when performed at different times using the same experts. Results of probabilistic fault displacement and seismic hazard analysis (PFD&SHA) should be compared to that obtained from the paleo fault offset data and to historical seismicity. Differences and their uncertainty should be discussed. Multiple-expert PFD&SHA tend to obscure the rationales and data used. Presentation of these analyses should be made as clear as possible and single-expert PFD&SHA using the extremes of opinions should accompany the multiple-expert analysis. The single-expert analyses should have well documented rationales and be shown to bracket final multiple-expert analysis results.

3.1.1 Analysis of Fault Displacement Hazards

The staff considers that, for assessment of fault displacement hazards, both deterministic methods[2] and probabilistic methods[3] will be used to establish the design bases. Credible alternative models of fault displacement should be incorporated into analysis of the hazard.

A prerequisite to the analysis of fault displacement hazard is to establish whether potential future slip along known or inferred faults is sufficiently credible to warrant the analyses by determining if Type I[4] faults or fault zones exist at the site. Investigations acceptable to the NRC staff for identifying Type I faults or fault zones are discussed in NUREG-1451 (McConnell et al., 1992).

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[2]Deterministic methods are those that consider likelihood of occurrence only in the context of whether the event is sufficiently credible to warrant consideration.

[3]Probabilistic methods are those that quantitatively consider likelihood of occurrence for an event during the lifetime of the facility.

[4]A Type I fault is a fault that is subject to displacement and is located and of sufficient length such that it may affect repository design or performance (NUREG 1451).

3.1.1.1 Fault Displacement Hazards Preclosure Design Basis

The design basis for fault displacement hazards for facilities important to safety, containment, and waste isolation should be the maximum fault displacement along Type I faults or fault zones that occur at or near the site. The maximum fault displacement is to be calculated deterministically from maximum fault dimensions or from observed maximum Quaternary fault offsets, whichever is larger. For supporting probabilistic analyses the design fault offset should be determined from offset probabilities derived from dated Quaternary[5] fault offsets. The probabilistic hazard level for design of structures systems and components important to safety will be the median for an annual fault offset recurrence of 10^{-4}/yr or the 84th percentile for an annual fault offset recurrence of 10^{-3}, whichever is larger.

3.1.1.2 Fault Displacement Hazard Postclosure Design Basis

The design basis for fault displacement hazards for facilities important to safety, containment, and waste isolation should be the maximum fault displacement along Type I faults or fault zones at or near the site. The maximum fault displacement is to be calculated deterministically from maximum fault dimensions or from the largest single Quaternary fault offset, whichever is larger. Supporting probabilistic analyses should be determined from dated Quaternary[5] fault offsets. The probabilistic hazard level of structures systems and components important to safety will be the median 10^{-5}/yr, fault offset, or the 84th percentile for an annual fault offset recurrence of 10^{-4}/yr. If a higher level of conservatism of the combined natural and EBS to meet EPA requirements, is required by performance assessment (PA), the design level implied by PA will control design.

3.1.2 Analysis of Seismic Hazards

The staff considers that for seismic hazards, both deterministic and probabilistic methods should be used to establish design bases. Data and expert opinion rationales used in these analyses must be fully documented. If logic trees are used in a probabilistic analysis, the entire logic tree for each expert should be illustrated and explained.

3.1.2.1 Preclosure Seismic Design Basis

For facilities important to safety, containment and waste isolation, the design should be based on a ground motion value that is the largest of: the deterministic value, the median value for a 1 in 10,000 yr event or the 84th percentile value of the 1 in 1,000 yr event.

3.1.2.2 Postclosure Seismic Hazards Design Basis

For facilities important to safety, containment and waste isolation, the deterministic, the 84th percentile 10^{-4}/yr ground motion or median 10^{-5}/yr probabilistic ground motion, whichever is higher, should be the design basis. The seismic design basis should be derived from an evaluation of tectonic features in the area. The design bases estimated from maximum earthquakes produced by these features should be defined at the free surface in terms of site-specific peak acceleration and in terms of velocity

[5]The staff has taken the position that for regulatory purposes, the age of the Quaternary Period is 2 my (see NRC, 1983b, page 373).

spectra. If PA indicates greater conservatism is required in the design of engineered systems for the repository to meet EPA requirements, PA will control design.

3.2 ELEMENTS OF AN ACCEPTABLE ANALYSIS OF FAULT DISPLACEMENT HAZARDS

An acceptable analysis of fault displacement hazards would include the following elements:

- Consideration of alternative tectonic models to develop credible hypotheses to assure that uncertainty in tectonic processes and events is encompassed in the analysis. Alternative tectonic models should address:
  - — subsurface fault geometry and changes in fault behavior with depth (along dip)
  - — fault segmentation and changes in fault behavior along strike, including probabilities of the breaking of asperities between segments (e.g., see Davidson and Scholz, 1985)
  - — distributive faulting, (e.g, secondary and branch faults)
  - — structural (mechanical) coupling between faults
  - — association of faulting with volcanism
- Consideration of geometry and rates of regional tectonic strain at the site and in the site region.
- Consideration of temporal and spatial clustering of fault displacements, including occurrence, fractal or chaotic occurrence distribution, and directional characteristics of slip
- Consideration of Quaternary slip rates, slip amounts, slip directions and recurrence intervals for faults in the vicinity of the site, with due consideration for the inherent difficulties in dating Quaternary displacements.
- Estimation of the maximum fault displacement for discrete slip events and cumulative fault displacement through the Quaternary Period. Analyses should consider features of analog extensional terrains as well as those in the Basin and Range.
- Estimation of probabilistic fault displacement (PFD), with consideration of type of slip (strike, dip, or oblique-slip displacement), for periods of 100, 1,000, and 10,000 yr.
- Faults in the current stress field (or projected stress fields over the performance period of the facility) that are oriented such that slip is likely, (See McConnell et al., 1992 and Morris et al., 1995) should be considered to be fully capable of renewed slip and earthquake generation unless no movement can be convincingly documented over the past 2,000,000 yr (the Quaternary Period).
- Consideration of Type I faults that may be present but not detected.

- Consideration of regional and local stress fields, including *in situ* stress and possible effects on the *in situ* stress state resulting from emplaced waste.

- Consideration of effects on hydrology that could be caused by cumulative fault displacement and by discrete maximum fault offset events through the Quaternary Period.

3.3 ELEMENTS OF AN ACCEPTABLE ANALYSIS OF SEISMIC HAZARD

An acceptable analysis of seismic hazards would include the following elements:

- Determination of the maximum magnitude earthquake for faults of sufficient size and distance that 0.1 g or more could occur at the site.

- Identification of the maximum deterministic earthquake and probabilistic magnitude-distance pairs to be used for design.

- Identification of seismic and alternative seismic source zones and faults.

- Justification for magnitude-frequency relationships used in analyses including comparison to the applicable recorded data available and consideration of the relationship stability with time. This analysis should be for individual faults and the region enclosing them, including background seismicity. The observed regional Gutenberg – Richter type recurrence should be shown to be compatible with recurrences assigned to background zones and faults within the region.

- Comparison of the effects of using Poisson and non-Poisson distribution functions when data do not permit a clear distinction.

- Comparison of ground motion attenuation curves with data including a discussion of:

  — data adequacy to define ground motion and its variability at all distances of concern

  — the methods used

  — If theoretical ground motion attenuation curves are developed, their probability distributions should also be calculated and compared with available data.

  — adequacy of extrapolation to magnitudes and distances for which strong motion data is missing or statistically inadequate

  — Near-field strong ground motion effects should be described and utilized for any seismic source within 15 km of any part of an HLW repository or associated facility. Fault directivity effects should be considered within 10 arc degrees of any part of a potential fault rupture plane within 15 km of an HLW repository

  — The probability of near-field acceleration spikes from the breaking of fault asperities should be considered

— If accelerations at the site are developed from computer modeling, several such analyses using different techniques should be employed and results treated as expert opinions

- Calculation of diminished ground motion with depth should use site specific material properties and geometry, and should be frequency dependent. Results of theoretical calculations should be compared to earthquake recordings from instruments at depth.

- Thorough justification of characteristic earthquakes, if used in the analysis.

- Examination of local site effects.

- Comparison of surface measured or corrected vertical and horizontal accelerations and velocities with:

  — those measured underground at the site and elsewhere

  — theoretically derived underground values from frequency dependent formulae

- Probabilistic analyses shall be as transparent as possible, and accompanied by bracketing-single-expert-opinion analyses with complete rationales for the opinions used.

- Examination of the effect of repeated small events on the canister.

- Fault displacement or seismic ground motion developed for design should not be reduced prior to or as a consequence of design calculation judgements, either directly or as a consequence of judgmental hazard level increases.

3.4 ELEMENTS OF AN ACCEPTABLE ANALYSIS OF EARTHQUAKE EFFECTS ON GROUNDWATER

- PFDA should include analyses of the mechanisms by which fault displacement and earthquake ground motion affect groundwater for both pre- and post-closure time periods, for example:

  — Opening of fractures which increase groundwater flow

  — Offset of aquifers or other permeable layers which could divert ground water flow

  — Canister rupture or degradation which result in a reduced time for radionuclides to be introduced to groundwater

  — Reduction in porosity which could squeeze interstitial water into the repository

- Establish mechanisms for groundwater elevation changes associated with earthquakes. If modeling is used, the methodology should be benchmarked against observed occurrences.

- Document analog situations to aid in the evaluation of groundwater changes that have accompanied earthquakes and that may accompany earthquakes at Yucca Mountain (YM).

- Develop the conditions and their probabilities for increasing or decreasing permeability along fault planes as a consequence of fault movement accompanying earthquakes. Ideally this information should be obtained from Basin and Range tectonic province earthquakes and geology.

3.5 CONSIDERATION OF TECHNICAL UNCERTAINTIES

The analyses of fault displacement hazards and seismic hazards must also consider technical uncertainties manifest in the study of natural events and processes. Technical uncertainty can be categorized as data or model uncertainty. Uncertainty may be reduced as more data and information about the repository system are available. Therefore, uncertainties and variabilities in the data and model parameters should be identified and properly taken into consideration in the analysis of fault displacement and seismic hazards. In addition, the analyses need also consider the uncertainty related to the variation in conceivable future conditions. Performance objectives for the geologic repository require relatively precise estimations of occurrence probabilities for disruptive phenomena (e.g., fault displacement). Uncertainty exits regarding acceptable means to produce these estimates.

3.6 EXPERT OPINION

Staff recognizes that tectonic models may be subject to expert opinion. Therefore multiple expert opinions may be used to bracket uncertainty in models and interpretations of data, but may not be used to replace reasonably obtainable data.

At a minimum, the use of expert opinion in FD&SHA shall have the following characteristics:

- Selection of experts by peer nomination.

- Use the top experts identified through peer nomination without regard to potential conflict of interest but with identification of potential conflicts.

- Elicitation of expert opinion should follow normative guidelines and the appearance of control or coercion of experts should be avoided.

- Appropriate documentation of the rationale for the experts responses.

- Detailed documentation and explanation of procedures for aggregation of expert opinion.

- Taping of elicitation sessions to provide a means of referring back to the interview particularly to obtain the context in which responses were received.

- All expert opinions and the methods of their aggregation should be completely documented.

- Pre-elicitation training to aid experts in the identification of bias and providing practice in providing quantitative judgments.

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- Both normative and subject matter experts should be involved in any formal elicitation process.
- Experts should be given feedback concerning the consequences of their opinions.
- A site visit by subject-matter experts is valuable to calibrate the interpretation of data and research performed by them in preparation for the elicitation.
- Requests for opinions on topics for which no rationale can be provided should be avoided.

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4 DISCUSSION

The following discussion parallels the list of technical positions given in Section 3.

4.1 ANALYSIS CONSIDERATIONS

PA may indicate that probability of failure of underground workings, facilities or engineered barriers (given the known natural hazards and their probabilities) would cause the combined natural repository system and its engineered components to not meet EPA criteria within the range of performance allocation between the natural system and engineered barriers agreed upon by the DOE and the NRC. If EPA criteria cannot be met using the deterministic or probabilistic criteria given in this STP, the level of performance required of the engineered portion of the repository so that the combined repository system will meet EPA criteria, will control design. This concept is abbreviated henceforth in this STP: . . . *if PA considerations suggest that greater conservatism is needed, PA will control postclosure design.*

The 84th percentile fault offset or ground motion value of a multiple expert PFDA or PSHA includes a measure of the experts' uncertainty and encompasses a standard deviation anticipated in possible future events during the performance period of the underground workings, shafts, sealed boreholes and engineered barriers. There is, however uncertainty in the probability distributions attributed to fault displacement hazards and seismic hazards. Therefore, an alternative criteria is proposed: the median value of 10^{-1} times the performance period hazard. This has the effect of permitting or allowing a one chance in ten of the design criteria being exceeded during the performance period. A similar rationale has been proposed for building codes, for example, ICBO (1991) Section 2334(b). The higher of the two hazard values would be an acceptable design criteria unless PA considerations require a higher level of conservatism for the postclosure repository performance period.

Following the above rationale, tunnels, shaft seals, and any other underground works of man should be assessed for their impact on the natural system's ability to retain waste for the full postclosure performance period. Therefore, postclosure criteria for fault displacement and seismic ground motion will be the deterministic value, the 84th percentile value associated with a 10^{-4}/yr event, the median value associated with a 10^{-5}/yr event, whichever is larger. If PA considerations suggest that greater performance is needed to meet EPA criteria, PA will control postclosure design.

For surface facilities important to safety during preclosure, with a limited nominal life span (e.g., 50 yr), a minimal design criteria should be higher than the stated rationale for underground facilities because large quantities of waste will be unloaded, and transferred within the facilities. Opportunities for human induced error and the potential for release of radioactivity or elemental radionuclides to the biosphere, in which the surface facilities are located, are larger than for underground facilities in which waste is stored but not unloaded or transferred. Therefore, the staff considers that a deterministic design criteria, an 84th percentile of the 10^{-3}/yr hazard or the median 10^{-4}/yr hazard, whichever is larger, to be an acceptable design criteria for structures important to safety. This assumes that the design procedure does not permit structural degradation to take place during shaking which would, in effect, introduce undefined unconservativsm into the criteria. This criteria is deemed valid for structures designed following good practice to remain within their elastic limits during shaking or when experiencing fault offset.

Postclosure criteria are directed toward engineered barriers which must be functional for 300 to 1,000 yr. Design criteria for engineered barriers are, therefore, controlled by this time span for preclosure as well. The natural barrier system must be functional for 10,000 yr. Therefore this time span controls the hazard for which the natural system and any modifications made by man, must be assessed. Surface facilities are likely to be renewed every 40 to 50 yr because of deterioration with time and advancing technology. The NRC (1995) proposes applying 10 CFR Part 72 and consequently 10 CFR Part 100 for analyses of hazards less frequent than 10^{-2}/yr to these facilities. Consequently the time span for MRS may apply to these facilities. Because of large uncertainties in PFD&SHA (e.g., National Research Council, 1988), deterministic design criteria will be primary unless probabilistic criteria as set forth in this document exceed the deterministic criteria or PA indicates that more stringent underground workings and facility or engineered barrier performance is required for the combined natural and engineered barriers to meet EPA requirements.

4.1.1 Analysis of Fault Displacement Hazards

A primary assumption supporting 10 CFR Part 60 requirements is that licensing decisions will be based, in part, on the results of hazard analyses related to processes and events which could potentially disrupt a repository. Thus, the design basis of facilities important to safety, containment, and waste isolation must take into account those processes and events with the potential to disrupt the operations and performance of a geologic repository. Tectonic processes and events have the potential to disrupt a repository and could lead to an unacceptable release of radionuclides. However, a precise understanding of tectonic processes may not be possible, and substantial uncertainties will likely exist in characterization and quantification of hazards related to fault displacement. One approach to mitigating the uncertainties related to fault displacement hazard is to avoid faults of concern. The staff has taken the position that Type I faults should be avoided, when this can be reasonably achieved, for locating structures, systems, and components important to safety or containment at a repository (McConnell and Lee, 1994).

However, the staff also recognized that the DOE may need to locate certain facilities in the vicinity of Type I faults (McConnell and Lee, 1994). In those cases, the analyses of fault displacement hazards must be thorough and the design basis for those facilities should be sufficiently conservative to provide reasonable assurance that repository performance will not be adversely affected.

An important part of the analysis of fault displacement hazards and derivation of design bases is assuring that due consideration is given to the uncertainties attendant to prediction of natural events and processes. However, the present understanding of tectonic processes and events is such that precise models and simulations of the underlying processes related to fault displacement are generally not attainable. As a result, large uncertainties will remain in the characterization of tectonic hazards, in general, and fault displacement hazards, in particular. Therefore, it will be difficult to place the contributions to geologic risk from fault displacement into accurate perspective. In the case of designs for individual nuclear facilities, this difficulty has commonly lead to the assumption of conservative design bases (NRC, 1979). The use of "deterministic" values for these design bases has been judged to be suitably conservative in past licensing actions (57 FR 47807).

The NRC has considered probabilistic methods in the development of seismic hazards. Therefore to ensure compatibility between FD&SHA the staff agrees that probabilistic methods may also be used for fault displacement analysis. Furthermore, postclosure performance criteria is based on a cumulative probability function of radionuclide release to the biosphere. Calculation of this function will require

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scenarios which include probabilistic measures for the effects of natural hazards expected at the site. Probabilities may be derived from deterministic criteria where needed or directly from paleo-fault-displacement data.

Investigations of historic and pre-historic fault displacements at potential sites in areas west of the Rocky Mountains provide confidence that faults of concern to a geologic repository can be identified or can be inferred to exist based on the consideration of alternative conceptual tectonic models. These fault displacement investigations should also provide sufficient understanding of the faulting process such that the maximum fault displacement for a particular fault or fault zone can be estimated and a sufficiently conservative design basis can be established.

For preclosure fault displacement hazards, the design of structures, systems, and components important to safety must demonstrate that differential fault displacement anticipated at the geologic repository operations area will not compromise necessary safety function. Similarly, postclosure design requirements necessitate that the EBS be designed assuming anticipated processes and events. In areas of active tectonics, where faulting has occurred during the Quaternary Period, differential fault displacement would be considered an anticipated event under 10 CFR Part 60 and the EBS must be designed to mitigate expected fault displacement.

For both preclosure and postclosure considerations, the most reliable indication of potential future fault displacements is the description of what has occurred in the geologic past during the Quaternary. The location of Quaternary faulting is the best criterion for suggesting where faulting may occur in the future (Bonilla, 1982). As a result, determination of the design basis for fault displacement hazards should be based on an analysis of the Quaternary record to establish the maximum displacement expected for faults present at the site.

Determination of the maximum displacement requires identification of discrete fault displacement events and should include consideration of potential effects of fault segmentation, if applicable, and alternative tectonic models. Where single events are not discernable in the Quaternary geologic record, cumulative displacement of reliably-dated geologic markers over several slip events can be used to approximate an upper limit for the maximum displacement. Where the maximum displacement cannot be determined from faults at the site, reasonable estimates can be drawn from analog faults with similar characteristics, preferably of the same type and within the geologic setting.

Published Type IV PSHA methodologies (National Research Council, 1988) are only for short lived facilities (e.g., 25-50 yr). There is not a consensus regarding the level of uncertainty in these analyses, for example, Bernreuter (1987). Therefore, high uncertainties may render these or longer time span hazard estimates too unreliable for use in regulating a HLW repository. Uncertainty estimates in long term probability assessments must be defensible and the methodology used to obtain these estimates must be justified in light of other methodologies which may indicate higher design values or higher uncertainties. Consequently, a deterministic analysis is recommended as the principle method for determining design bases unless probabilistic methods or PA indicate that higher values should be used.

4.1.1.1 Preclosure Fault Displacement Design Basis

That the time of potential public exposure to risk is less for the shorter preclosure waste loading and retrievability period than for the postclosure period is recognized by the staff. A deterministic fault offset associated with a given fault length, or the largest single Quaternary fault offset, if determinable, may be used to set preclosure design criteria. Alternatively, based on the rationale of Section 4.1, the 84th percentile of the probabilistic 10^{-3}/yr fault offset hazard should be used if it is larger than the deterministic offset.

4.1.1.2 Postclosure Fault Displacement Design Basis

Following Section 4.1, a deterministic fault offset, a median 10^{-5}/yr offset or the 84th percentile of the 10^{-4}/yr offset, whichever is larger, should be the design basis. However, if PA scenarios suggest that greater conservatism is required, PA will govern the design basis.

4.1.2 Analysis of Seismic Hazards

For preclosure and postclosure design of structures, systems, and components important to safety and containment, the staff considers both deterministic and probabilistic approaches. Using both approaches will provide a broader prospective of the seismic hazard. The deterministic approach will ensure that the resultant design provides protection against the worst scenario that should be considered in the design of the repository. The probabilistic approach will ensure that uncertainties have been included in the assessment. Results obtained from PSHA will complement results from the deterministic approach by providing a complete picture of seismic hazards at the site. Therefore, it is recommended that a deterministic seismic hazard evaluation, supplemented by a Type IV (multiple model PSHA) or Type V (hybrid procedure) (National Research Council, 1988), be performed.

The ultimate design criteria should be conservative to mitigate uncertainties and the possibility of unanticipated events. Although a HLW repository does not have an active ongoing fission reaction, its full compliment of radioactive material is orders of magnitude greater than for any single nuclear power plant (NPP). These factors are considered by the staff to at least compensate for each other in judgements of relative risk to the public.

4.1.2.1 Preclosure Seismic Hazards Design Basis

The median probability of core failure for NPPs, considering their deterministic design bases, has been assessed to be on the order 10^{-5}/yr (Short et al., 1991). This value was recommended by the NRC for a revision of 10 CFR Part 100 as a probabilistic design basis for NPPs (NRC, 1994) and proposed DBE rulemaking would make it apply to an HLW repository as well (NRC, 1995). The staff, therefore, believes that this hazard level should be considered in the analysis of seismic and fault displacement hazards. This value, however, does not contain uncertainty information. The anticipated preclosure period of performance and retrievability may approach an order of magnitude longer than the 50 yr assigned to most U.S. civil structures. Following the rationale used to construct building code maps (Algermissen et al., 1977) but with some added conservatism in consideration of the potential to expose populations to above ambient radioactivity, the 84th percentile fault offset associated with a 1,000 yr return period, should also be considered in the analysis for systems, structures and components important to safety for the preclosure period.

The seismic design basis should consider investigations of historic and instrumentally recorded earthquakes in sufficient detail that the design earthquakes would represent a conservative value. The ground motion at the site should be evaluated assuming appropriate energy transmission effects and assuming that the maximum earthquake associated with each geologic structure or each source zone occurs at the point of closest approach of the structure or source zone to the site. If different potential earthquakes would produce the most severe ground motion in different frequency bands, these earthquakes should be specified. The earthquakes considered for design must assure that structures, systems, and components important to safety are such that these events will not interfere with necessary safety functions. Section 4.3 describes the approaches which can be used to identify the design basis earthquakes. Pre-closure seismic hazards design criteria should be deterministic, the median ground motion associated with a 10^{-5}/yr event or the 84th percentile ground motion associated with a 10^{-4}/yr event, whichever is greater. Because underground facilities will become a part of the postclosure repository, the design of underground facilities should also consider PA requirements. If they are greater than probabilistic or deterministic criteria previously listed, PA criteria should control the design of these facilities.

4.1.2.2 Postclosure Seismic Hazards Design Basis

Following Section 4.1, a deterministic earthquake ground motion seismic hazard, a 10^{-5}/yr ground motion or the 84th percentile of a 10^{-4}/yr ground motion whichever is larger, should be the design basis. However, if PA scenarios suggest that greater conservatism is required, PA will govern the design basis.

4.2 ELEMENTS OF AN ACCEPTABLE ANALYSIS OF FAULT DISPLACEMENT HAZARDS

The following description summarizes approaches and parameters which can be used to analyze fault displacement and the resultant potential for disruption of a geologic repository as described in Subsection 3.2.

4.2.1 Alternative Tectonic Models

Alternative tectonic models deemed credible based on available data and regional geologic considerations should be used to analyze the potential for fault displacement and the associated potential for repository disruption by faulting. The alternative models should address the following geologic factors of concern:

4.2.1.1 Subsurface Fault Geometry

Tectonic models should provide reasonable representations of subsurface fault geometry based on knowledge about the geologic setting and existing field data from the site. Mechanically and kinematically viable assumptions about mechanisms of deformation should be incorporated into the faulting models. Consideration should be given to possible variations in behavior of faults with depth, and what the potential effects of such variations may be on the repository. All available data bearing on interpretation of subsurface geometry for Type I faults within the geologic setting should be taken into account in the development of viable alternative tectonic models.

4.2.1.2 Fault Segmentation

Tectonic models should consider all available data bearing on evidence for along-strike segmentation of displacements on faults within the geologic setting, and on evidence related to changes in along-strike behavior of faults. Data on trace lengths of individual fault segments and fault slip history (e.g., rate, amount, and type of slip) should make it possible to quantitatively relate fault segment length with fault slip history. Fault geometry should also be correlated with along-strike segmentation and changes in fault behavior. Historical evidence for discontinuous faulting along fault traces should be considered in association with data on subsurface geometry of the faults along which segmentation is known to have occurred. Because of the large uncertainties associated with the postclosure time period including fault segmentation, characteristic earthquakes, and attendant characteristic fault slips may not be applicable (Davidson and Scholz, 1985).

4.2.1.3 Distributive Faulting

Models should consider all available data bearing on evidence for distributive faulting along and across zones of faulting within the geologic setting. Fault geometry and fault slip history should be correlated with evidence for distributive faulting, and deformation related directly to distributive slip should be understood. Data such as amount of cumulative slip across a fault zone versus amount of slip on individual faults in the zone may prove useful for assessing potential effects of distributive faulting on a repository. Historical evidence for distributive faulting in fault zones must be considered in association with subsurface geometry of the faults along which distributive faulting is known to have occurred. This approach may make it possible to relate increased likelihood of distributive faulting with a specific fault geometry or style of faulting.

4.2.1.4 Structural Coupling Between Faults

Fault models should consider all available data bearing on likelihood of mechanical coupling between major, apparently independent, faults for historical faulting events. Subsurface fault geometry is an important consideration for assessing likelihood of coupling between faults. Some geometries (e.g., listric-detachment fault systems) make it easier to accommodate direct structural coupling than do others (e.g., planar fault systems) at the site scale. On the regional scale, the exact character of structural coupling between faults may be even less obvious. An example of this point can be seen in the fault movement and seismicity (M=5.6) which occurred at Little Skull Mountain on June 29, 1992. This activity was interpreted as a triggered response to faulting and seismic activity associated with the Landers, California, event (M-7.4) on June 28, 1992.

4.2.1.5 Association of Faulting and Volcanism

Fault models should consider all available data bearing on association of faulting and volcanism. Field evidence bearing on structural control of volcanism (e.g., cone alignments) and synchronous timing of eruptions and faulting (e.g., volcanic ash in fault zones) should be considered in order to quantify temporal and spatial correlations of faulting and volcanism. Geometry and slip history of faults which appear synchronous with volcanism should be described to provide additional information on possible correlations between faulting and volcanism. On a regional scale, association of faulting and volcanism will be related to spatial and temporal relationships between volcanism and regional tectonics. On a site scale, the association will be related to spatial and temporal relationships between volcanism and local structures which were generated in response to regional tectonic stresses.

4.2.2 Temporal and Spatial Clustering of Fault Displacements

Data bearing on timing and location of faulting in the site region should be used in the analysis of potential for fault displacement at a geologic repository. Data such as that presented on geologic, maps (for specifying location of faults) and geochronological information (for indicating ages of faulting) should prove useful for assessing temporal and spatial patterns of fault displacement. Regional strain history is also important for assessing the likelihood of fault displacement, since spatial and temporal clustering of fault displacements bear a relationship to regional strain. If Quaternary faulting has occurred in the region or at the site, then the existence of Type I faults at the site must be considered and analysis of temporal and spatial patterns of faulting may prove useful in addressing the likelihood of future fault displacement at the site.

4.2.3 Slip Rates and Recurrence Intervals of Faulting at the Site

Slip rates and recurrence intervals determined for faults at the site should provide important data for assessing likelihood of future fault displacement at the site. Determination of whether rates are increasing or decreasing and whether recurrence intervals are lengthening or shortening is important for assessing likelihood of displacement and consequent likelihood of repository disruption by fault displacement. Geometry of faults is another important aspect for assessing slip rates and recurrence of faulting at the site.

4.2.4 Deterministic Fault Displacement and Cumulative Displacement Through the Quaternary Period

To determine the maximum fault displacement per event during the Quaternary Period, it will be necessary to assess the amount of slip along Type I faults from single displacements of datable offset markers. To determine cumulative fault displacement through the Quaternary, it will be necessary to assess the amount of slip along Type I faults based on multiple displacements of datable offset markers spanning the Quaternary. Type of slip and geometry of faults are other important aspects of Quaternary faulting for consideration in assessing maximum fault displacement.

4.2.5 Probabilistic Fault Displacement Hazard (Including Periods of 100, 1,000, and 10,000 Years)

Determination of fault displacement will require an assessment of fault displacement likely to occur an Type I faults over the next 100, 1,000 and 10,000 yr. This assessment should be based on the rate, amount and type of slip acquired from single and multiple displacements of datable Quaternary stratigraphic markers. Analysis of earlier displacements may be necessary to better understand recurrence intervals for Type I faults at the site. Geometry of faults is another important aspect for consideration in assessing maximum fault displacement (Ferrill et al., 1995). Determination of maximum fault displacement will follow statistical analysis procedures which may be augmented by analyses similar to those used by Lawrence Livermore National Laboratory (LLNL) (Bernreuter et al. 1989) and EPRI, (1988) in the determination of probabilistic seismic hazards. The definition of maximum fault displacement will include:

- Recurrence intervals and their probability distributions for displacements on major faults and fractures, and the amounts of displacement expected.

- Fracture distribution and probabilities of displacement versus the amount of displacement expected.

4.2.6 Type I Faults Present But Not Observed

Due consideration must be given to the possibility that all Type I faults present at a site may not have been identified during site characterization. This consideration may require the use of alternative tectonic models for analyzing and understanding faulting in the site area.

4.2.7 Effects on *In Situ* Stress from Emplaced Waste

It will be necessary to mathematically consider possible effects of *in situ* stress generated by the emplaced waste on faults in the site area. This consideration will require analysis of the anticipated induced state of stress caused by emplaced waste and its comparison with the stress needed to produce failure along known fault surfaces at the site. Information on the *in situ* state of stress at the site will be part of the data needed to conduct this analysis (see Ferrill et al., 1995).

4.3 ELEMENTS OF AN ACCEPTABLE ANALYSIS OF SEISMIC HAZARDS

The following subsections summarize the deterministic and probabilistic approaches and parameters which can be used to analyze seismic hazards (vibratory ground motion) at the geologic repository, as described in Subsection 3.3.

4.3.1 Maximum Magnitude Earthquake

The maximum magnitude earthquake that could occur on Type I faults within the geologic setting should be identified. The maximum magnitude earthquake should be based on historic experience in the region and specific consideration of the earthquake history, and geologic history of movements on Type I faults. Fault length, fault displacement, rupture area, and rupture length of these faults should be identified and whenever possible the return period on these faults should be estimated.

4.3.2 Identification of the Earthquakes to be Used For Design

If several different maximum potential earthquakes produce the largest ground acceleration in different frequency bands, the vibratory ground motion specified for design earthquake must be as conservative in each frequency band as that for each earthquake. When developing site specific response spectra both horizontal and vertical components should be used. Records chosen for generating the spectra should have similar source, propagation path, and recording site properties as the controlling earthquake. Recorded motions must represent the free field conditions and be free of or corrected for any soil-structure inter-action effects that may be present because of the location and/or housing of recording instruments. Important source properties include magnitude, and, if possible, fault type and tectonic environments. Propagation path properties should include distance, depth and attenuation.

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- Design earthquakes should be specified for the surface and at repository depth. The repository consists of engineered surface facilities and underground workings in which materials may behave non linearly. A variety of engineering analysis methods will be required and a suite of internally consistent input parameters and their probabilities will be needed. The design earthquake will be defined as:

  — Typical horizontal and vertical time functions (strong motion seismograms);

  — Probabilistic compound spectra which have appropriate frequency contributions from all major contributors to seismic risk;

  — Maximum vertical and horizontal peak acceleration, velocity, and displacement.

- Relevant site properties include shear wave velocity profile, and other factors that affect the wave amplitudes at different frequencies. A sufficiently large number of site-specific time histories and/or response spectra should be used to obtain an adequately broad band spectrum and to encompass the uncertainties in these parameters.

- Where a large enough ensemble of strong motion records are not available, response spectra may be approximated by scaling that ensemble of strong motion data that represent the best estimate of source, propagation path, and site properties. Sensitivity studies should show the effect of scaling.

- If strong motion records are not available, site-specific peak acceleration, velocity and displacement should be determined from appropriate magnitude, distance and foundation conditions. The response spectra may be determined by scaling the acceleration, velocity and displacement values using approximate amplification factors.

- Response spectra developed by an empirical-theoretical model of ground motion may be used to supplement site specific spectra. Input parameters and the appropriateness of the model is to be completely documented.

- Probabilistic estimates of seismic hazard should be calculated following the approach described below.

4.3.3 Identification of Seismic and Alternative Seismic Source Zones and Source Faults

To identify seismic source zones, maps of historic and instrumentally recorded earthquakes should be provided to support the technical basis for delineating seismic source boundaries. However, due to uncertainties about the process of earthquake generation in the United States, a number of alternative models should be considered to adequately quantify scientific opinions.

The following is a list of products that must be provided as part of the seismic source evaluation documentation:

- Maps showing historic and instrumentally recorded seismicity and the tectonic features in the study area;

- A map showing those tectonic features that are believed to be seismically active; and

- For each tectonic feature believed to be seismically active or inactive, a discussion of the technical basis to support the hypotheses.

In most of the hazard analyses performed to date, seismic sources are modeled in seismotectonic zones as point sources (Bernreuter and others, 1989). It is anticipated that seismic sources will be modeled in source zones either as line, area, dipping plane, volume sources, or combinations. When delineating seismic sources, feasible alternatives to the proposed seismic source configuration should be presented, since they may lead to different probabilities of exceedance in the computed hazard curves. For example, if a fault is identified as a line source, it should be stated whether the fault is treated in the analysis as a single long fault or a segmented fault and the bases for the assumption should be provided. This identification will help in assigning the appropriate maximum magnitude to be used in the analysis.

4.3.4 Justification for Magnitude-Frequency Relationships

For the earthquake occurrence model, the location and size of earthquakes for each seismic source zone developed should be quantified and the earthquakes in that zone should be corrected for completeness [Kelly and Lacross (1969), Stepp (1972), Lee and Brillinger (1979), Veneziano et al., (1984)]. The minimum earthquake magnitude (lower bound magnitude) and the maximum earthquake magnitude (upper bound magnitude) that can be generated by seismic sources should be identified. Earthquakes of small magnitude (less than 5.0) are usually not considered in estimating the activity rate in nuclear reactor analysis, because they rarely cause structural damage. In the case of a HLW repository, small magnitude events should be addressed, since they may contribute to cumulative physical changes in the ground-water flow system. It should be noted that the configuration of the seismic-zones boundaries will dictate the earthquakes that will be used to calculate the seismicity rate and the seismic parameters for the zones. A catalog of historic and instrumental seismicity is generally prepared to estimate the seismic parameters. Bender (1982) found that for seismic source zones in which the total number of earthquakes is less than 40, a significant error in the computed b values will occur. Therefore, when analyzing earthquake occurrence, the following items should be considered:

- The completeness of the earthquake catalog

- The uncertainty associated with the instrumental estimate of M

- The regressions on M and

- The constraint of using Poisson's or other distributions

4.3.5 Examining Poisson and Non-Poisson Distributions for Recurrence Relations

The probabilistic approach discussed in this guidance follows the LLNL (Bernreuter et al., 1989), and EPRI (1988) methodologies and is similar to that used by the office of Nuclear Reactor Regulation for calculating seismic hazards at reactor facilities. These approaches are acceptable for use in both the pre-closure and postclosure period of operation of the geologic repository. For the pre-closure period, (100 yr or less), where it can be assume that there is a cyclic recurrence of earthquakes, the Poisson model may be used. For the postclosure period (10,000 yr.) the Poisson model may not be the appropriate distribution model to use because its adequacy has not been established for such an extended time period. However, Cornell and Winterstein (1986), in examining high seismicity areas, found that the Poisson model may be applicable for long time-periods. To identify the appropriate distribution to be used at the site of concern for such a long time-period, it is acceptable to also consider earthquake records from other areas with similar tectonic and seismological features to that of the site under investigation.

4.3.6 Comparison of Ground Motion Attenuation Curves

Empirical data will be used to estimate attenuation models (Campbell, 1981, 1982; and Joyner and Boore, 1981, and 1982). However, there is considerable uncertainty in estimating the intensity of ground motion resulting from an earthquake of a given size and distance from a source, because of inadequate data. Attenuation models now in existence are generalized models and may not be applicable to sites with different tectonic styles. Therefore, the DOE should consider development of appropriate attenuation models for YM if possible.

4.3.7 Thorough Justification of Characteristic Earthquakes, if Used in the Analysis

Characteristic earthquakes are those earthquakes which are generated from the rupture of certain segments of the fault. Characteristic earthquakes are usually less conservative than those generated from total rupture of the fault length, and they show a different recurrence relation than those of a Gutenberg-Richter relationship. Use of characteristic earthquakes should be justified on the basis of Quaternary fault displacement and the historic earthquake records. If a strong rationale for segmented faults cannot be developed, potential earthquake magnitudes to be associated with a Class I fault will be based on its total length.

4.3.8 Examination of Local Site Effects

The design earthquake motion for the surface facilities is defined in the "free field, "for example, at the ground surface. Because of the deformability of the supporting rock or soil, the resulting motion of a base slab will differ from the corresponding free field motions. Therefore, when modeling soil structure interaction, the following factors should be considered: (i) the extent of the embedment, (ii) the depth of the soil, and (iii) the depth of soil strata. All soil structure interaction must recognize relevant uncertainties including: (i) transmission of input motion to the site, (ii) uncertainty in soil modeling, (iii) nonlinear soil behavior, and (iv) lack of symmetry in soil deposits.

4.3.9 Comparison of Theoretical Surface and Subsurface Vertical and Horizontal Ground Motion With Recordings at Depth

When designing for structures, systems, and components important to safety the horizontal component of acceleration is usually considered. Horizontal acceleration is usually larger than the vertical acceleration recorded at some distance on the ground surface. Vertical acceleration is usually assumed 2/3 of the horizontal at some distance from the source. Such a ratio in the analysis for underground facilities or in the near-field may not be appropriate and, if used, should be justified by examining an appropriate set of data over an appropriate range of frequencies of interest. Accelerations at depth are theoretically wavelength dependent with a maximum reduction of two times the surface acceleration (Gutenberg and Richter, 1956).

4.3.10 Multiple-Expert Probabilistic Analyses Should be "Transparent"

Multiple-expert probabilistic analyses should be easily as transparent as possible. Single expert probabilistic analyses with a thorough justification and rationale for expert opinions are more easily understood than multiple expert analyses with aggregated final opinions. Therefore, to enhance transparency, multiple-expert probabilistic analyses should be accompanied by single expert analyses with complete rationales for opinions that bracket the extremes of opinions used in the multiple expert analysis.

4.3.11 Examination of Effect of Repeated Small Events on Waste Canisters

The rate of occurrence of small earthquakes is usually higher than those for large earthquakes. After a long span of time waste containers will become corroded and their integrity weakened and they are more susceptible to rupture induced by ground motion. Therefore, recurrence intervals for both major risk contributing earthquakes and accompanying smaller events should be developed so potential damage caused by repeated earthquakes can be assessed.

4.3.12 Limit Post-Analysis Ground-Motion Reductions

Proposed design procedures (U.S. Department of Energy, 1994a,b) reduce ground motions derived by probabilistic methods before their application to the design of systems, structures and components important to safety. The reductions are based on engineering judgement concerning the ductility of ordinary structures and a comparison of the hazard probability with other types of structures. Staff does not believe these proposed reductions of ground motion prior to design calculations are justified because of:

- The high level of uncertainty requiring expert judgements in ground motion analyses
- The unusually large amounts of fissionable material to be stored and handled
- The fact that HLW repository facilities are not ordinary buildings
- The desire for compensating conservative designs

Ground motion input to structural design should not be reduced prior to design calculations for structures, systems and components important to safety or waste retention.

4.4 CONSIDERATION OF TECHNICAL UNCERTAINTIES

Because of the short duration of the earthquake data set in the United States (200 to 300 yr), there are uncertainties associated with each of the parameters used in the seismic hazard analysis. Also, there are other uncertainties caused by dependencies among the seismic parameters themselves. The uncertainties can be reduced if additional data can be acquired, but in the field of seismology, this may be difficult to accomplish, because earthquakes are relatively infrequent compared to other natural

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phenomena. Therefore, uncertainty associated with the different input parameters should be properly identified, assessed, and expressed clearly. Uncertainty may be expressed in logic trees (National Research Council, 1988) or by "confidence bounds" on input parameters and calculated values.

4.5 EARTHQUAKE AND FAULT OFFSET EFFECTS ON GROUNDWATER

Concern was expressed by the CNWRA FD&SHA advisors that analysis of the effects of fault displacement and earthquake ground motion on groundwater may not be analyzed. The staff recognizes that such effects are an element of PA. However, to ensure that earthquake effects are technically analyzed using field and laboratory data to support PA scenarios, a staff position is taken that FD&SHA will consider this effect.

4.6 EXPERT OPINION

Expert opinions are necessary when there are large uncertainties in the analysis of data, when data is unavailable, or in development of tectonic models. The mixing of data and judgements in PFD&SHA can result in questionable results. Therefore, the use of expert opinions to establish fault displacement and seismic hazards and their quantitative uncertainties should be subject to accepted rules (DeWispelare and Bonano, 1995). NRC staff are in the process of preparing an STP on the subject of expert elicitation in which the choice of experts is to be determined by peer assessment with potential conflicts of interest identified but not necessarily used as a disqualification. Concern has been expressed that radical opinions must somehow be weighted or criteria developed for their dismissal. Staff, however, believe that uncertainties are large and that if expressed by peer chosen experts, they should be considered without weighting or the appearance of imposed restraint or intimidation.

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6 GLOSSARY (FROM EPRI COMMITTEE ON SEISMIC RISK, 1989)

Annual Probability of Exceedance: The level of probabilistic seismic hazard or seismic risk associated with an exposure time of one yr.

Attenuation Relationship: A mathematical equation that defines the relationship between a ground-motion parameter, earthquake magnitude, and source-to-site distance. These equations are usually derived from the analysis of earthquake records.

Background Seismicity: Seismicity that cannot be attributed to a specific fault or source zone.

Ground Motion: A quantitative description of the vibration of the ground resulting from an earthquake, usually given in terms of an acceleration time series (an accelerogram) or a response spectrum.

Gutenberg-Richter Relationship: An empirical relationship between N, the expected number of earthquakes per yr with magnitude greater than M, and earthquake magnitude, for a specified source zone.

Probabilistic Seismic Hazard: The probability that a specified seismic hazard, usually a ground motion parameter, will exceed some quantifiable level at a specific location during a given exposure time.

Return Period: The average time between occurrences of a specified level of ground motion at a specific location; it is equal to the inverse of the annual probability of exceedance.

Response Spectrum: The maximum response to a specified acceleration time series of a set of damped single-degree-of-freedom systems, plotted as a function of the undamped natural periods or undamped natural frequency of the system.

Seismic Hazard: Any physical phenomena associated with an earthquake (e.g., ground motion or ground failure) that has the potential to produce a loss.

Seismic Hazard Analysis: The calculation of probabilistic seismic hazard for a site or a group of sites, the result of which is usually displayed as a seismic hazard curve or seismic hazard map.

Source Zone: An area considered to have a uniform rate of seismicity or a single probability distribution for purposes of a seismic hazard or seismic risk analysis.

Uniform Seismic Hazard Spectrum: A response spectrum whose amplitudes represent a uniform level of probabilistic seismic hazard at all periods or frequencies.

Uncertainty: Refers to the state of knowledge concerning a physical phenomenon, it can be reduced by more detailed evaluation or gathering of additional data.

Revised pages (1-1, 1-3, 2-8, and 2-9)

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INPUT ON PROBABILISTIC METHODS FOR A STAFF TECHNICAL POSITION ON FAULT DISPLACEMENT ANALYSIS AND SEISMIC HAZARD ANALYSIS

Prepared for

Nuclear Regulatory Commission
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1 INTRODUCTION

1.1 BACKGROUND

A fault displacement and seismic hazard analysis (FD&SHA) for a high-level nuclear waste (HLW) repository should combine deterministic and probabilistic analyses. Technical criteria for FD&SHA are currently being formulated by Nuclear Regulatory Commission (NRC) staff. This report provides the Center for Nuclear Waste Regulatory Analyses (CNWRA) suggestions for such criteria that resulted from technical support efforts for NRC/Nuclear Material Safety and Safeguards (NMSS) over the past four years. The author of this report takes cognizance of NRC (1995) Design Basis Event (DBE) rulemaking, in which Subpart E of 10 CFR Part 72 is included by reference for natural events less frequent than 10^{-2}/yr. Subpart E of 10 CFR Part 72 requires use of 10 CFR Part 100, Appendix A for nuclear power reactors with regard to earthquake design bases. A proposed revision of 10 CFR 100, Appendix A, recommends a median 10^{-5}/yr hazard level for probabilistic earthquake design of nuclear power reactors. These proposed regulatory changes make suggestions presented here tentative.

Probabilistic methods of determining seismic input to nuclear facility design has evolved through several NRC programs to reevaluate design margins in existing nuclear power plants (NPPs) after changes in perceived seismic risk had occurred. Early efforts in this regard are summarized by Bernreuter and Minichino (1982). Later developments, for example, Bernreuter et al. (1987) outlined the development of two probabilistic seismic risk computer codes that used expert opinions as input in addition to numerical data. The SEISM computer code (also known as SHC) developed by Lawrence Livermore National Laboratories (LLNL) for the NRC was one of them. EQHAZARD, developed by the Electric Power Research Institute (EPRI) for the Seismic Owners Group (SOG) of NPPs in the eastern United States, was the other. As a consequence of evaluation of design margins, the NRC is considering a revision of 10 CFR Part 100 to include probabilistic methods of defining Safe Shutdown Earthquakes (SSEs) for NPP design. This is a significant departure from the NRC past regulatory philosophy which embraced only deterministic methods for setting initial seismic design criteria.

Because of broad interest in probabilistic seismic hazard methods, a Panel on Seismic Hazard Analysis organized under the Committee on Seismology of the National Research Council, prepared a review of these methods (National Research Council, 1988). The panel was charged with the assessment of capabilities, limitations, and future trends in probabilistic seismic hazard analysis (PSHA) in the context of alternatives. The study and report were funded by the NRC, the U.S. Department of Energy (DOE), the U.S. Geological Survey (USGS), the Air Force Offices of Scientific Research (AFOSR), the Federal Emergency Management Agency (FEMA) and the Defence Advanced Research Projects Agency (DARPA).

The NRC Office of NMSS, Division of Waste Management (DWM) initiated efforts at the CNWRA to assess methodologies for potential application to a HLW repository with a 10,000 yr period of performance, which contrasts with a nominal 40 yr life expectancy for NPPs and most other civil structures. Part of the CNWRA program was to acquire one or both of the seismic risk computer codes and implement them on their computers. The NRC/LLNL code was acquired and modified to perform PSHA at western U.S. sites. A hazard calculation was made using published expert opinions, and a probabilistic fault displacement analysis (PFDA) capability was implemented in the code and tested (Hofmann, 1994).

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There are concerns that the DOE combined ground motion determination and design philosophy may not be adequately conservative to ensure that the public will not be exposed to undue risk, because the amount of radioactive material planned for the repository is orders of magnitude larger than contained in a single NPP, the repository's period of retrievability may be several times as long as an expected NPP time of service, and the repository's planned performance period is about 200 times as long. Although the first of the series of three DOE seismic related Topical Reports has been prepared, all details of seismic design philosophy and the results of that philosophy are not final.

1.2 OBJECTIVES

The objective of this report, pending more complete information regarding the DOE seismic input determination and proposed ground motion reduction before use in design calculations, is to summarize CNWRA PFD&SHA efforts germane to the development of an analysis STP. Suggested probabilistic input to an internal draft analysis STP, from DWM/CNWRA PFD&SHA efforts, is in Appendix A of this report. Further STP development, however, will depend on whether details in the DOE Topical Reports, taken together, are in reasonable agreement with NRC staff concerns. Because of the limited 3 yr time allotted NRC for review of the DOE License Application (LA), the NRC must be in a position to develop an analysis STP for ground motion and fault displacement should it become apparent that DOE and NRC staff are in significant disagreement over planned levels of conservatism in ground motion or fault displacement. An objective of this report is to document the results of CNWRA activities and provide input to a draft STP.

1.3 STAFF TECHNICAL POSITIONS AS TECHNICAL GUIDANCE

The STPs are issued to describe and make available to the public methods acceptable to the NRC staff for implementing specific parts of the Commission's regulations, and to provide regulatory guidance to the DOE. The STPs are not substitutes for regulations, and compliance with them is not required. Methods and solutions differing from those set out in the STP will be acceptable if they provide a basis for the findings requisite to the issuance of a permit or license by the Commission.

Published STPs will be revised, as appropriate, to accommodate comments and to reflect new information and experience.

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2.2 SUMMARY OF THE MAY 17-18, 1993, CENTER FOR NUCLEAR WASTE REGULATORY ANALYSES ADVISORS MEETING AND REPORTS ON FAULT DISPLACEMENT AND SEISMIC HAZARD ANALYSIS

NRC and CNWRA staff made presentations at this meeting and posed questions to the FD&SHA advisors. The advisors had been sent an internal draft of an analysis STP. All responded with recommendations prior to the meeting. Two advisors revised their recommendations following the meeting. There is considerable detail in the individual reports. Major categories of recommendations are summarized here:

- Terminology
- Use of Deterministic Analysis
- Setting NRC Probabilistic Analyses Requirements
- Elicitation of Expert Opinion
- Credibility and Weighting of Expert Opinion
- Alternative Tectonic Models
- Stability of the Tectonic Regime
- Uncertainties
- Data Collection
- Relationship of PFD&SHA to Groundwater and Iterative Performance Assessment (IPA)
- Transparency of PFD&SHA
- Attenuation with Depth
- Costs

Some of these items are addressed in various sections of Appendix A of this report.

2.2.1 Terminology

Two experts were strongly opposed to the use of terminology such as maximum credible earthquake (MCE), maximum credible fault displacement (MCFD), and such words as "precise" or "sufficiently credible." Three experts did not comment on this topic.

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2.2.2 Use of Deterministic Analyses

Opinion was divided on this issue. An advisor stated that deterministic analysis are needed to establish basic data, distinguish among hypotheses, test models, and provide "reality checks," but complete data and physical models are never achievable so probabilistic analysis is important and necessary. Another expert stated that the deterministic approach can be used to evaluate the hazard from the most obvious individual features and that given how much *a priori* geologic and tectonic knowledge needs to be incorporated, a deterministic approach could provide meaningful and defensible results. This expert also pointed out that because of the poor quality of the input data and implementation there are pitfalls to the probabilistic method. Speaking of the complexity of the process, he stated "It is like having pureed vegetable soup at a French restaurant. It tastes OK to everyone but no one can identify the ingredients."

The other side of the argument was taken by three of the experts with two being somewhat ambivalent and one adamant. The latter stated that the idea of a dual approach is inconsistent with the concept of a stable, for example, technically defensible licensing process that is workable by both the applicant and the NRC staff. "Eliminate the dual deterministic - probabilistic approach. Use only a probabilistic FD&SHA." One expert stated that the ultimate need, in order to meet the Environmental Protection Agency (EPA) criteria, of a quantitative description of randomness and uncertainty provides the basis for probability-based criteria. Also stated was that a site investigation should be supported with a deterministic analysis. In support of a probabilistic procedure, another advisor suggested that several questions would have to be answered implying that only a probabilistic approach could do so. Questions posed were "(i) how was the MCE 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 yr and the next 10,000 yr; and (iv) what differential fault displacements and ground shaking levels will result from each of the hypothesized events? and so on." This advisor also states that a single value estimate will lead to suspicion, can be easily disputed by any opposition party and that a deterministic analysis provides for a simpler, more understandable or transparent approach, however the single value is not defensible in the light of all the model, parameter and phenomenological uncertainties. This advisor concludes that a deterministic approach will not be defensible in the light of all the uncertainties and the inherent randomness of earthquake phenomena.

This topic is addressed in Sections 3.3 and 4.3 of Appendix A.

2.2.3 Setting Probabilistic Analysis Requirements

The DOE is expected to develop its seismic design using probabilistic accelerations or spectra. The NRC needs to develop HLW repository seismic acceptance criteria. Currently, an acceleration or spectra which recurs once every 100,000 yr is recommended by the NRC as acceptance criteria for NPPs in a proposed revision to 10 CFR Part 100. Two of the FD&SHA advisors included the setting of such criteria by the NRC as an item that should appear in the analysis STP.

> "As soon as NRC establishes its numerical criteria [See Part C(3), below], it can ask DOE to provide current design values."