TOPICAL REPORT YMP/TR-002-NP: METHODOLOGY TO ASSESS FAULT DISPLACEMENT AND VIBRATORY GROUND MOTION HAZARDS AT YUCCA MOUNTAIN

Revision 1

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for Wesley E. Barnes, Project Manager
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ABSTRACT

This topical report documents the methodology that will be used in a probabilistic assessment of the fault displacement and vibratory ground motion hazards at Yucca Mountain. The seismic hazards identified by this methodology will be used to support design, performance assessment, and regulatory compliance activities. The identified seismic hazards will be input to a preclosure seismic design methodology, described in a subsequent topical report, for the potential geologic repository at Yucca Mountain. The results of the methodology will also be input to total system performance assessments of long-term waste isolation at the site, which may generate postclosure seismic design requirements. In this context, the seismic hazard assessment will be used to evaluate earthquake-related favorable conditions and potentially adverse conditions, as defined in Title 10, Part 60 of the Code of Federal Regulations (10 CFR 60).

The methodology comprises a five-step process for the assessment of vibratory ground motion hazard. First, seismic sources are identified. Second, the maximum magnitude and earthquake recurrence relationship for each source are described. Third, ground motion attenuation relationships are developed for the site region. Fourth, multiple seismic hazard curves are developed by integrating over each combination of inputs determined in the first three steps. The multiple curves represent the variability in the various inputs. Finally, a distribution of the suite of hazard curves is expressed as a mean curve and curves representing particular percentiles of the distribution. An analogous process is followed for the assessment of the fault displacement hazard.

The methodology described in this report is a probabilistic approach to seismic hazard assessment. This approach allows the frequency of earthquake occurrences to be incorporated in the analysis. It also allows uncertainties to be quantified and displayed in the final hazard results. The probabilistic methodology is consistent with the requirements of total system performance assessment and the design process. In addition to describing the hazard assessment methodology, the report discusses the seismic hazard methodologies of other studies and some historical applications of probabilistic seismic hazard analyses in a nuclear regulatory framework.

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1.0 INTRODUCTION

Title 10 of the Code of Federal Regulations, Part 60 (10 CFR Part 60) requires that natural phenomena will not unduly compromise either safety functions of structures, systems, and components (SSCs) of the Geologic Repository Operations Area (GROA) or radioactive waste containment and isolation. In addition, retrievability of waste during the preclosure period must be maintained, features that might affect repository design and performance must be described and assessed, and potentially adverse conditions must be adequately investigated and evaluated. To satisfy these requirements, the hazards of vibratory ground motion and fault displacement must be assessed.

Although 10 CFR Part 60 establishes the general need to study ground shaking and fault displacement hazards due to earthquakes, it provides neither specific guidance on how these hazards should be investigated, assessed, and evaluated, nor on how appropriate design loads should be determined. The Department of Energy (DOE) submitted its preliminary approach for assessing seismic hazards[1] in its *Site Characterization Plan Yucca Mountain Site* (SCP) (DOE 1988). The DOE updated its approach to seismic hazards assessment in Revision 0 of this Topical Report, which was submitted to the Nuclear Regulatory Commission (NRC) staff for review. Revision 1—this document—incorporates changes to resolve the staff's comments on the first submittal.

1.1 OBJECTIVE AND SCOPE

The objective of this Topical Report is to describe the DOE's methodology to assess vibratory ground motion and fault displacement hazards at Yucca Mountain, Nevada. When implemented, the methodology will provide results to support preclosure seismic design of the proposed high level nuclear waste repository. In addition, the results will be used in the evaluation of the long-term performance of the repository with respect to the containment and isolation of waste. The results will also be used to evaluate *potentially adverse conditions*, as defined in 10 CFR Part 60.

This Topical Report is the first of three topical reports that together will document the basis for DOE's seismic design of the repository. The first report describes the DOE's methodology to assess fault displacement and vibratory ground motion hazards at Yucca Mountain. The second topical report (YMP 1997) establishes preclosure seismic design criteria and appropriate seismic hazard levels for design. A third seismic topical report is planned that will describe the application of the seismic hazard assessment methodology and the development of the corresponding seismic design inputs (e.g., seismic response spectra, time histories and fault displacement levels). The objective of the series of topical reports is to obtain NRC staff concurrence on the DOE's assessment of seismic hazards and the resulting preclosure seismic design criteria in advance of submitting an application for authorization to construct a repository at Yucca Mountain.

1.2 REGULATORY REQUIREMENTS

The applicable NRC regulatory requirements for the disposal of high level radioactive wastes in geologic repositories are found in 10 CFR Part 60. The need to assess vibratory ground motion and fault displacement hazards derives from a number of these requirements.

1 The term "seismic hazards," as used in this topical report, refers to the hazards associated with both vibratory ground motion and fault displacement.

Subpart B to Part 60 addresses the regulatory requirements for the license application (LA). Within Subpart B, Section 60.15 provides that the DOE shall conduct site characterization activities to collect information to support its LA; Section 60.21 identifies the information and assessments to be included in the LA; and Section 60.21 (c) describes the information required to be in the Safety Analysis Report accompanying the LA, including a description and assessment of those features of the site that might affect repository design and performance. Seismic-related hazards are among the many features that must be assessed in the Safety Analysis Report to support a finding of reasonable assurance that the NRC performance objectives and criteria can be met.

Subpart E addresses the performance objectives and technical (siting and design) criteria which will support a finding that the issuance of a license to receive and possess high level waste will not constitute an unreasonable risk to the public health and safety. Within Subpart E, Sections 60.101 (a) (2) and (b) note that although these objectives and criteria may be stated in unqualified terms, it is not expected that the DOE will provide complete assurance that they can be met. Rather, the DOE must provide reasonable assurance, taking into account the time period, hazards, and uncertainty involved, that it can develop a geologic repository without unreasonable risk to the health and safety of the public.

The Subpart E siting criteria referred to above are identified in Section 60.122, which provides that favorable conditions associated with the geologic setting, together with the engineered barrier system, must provide reasonable assurance that the performance objectives relating to waste isolation will be met. In addition, this section also addresses the concern that if specifically identified potentially adverse conditions are present, then the ability of the repository to meet its performance objectives may be compromised. Potentially adverse conditions, if present, must be adequately investigated and evaluated for their impact on waste isolation. Potentially adverse conditions that must be considered for a geologic repository are listed in Section 60.122 (c).

As noted below, the potentially adverse conditions that relate to ground shaking hazards and fault displacement hazards are found in Sections 60.122 (c) (3), (4), (11), (12), (13), (14), and (20).

(c) (3) "Potential for natural phenomena such as landslides, subsidence, or volcanic activity of such a magnitude that large-scale surface water impoundments could be created that could change the regional groundwater flow system and thereby adversely affect the performance of the geologic repository."

(c) (4) "Structural deformation, such as uplift, subsidence, folding, or faulting that may adversely affect the regional groundwater flow system."

(c) (11) "Structural deformation such as uplift, subsidence, folding and faulting during the Quaternary Period."

(c) (12) "Earthquakes which have occurred historically that if they were to be repeated could affect the site significantly."

(c) (13) "Indications, based on correlations of earthquakes with tectonic processes and features, that either the frequency of occurrence or magnitude of earthquakes may increase."

(c) (14) "More frequent occurrence of earthquakes or earthquakes of higher magnitude than is typical of the area in which the geologic setting is located."

(c) (20) "Rock or groundwater conditions that would require complex engineering measures in the design and construction of the underground facility or in the sealing of boreholes and shafts."

The Subpart E design criteria referred to above are identified in Sections 60.131-134. Section 60.131 (b) (1) addresses design criteria to protect against natural phenomena and environmental conditions, which would include ground shaking hazards and fault displacement hazards.

Before a reasonable assurance determination can be made regarding whether the siting and design criteria identified above have been met, appropriate seismic hazard levels must be selected to assess their effect on design. This assessment in turn depends on the selection of an appropriate methodology to assess the seismic hazards. As described in this topical report and its appendices, the DOE proposes to apply a probabilistic methodology to assess any significant seismic hazards that might adversely affect the performance of the repository[2]. The DOE is seeking NRC staff concurrence that the methodology proposed in this report is suitable for assessing seismic hazards for seismic design of the Yucca Mountain facilities, and that if implemented properly, the methodology should lead to the development of the data needed to complete the assessments required under 10 CFR Part 60 relating to the effects of seismic hazards.

1.3 BACKGROUND AND MOTIVATION

The DOE presented an approach for assessing seismic hazards in the SCP (DOE 1988). In its review of that approach, the NRC staff identified a number of items for which additional development and clarification were deemed necessary (NRC 1989). In addition, since publication of the SCP the NRC staff has developed guidance on investigations needed to identify fault displacement and ground motion hazards (NRC 1992) and on consideration of fault displacement hazards in seismic design (NRC 1994). Also subsequent to the development of the SCP, more powerful methods for assessing seismic hazards and for carrying out seismic design have been developed and refined. These improved methods have now gained a large degree of professional and regulatory acceptance. Therefore, based on feedback from the NRC staff and on technical progress in the fields of seismic hazard assessment and seismic design, the DOE has reevaluated its approach to assessing vibratory ground motion and fault displacement hazards and to determining loads appropriate for seismic design of the Yucca Mountain repository.

The revised methodology described in this topical report is based on probabilistic analyses that incorporate a broad set of data on the behavior of faults, earthquake recurrence, and earthquake ground motion. The methodology explicitly incorporates and quantifies uncertainty due to randomness and diversity of data interpretation[3] and displays this uncertainty in the final hazard results. Formal expert elicitation is used to obtain interpretations of seismic sources and earthquake ground motion relationships that capture the range of interpretations that are supported

[2] DOE's initial plans for obtaining data and performing analyses relating to seismic and fault displacement hazards are contained in Section 8 of the SCP for the Yucca Mountain Site (DOE 1988). The modified approach described in this report will require changes to existing study plans and perhaps the development of new study plans. These changes will be documented in an SCP semiannual progress report.

[3] More precisely, "randomness" denotes *aleatory* uncertainty which, for all practical purposes, cannot be known in detail or cannot be reduced, although it is susceptible to analysis concerning its origin and magnitude (SSHAC 1995). "Diversity of data interpretation" represents *epistemic* uncertainty, which arises because of imperfect scientific understanding for the present, but which, in principle, is reducible through further research (SSHAC 1995).

by the data. The hazard analysis produces a distribution of hazard curves showing the annual probability with which various levels of ground motion or fault displacement are exceeded.

The results of the seismic hazards assessment will be used in the seismic design process and to evaluate the postclosure waste containment and isolation performance of the repository. For the preclosure period (about 150 years), design concerns are waste containment during handling and emplacement, worker safety in surface facilities and underground excavations, and maintenance of waste retrievability. For the postclosure period, seismic design concerns are the location of emplaced waste relative to any active faults and the potential for fault displacement or rockfalls (caused by vibratory ground motion) to accelerate the corrosion failure of waste packages or adversely affect the engineered barrier system. The seismic hazard curves for vibratory ground motion and fault displacement will form the basis for determining the appropriately conservative seismic design loads for the repository SSCs.

For assessment of long-term repository performance with respect to waste containment and isolation, the expected probabilistic nature of the Environmental Protection Agency standard requires a probabilistic evaluation of vibratory ground motion and fault displacement hazards.[4] Time periods of concern include the containment period (300 to 1000 years) and the postclosure period for waste isolation performance (10,000 years or longer). Probabilistic hazard curves will be used directly as input to analyses of earthquake consequences (e.g., permeability changes resulting from faulting and damage to waste canisters or seals from faulting or ground motion).

Because of the proximity of the Yucca Mountain site to areas of past and potential future underground nuclear explosions (UNEs) at the Nevada Test Site (NTS), vibratory ground motion from UNEs and the potential for UNEs to trigger fault displacement also must be considered in establishing the repository seismic design basis. However, because the likelihood of future underground nuclear weapons tests cannot meaningfully be assessed and because the predicted effects of UNEs at the site are minimal, the DOE is assessing UNE hazards deterministically, rather than probabilistically. Details are provided in Appendix A.

1.4 OVERVIEW OF THE REPOSITORY SEISMIC DESIGN PROCESS

To facilitate an understanding of how the DOE's methodology to assess seismic hazards fits into the overall framework of the seismic design process, a brief discussion of the overall concept is presented here.

SSCs important to safety must, ultimately, be built to a single design that meets all requirements, including those for both preclosure and postclosure performance. The process being employed by the DOE to assure that the repository design meets all seismic requirements is illustrated in Figure 1.

Preclosure seismic design comprises three steps. The first step is assessment of seismic hazards, the subject of this report. In the second step, preclosure seismic design criteria and seismic hazard levels appropriate for design are determined. This step is documented in the second seismic

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[4] A standard for the public health and safety at Yucca Mountain is being developed pursuant to Section 801 of the Energy Policy Act of 1992. Although the Environmental Protection Agency standard is in the process of revision, the DOE expects that the new standard will be probabilistic. Of course, DOE will re-assess its methodologies when the final standard applicable to Yucca Mountain is issued to ensure that its assumptions remain valid or, where necessary, to make appropriate corrections.

topical report (YMP 1997). In the third step, preclosure seismic design inputs (e.g., ground motion response spectra and time histories, fault displacements, and fault setback distances) will be developed for the established hazard levels. The DOE plans to document the results of the last step in a third seismic topical report.

The DOE's preclosure seismic design process complies with the NRC's recent rulemaking (60 FR 15180) for 10 CFR 60, which created two categories of design basis events. These events are defined by qualitative descriptions of their likelihood of occurrence before closure of the repository. As detailed in the second seismic report (YMP 1997), the DOE refers to the two categories of design basis events as *Frequency-Category-1* and *Frequency-Category-2* and intends to use mean annual probabilities of 1×10^{-3} and 1×10^{-4}, respectively, as reference values in determining the Frequency-Category-1 and -2 design basis vibratory ground motions. For design-basis fault displacements, where potentially active faults cannot be avoided, the DOE intends to use mean annual probabilities of 1×10^{-4} and 1×10^{-5}, respectively, for the Frequency Category-1 and -2 design-basis fault displacements. Consistent with NUREG-1494 (NRC 1994), the DOE will avoid placing facilities over Type I faults wherever it is feasible to do so. Avoidance, here, means siting facilities far enough from Type I faults such that an explicit fault-displacement design is not necessary.

Once the design-basis seismic hazards are established, standard design procedures are followed. The DOE has reviewed existing NRC standard review plans for nuclear power reactor seismic designs and has identified those plans which can appropriately be applied to the design of repository surface facilities (YMP 1997). For the seismic design of underground facilities, for which no NRC guidance documents are available, the DOE has detailed a design approach that utilizes empirical methods, which are based on tunneling and mining experience, and numerical methods, which can model the effects of the particular thermal and seismic loads that must be accommodated by repository ground support systems.

Permanent items of the repository may have to satisfy postclosure as well as preclosure seismic design requirements. As shown in Figure 1, the seismic hazard assessment in step 1 feeds assessments of the postclosure waste containment and isolation performance of the repository. These assessments explicitly consider the effects of earthquakes and other potentially disruptive tectonic processes and events. The iterative process of assessing performance and identifying design solutions may lead to the establishment of seismic and other design requirements for permanent items of the repository. If both postclosure and preclosure seismic design requirements apply to a repository SSC, the most stringent requirement controls the SSC design.

1.5 RECENT EXPERIENCE

Licensing proceedings for nuclear power plants highlighted the limitations of a strictly deterministic approach to assessing seismic hazard. These limitations led the NRC to revise its seismic siting criteria for nuclear power reactors in Appendix A to 10 CFR Part 100 to incorporate probabilistic procedures along with deterministic ones (see Section D1.4).

One limitation of the traditional deterministic approach is its failure to incorporate complete information on frequency of occurrence[5]. To make risk-consistent decisions, frequency of occurrence is a necessary piece of information because risk is directly related to likelihood of

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[5] "Frequency of occurrence" and "recurrence" are used in this context to indicate the rate of occurrence of earthquakes, ground motions, and fault displacements, usually expressed per year.

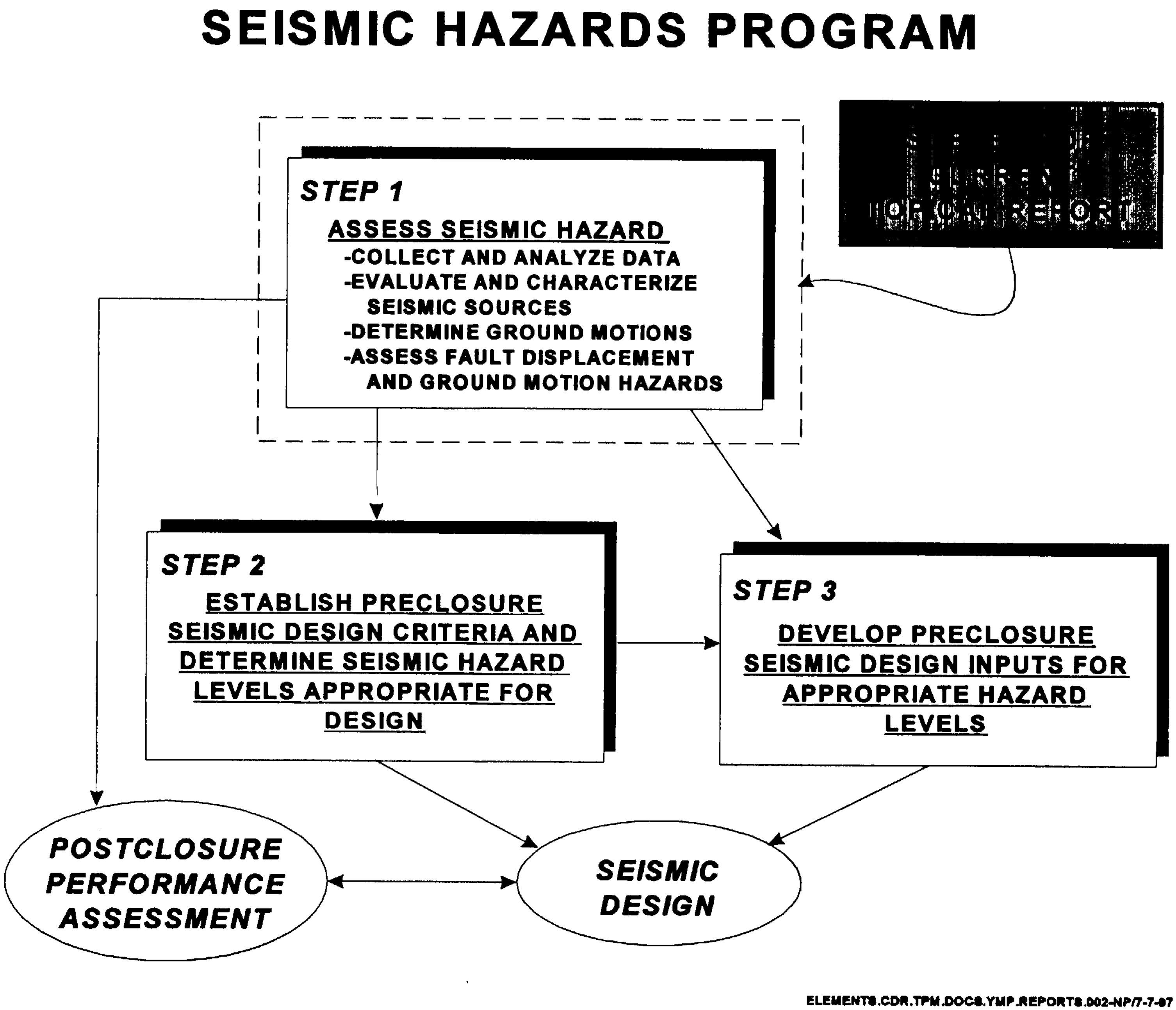


Figure 1. Basic Elements of the Seismic Hazards Program

occurrence. All other factors being equal, a fault whose maximum magnitude recurs every 100 years poses a greater risk than one with a recurrence interval of 100,000 years. The DOE methodology directly incorporates frequency of occurrence by assessing the hazard probabilistically. As detailed in the second seismic topical report (YMP 1997), the DOE chose the seismic hazard levels that are appropriate for preclosure repository design to be consistent with the hazard levels that correspond to the NRC-accepted seismic design bases of the more recently licensed nuclear power reactors in the United States.

Traditional deterministic approaches also are limited in their ability to handle uncertainty. Typically, randomness (aleatory uncertainty) and diversity in data interpretation (epistemic uncertainty) are not explicitly incorporated in the deterministic approach. Thus, information that should be available in the regulatory decision-making process is not available in a form in which its impacts can be easily evaluated. In contrast, probabilistic methods explicitly parameterize randomness and capture diversity in data interpretations and propagate this uncertainty through to the final results. Probabilistic hazard results, expressed as distribution fractiles or confidence levels, provide a more complete description of the hazard.

An additional advantage of the probabilistic method is that it allows the significance of individual seismic sources to be evaluated. The total hazard at a given probability level can be disaggregated to identify the source or sources that contribute most strongly. The probabilistic method thus provides a logical basis for assessing the significance of faults with respect to design and performance assessment, in conformance with the NRC staff's guidance in NUREG-1451 (NRC 1992, section 3.1.3 (1) (b)).

Finally, although probabilistic methodologies have been applied primarily to the assessment of vibratory ground motion hazard, their advantages apply equally to fault displacement hazard. Characterization of fault-displacement hazard is also uncertain because of randomness and diversity in data interpretation and must, therefore, be assessed probabilistically to support a risk-consistent design. The DOE methodology provides a consistent approach to characterizing the hazards of vibratory ground motion and fault displacement, supports performance assessment and seismic design applications, and provides a comprehensive information base for regulatory decision making.

1.6 ORGANIZATION OF THE REPORT

This report is organized to present the basic components of the methodology in the main body of the report and to provide more details on each component and background information in appendices. Section 2 presents the overall philosophy, basic framework, and procedures of the methodology. Appendix A presents the approach to seismic source characterization, Appendix B describes how ground motion issues will be addressed, and Appendix C provides more detail on the hazard assessment procedures for both vibratory ground motion and fault displacement. In Appendix D, some recent efforts aimed at the assessment of seismic hazards are summarized to demonstrate the experience base upon which the methodology is founded. Cited references are listed in Appendix E.

2.0 METHODOLOGY TO ASSESS VIBRATORY GROUND MOTION AND FAULT DISPLACEMENT HAZARDS

The methodology to assess seismic hazards at Yucca Mountain must address the regulatory requirements in 10 CFR Part 60, as described in Section 1.2. These requirements may be briefly summarized as follows:

- Structures, systems and components in the repository must be designed so that anticipated natural phenomena do not interfere with safety functions and radioactive waste containment and isolation.
- Retrievability of waste during the preclosure period must be maintained.
- Features that might affect repository design and performance must be described and assessed.
- Potentially adverse conditions must be adequately investigated and evaluated.

To meet these requirements, a seismic hazards assessment methodology should provide quantitative hazard results

- For both the preclosure and postclosure periods,
- For both fault displacement and vibratory ground motion,
- That can be used for design of both surface and subsurface facilities, and
- That can be used for assessment of long-term waste containment and isolation performance.

The probabilistic methodology satisfies the above requirements and provides the needed results.

In developing the methodology, a goal was established to incorporate a number of attributes that are beneficial to hazards assessment and to regulatory review. These attributes are discussed in Section 2.1. Section 2.2 provides the overall framework into which the methodology fits. Next, the methodology itself is summarized in Section 2.3. Section 2.4 discusses some related methodology issues. Finally, in Section 2.5, the major points of this report are summarized.

2.1 DESIRED ATTRIBUTES OF A SEISMIC HAZARD METHODOLOGY

A methodology to assess seismic hazards at Yucca Mountain must provide technically sound results that meet the regulatory requirements, are amenable to regulatory review, and make appropriate use of site characterization data to assess seismic hazard and its uncertainty. To help in meeting these goals, the methodology incorporates the following attributes:

1) **Experience-Based**. The methodology takes advantage of the experience gained from recent assessments of seismic hazards. While there is a large base of regulatory experience for nuclear power plants that deals with seismic design inputs that were developed deterministically for a "maximum credible earthquake" (the traditional deterministic approach), over the past two decades probabilistic methods have evolved to become the generally preferred state-of-the-practice for assessing vibratory ground motion at critical facilities. By incorporating recurrence information and input uncertainty, these methods provide a more complete evaluation of hazard for design, long-term performance assessment,

and regulatory review than do deterministic methods. They provide additional information beyond that which was available in the traditional deterministic approach that can be used to determine design basis earthquakes within a risk-consistent framework. Recent applications of probabilistic methodologies, associated lessons learned, and ongoing evaluations and integration of seismic hazard methodologies (e.g., SSHAC 1995) provide the basis for the methodology described in this report. In Appendix D, pertinent information on recent methodologies and their relevance to the current methodology are summarized.

2) **Data-Driven**. Development of inputs to the seismic hazards methodology and the associated input variabilities are based on site-specific data. A broad program of site characterization activities has been carried out to gather data relevant to seismic hazards at the proposed Yucca Mountain site, and the hazard assessment methodology utilizes all relevant data, including information on earthquake recurrence. The methodology also allows seismic hazard assessments to be easily updated in light of new information.

   Data required for the characterization and evaluation of seismic sources, fault displacements, and ground motions are described in Appendices A and B.

3) **Issue-Focused**. The methodology addresses specific technical issues associated with disposal of spent nuclear fuel and high level waste in a geologic repository. For example, the probabilistic hazard results provide a rational basis for examining and comparing the hazard for the preclosure period (approximately 150 years) and also for long-term performance assessment during the postclosure period (10,000 years or longer). The methodology can also accommodate, through its incorporation of input uncertainty, such issues as temporal and spatial clustering of earthquake occurrence and simultaneous rupture on multiple faults (see Section 2.3.1.2).

4) **Properly Treats Uncertainty**. The methodology provides a complete and unbiased assessment of seismic hazards by incorporating and properly treating input uncertainty. This uncertainty includes both diversity in data interpretations (epistemic uncertainty) and randomness in the earthquake process (aleatory uncertainty). The methodology utilizes formal expert elicitation to capture uncertainty. Multiple experts or multiple teams of experts provide alternative interpretations of physical processes (e.g., style of faulting) and alternative values of parameters associated with those processes (e.g., values for slip rates, maximum magnitudes, and variances in ground motion levels). This explicitly quantified uncertainty is then directly incorporated into the hazard calculations. This methodology contrasts with traditional deterministic approaches, in which uncertainty is accounted for subjectively in the selection of a deterministic design basis earthquake.

5) **Flexible**. The methodology accommodates the full range of credible scientific interpretations, approaches, and data. While conventional approaches are likely to play a major role in evaluating and characterizing seismic sources, new approaches that evolve during site characterization can also be included. Further, the methodology allows rational consideration of unlikely or highly uncertain scenarios. For example, the methodology accommodates the notion of seismic sources occurring in regions where faults are presently unmapped or unknown. Likewise, it can explicitly incorporate concepts of "new" faulting and zones of fault deformation. This flexibility is inherent in the probabilistic framework in which alternative input interpretations are explicitly incorporated. In contrast, in deterministic methods a single interpretation typically is selected, and information related to alternative interpretations is not explicitly included in the final hazard assessment.

6) **Facilitates Sensitivity Analysis.** The methodology intrinsically facilitates the conduct of sensitivity studies. Such analyses identify important contributors to the hazard results and the relative importance of various data and interpretations. Similarly, they are used to highlight relationships or parameters for which differences in interpretation or data do not strongly influence the hazard at the site. Hence, the methodology aids in setting priorities for additional data collection and analysis efforts so that the most important technical issues are addressed, resulting in the greatest reductions in uncertainty.

7) **Well Documented.** The methodology requires documentation of the data sets, interpretations, and uncertainties. The documentation will be sufficiently detailed to allow a third party to review the technical basis for interpretations, the support for the interpretations in the available data, and the uncertainties associated with the evaluation. This documentation will aid in providing reasonable assurance that the vibratory ground motion and fault displacement hazards at Yucca Mountain have been adequately assessed and evaluated.

2.2 FRAMEWORK OF THE METHODOLOGY

The overall seismic hazards program is composed of four parts:

A. Collection and analysis of data

B. Assessment of seismic hazards

C. Development of seismic design inputs for appropriately conservative hazard levels

D. Use of the hazard results in the assessment of long-term waste containment and isolation performance.

This topical report presents the methodology to carry out part B of the overall program. The methodology is developed with a knowledge of the applications in seismic design and long-term performance assessment that it must support (part D), and it relies on data from site characterization activities (part A) for its implementation. The scope of this topical report is restricted to the issue of seismic hazard assessment; issues related to determining appropriate seismic hazard levels for design and for developing seismic design inputs (part C) are covered in the second seismic topical report (YMP 1997). By defining the scope of the current topical report in this manner, it is possible to focus on the issue of seismic hazards assessment independently of issues related to the appropriate conservatism in design. The hazard assessment methodology will support development of seismic design inputs regardless of the level of conservatism that is chosen for design.

The first step in the seismic hazards program is the collection and analysis of relevant data. Consistent with NRC staff guidance in NUREG-1451 (NRC 1992), these data will be used to identify, evaluate, and characterize seismic sources that have the potential to significantly affect the design or performance of a repository at Yucca Mountain. The studies and the methods being used for data collection are described in various Study Plans (Figure 2, block 1).

The methodology to assess seismic hazards begins with the characterization and evaluation of seismic sources (Figure 2, block 2). In parallel with this effort, the levels, characteristics, and attenuation of vibratory ground motion and fault displacement are analyzed (Figure 2, block 3). The results of these two efforts are then integrated in a probabilistic seismic hazard analysis. This results in distributions of seismic hazard curves showing the annual probability that different levels

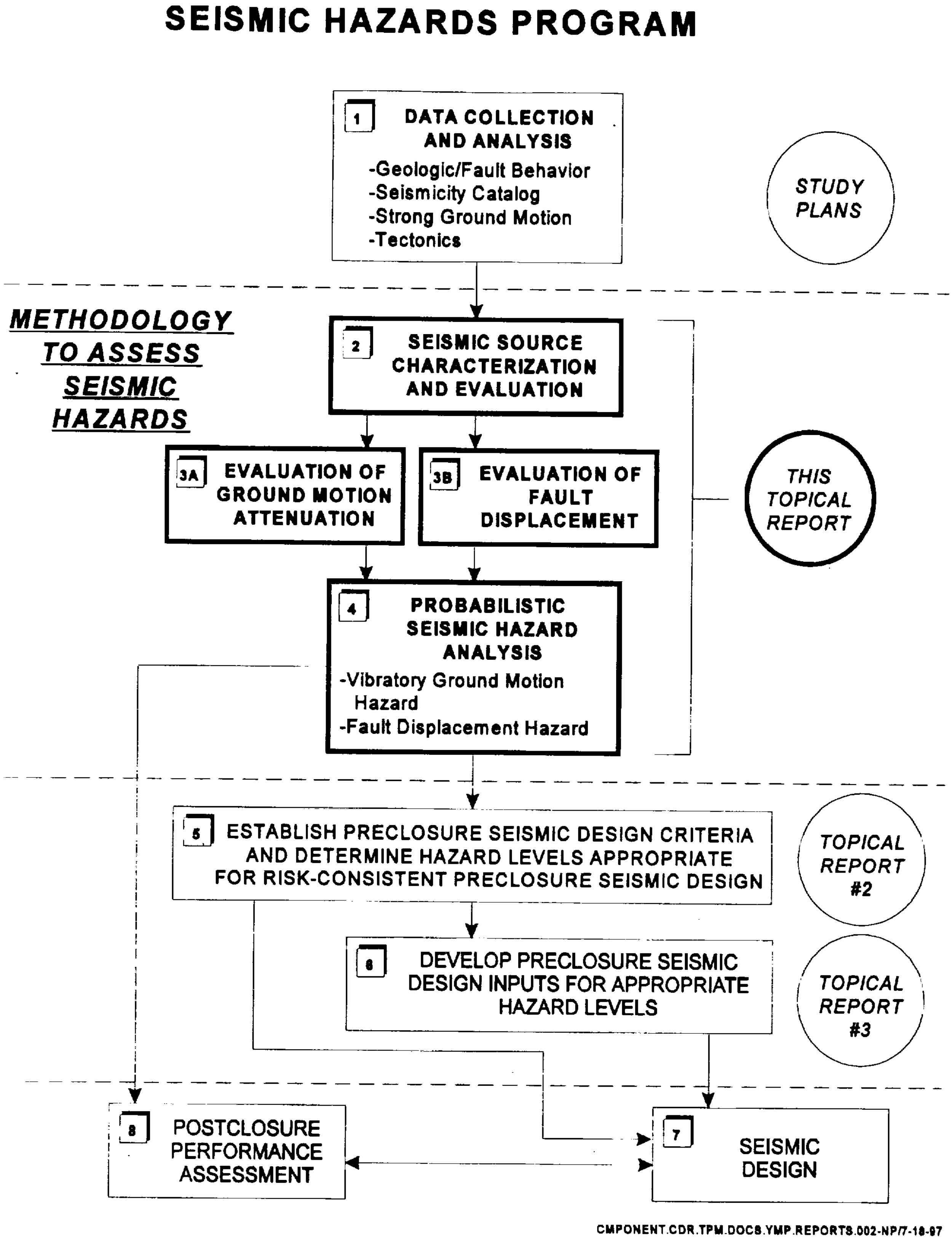


Figure 2. Components of the Methodology to Assess Seismic Hazards Within the Framework of the Overall Seismic Hazards Program

of vibratory ground motion and that different levels of fault displacement will be exceeded (Figure 2, block 4).

The hazard curves resulting from the methodology provide direct input to long-term waste containment and isolation performance assessments (Figure 2, block 8) and provide a basis for development of preclosure seismic design inputs. For some applications, the probabilistic hazard results will be disaggregated to identify dominant sources contributing to a particular hazard level. The hazard from these sources can then be assessed deterministically to support the development of design inputs. For other applications, uniform hazard spectra may be determined. While such spectra do not correspond to any single earthquake, they represent response spectral amplitudes with a uniform probability of being exceeded. The preclosure seismic design criteria and the determination of appropriate hazard levels for preclosure seismic design (Figure 2, block 5) are documented in the second seismic topical report (YMP 1997). The resulting preclosure seismic design inputs (Figure 2, block 6) will be presented in a planned third seismic topical report. The postclosure performance assessments explicitly consider the effects of earthquakes and other potentially disruptive tectonic processes and events. The iterative process of assessing performance (Figure 2, block 8) and identifying design solutions (Figure 2, block 7) may lead to the establishment of seismic and other design requirements for permanent items of the repository. If both postclosure and preclosure seismic design requirements apply to a repository SSC, the most stringent requirement will control the SSC design.

2.3 DESCRIPTION OF THE METHODOLOGY

This section describes the procedures that will be used to assess vibratory ground motion and fault displacement hazards. Details of the procedures are provided in Appendices A through C.

2.3.1 Assessment of Vibratory Ground Motion Hazard

Five steps are involved in deriving a distribution of hazard curves for vibratory ground motion:

Step 1: Determine the spatial distribution of seismic sources. In the region around the site, identify faults and volumetric zones that will be the sources of future seismic activity. Characterize the uncertainty in the spatial description of each source.

Step 2: For each seismic source, describe the rate of occurrence and relative size (e.g., magnitude or moment) distribution of future seismicity. Evaluate the maximum magnitude for each source. Characterize the uncertainty in recurrence relations and in maximum magnitude.

Step 3: For the site region, evaluate or determine relations that express how the amplitude of ground motion parameters varies with earthquake magnitude and source-to-site distance. Characterize the uncertainty in these ground-motion attenuation relations.

Step 4: Integrate over each combination of inputs determined in steps 1 through 3 to calculate a hazard curve expressing the annual probability that a given value of ground motion will be exceeded. Carry out the integration for all combinations of inputs to incorporate the variability in inputs.

Step 5: Express the results of step 4 as a distribution of seismic hazard curves that can be represented by a mean curve and curves representing selected percentiles of the distribution.

Each of these steps is discussed below and is shown schematically in Figure 3.

2.3.1.1 Evaluation of Seismic Sources

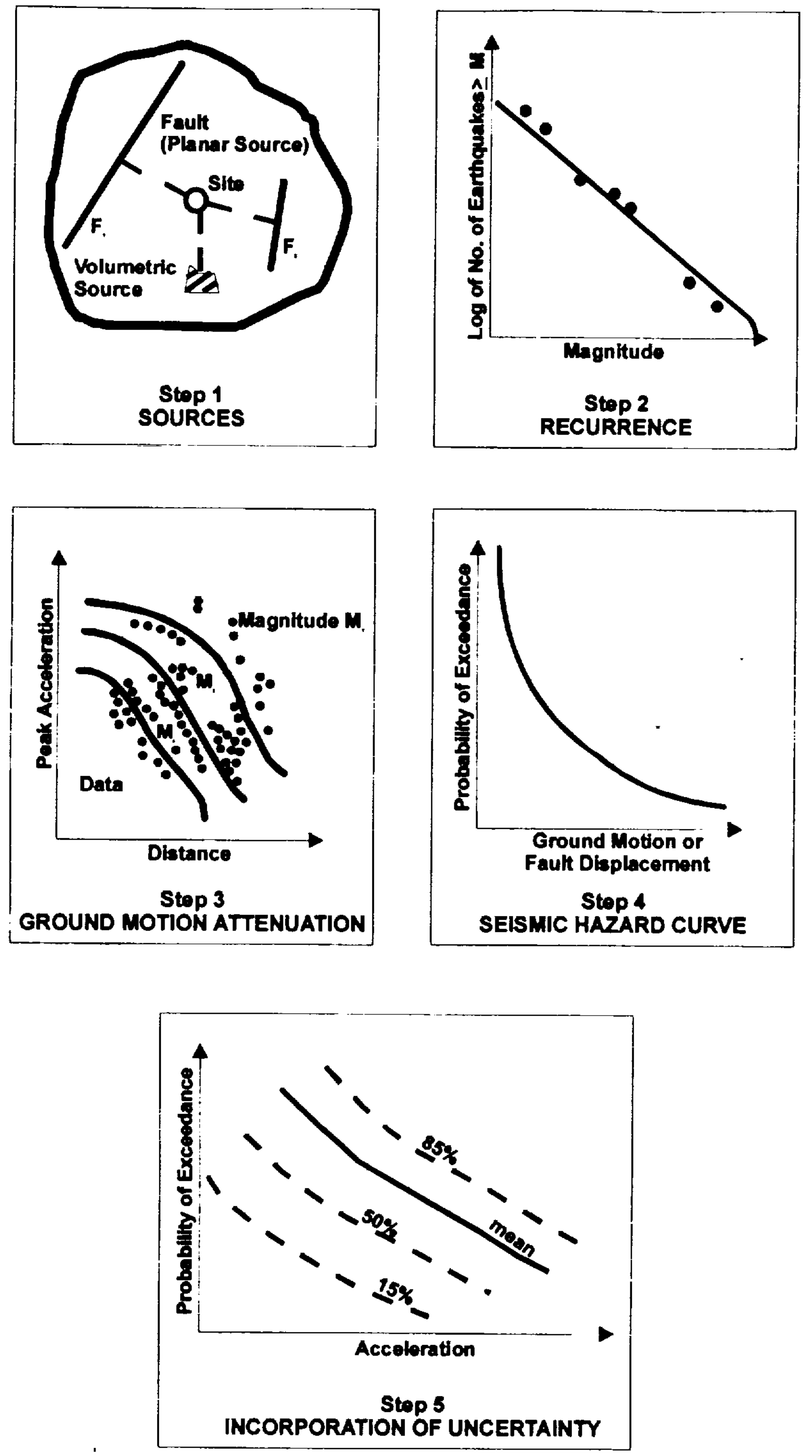
A seismic source represents a portion of the earth's crust with a potential to generate future earthquakes. Within a seismic source, the probability of earthquake occurrence and the size of the maximum magnitude are generally considered to be invariant. Seismic sources include faults that have the potential to affect repository design or long-term waste isolation performance—"Type I" faults in the nomenclature of NUREG-1451 (NRC 1992). Seismic sources also depict volumetric zones in which future earthquakes may occur, but for which specific faults are not identified. Seismic source zones may also be used to model future UNEs or other manmade sources of seismic energy.

In identifying and characterizing seismic sources, the scale of features to be considered and the levels of investigation vary with distance from the site. Because ground motion attenuates with distance, as the distance to the site increases earthquake size must increase to produce significant ground motion at the site. The size of an earthquake that a feature can generate is related to its physical dimensions. Thus, as one gets farther from the site, larger faults are required for a significant ground motion potential to exist at the site. Seismic source identification will be accomplished iteratively; as preliminary hazard assessments are conducted, sensitivity analyses will show the types of sources (size, distance, and rate combinations) that contribute significantly to the hazard. The inventory of potential sources will be reexamined taking these analyses into account to determine if the inventory is complete.

Each seismic source will be evaluated to provide its three-dimensional spatial description (including uncertainty in that description), probability of activity, and dependency of activity on other seismic sources. Alternative interpretations of the spatial extent of a seismic source that are permitted by the available data will be documented and weighted according to the ability of the interpretation to explain the data. The spatial description of a seismic source includes an evaluation of the depth of earthquakes associated with the source. For each source, a probability of activity is assessed, which expresses the probability that the source is seismogenic, based on evidence of activity or potential activity during the Quaternary period. The assessments are based on available data, including those from field mapping and trenching, and take into account alternative tectonic interpretations and the orientation of the stress field. Dependencies between seismic sources are also evaluated. For example, a seismic source interpretation based on a particular tectonic model may be inconsistent with another seismic source interpretation based on another tectonic model. Such sources would have a mutually exclusive dependency.

2.3.1.2 Evaluation of Earthquake Recurrence and Maximum Magnitude

Each seismic source is characterized by an earthquake recurrence relationship, a maximum magnitude, and the uncertainty in these parameters. For recurrence, the relationship expresses the expected number of earthquakes per year of magnitudes greater than some minimum magnitude, m^o. As discussed in Appendix A, this distribution is developed from observed seismicity and geologic data. As the level of seismicity in the Yucca Mountain region is quite low and the historical record is short (about 100 years), geologic data such as paleoseismic recurrence intervals and slip rates are expected to provide the primary basis for recurrence characterization of the local fault sources. For volumetric source zones, the historical and instrumental seismicity records are expected to form the primary data for characterization of recurrence. Alternative interpretations that are consistent with the data will be evaluated to describe the uncertainty in recurrence



(modified from Reiter, 1991)

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Figure 3. Basic Steps of the Methodology to Assess Vibratory Ground Motion Hazard

relations. Although not expected, the seismic-source-characterization experts may specify time-dependent earthquake recurrence relationships to reflect interpretations of temporal clustering or to specify a "renewal" model in which the time of the next earthquake depends on the time of the last earthquake (see Section A.4.5.1). In addition, interpretations of spatial clustering and interpretations of simultaneous rupture on multiple faults can be incorporated in the methodology by specifying dependencies between the activity parameters of source zones.

As described in more detail in Appendix A, maximum magnitude is assessed for each seismic source. For fault sources, regression relations between moment magnitude and surface rupture length, rupture area, and rupture displacement are employed, depending on the data set provided by site characterization. Uncertainty is assessed on the basis of consistency shown by the different regression calculations, the relative quality of the different data types, and alternative interpretations of the data. An approach to estimating the magnitude to associate with simultaneous ruptures on multiple faults will be developed if the probability of such ruptures is interpreted to contribute to the hazard at the site (as is expected to be the case). For volumetric source zones, upper-bound magnitudes will be based on an evaluation of the largest earthquakes that do not rupture the earth's surface and analogies to other seismic sources.

2.3.1.3 Evaluation of Ground-Motion Attenuation Relationships

Depending on the effects that must be described, the ground motion assessment procedure may include empirical, theoretical, and hybrid theoretical-empirical ground motion models. Empirical models may be sufficient for most seismic sources, and theoretical models may be used primarily to evaluate near-field effects. More details of the evaluation are presented in Appendix B.

Empirical regression relations for ground-motion attenuation will be evaluated or determined from a large set of earthquake strong motion recordings collected in the western United States. This data set includes records from sites having geological and seismic velocity characteristics similar to those at Yucca Mountain. Empirical ground motion relations describe the dependence of peak acceleration, peak velocity, and response spectral amplitudes on earthquake magnitude and a measure of the distance between the source and the site. Models for vertical and horizontal motions will be evaluated separately. If warranted, separate empirical relationships can be developed for shallow and deep earthquake sources and for different styles of faulting. Model evaluations will include explicit assessments of uncertainty.

Theoretical evaluations of ground motion use established physical descriptions of the earthquake source and the wave propagation path. Using theoretical models and the specific geometry of faults in relation to the site, near-field effects such as the difference between foot-wall and hanging-wall motions and near-fault directivity effects can be assessed. Uncertainty in theoretical model predictions is assessed on the basis of the range of models that are consistent with available data and on the variability of input model parameters.

2.3.1.4 Probabilistic Hazard Calculations for Vibratory Ground Motion

As developed by Cornell (1968), the probabilistic hazard methodology calculates the annual probabilities that various measures of ground motion (e.g., peak horizontal ground acceleration) will be exceeded at a site. The probabilistic hazard curve represents the integration, over all earthquake sources and magnitudes, of the probability of future earthquake occurrence and, given an earthquake occurrence, its effect at a site of interest. In general, the temporal occurrence of earthquakes is represented as a Poisson (memoryless) stochastic process. Typically, earthquake distribution in magnitude is represented by an exponential distribution that is truncated at a minimum magnitude of engineering significance and at the maximum magnitude for the source. However, as discussed in Appendix A, deviations from the exponential distribution may be appropriate for fault-specific seismic sources.

Under the assumption that earthquake recurrence in every seismic source can be modeled as an independent Poisson process, the probability that, at a given site, a ground motion parameter, Z, will exceed a specified value, z, during a specified time period, T, is given by:

$$P(Z>z) = 1.0 - e^{-\nu(z)\cdot T} \leq \nu(z)\cdot T \qquad (1)$$

Here $\nu(z)$ is the average frequency during time period T that the parameter Z exceeds z at the site as a result of earthquakes on all sources in the region. The inequality at the right of Equation 1 is valid regardless of the probabilistic relationship for earthquake occurrence, and $\nu(z)\cdot T$ provides an accurate estimate of the hazard for probabilities of 0.1 or less provided $\nu(z)$ is the appropriate value for the time period of interest.

The frequency of exceedance, $\nu(z)$, incorporates both epistemic and aleatory uncertainty in the time, size, and location of future earthquakes and in the level of ground motions they produce at the site. It is computed by the expression:

$$\nu(z) = \sum_{n=1}^{N} \alpha_n(m^o) \int_{m=m^o}^{m^u} \int_{r=0}^{\infty} f_n(m) \cdot f_n(r|m) \cdot P(Z>z|m,r)\ dr\ dm \qquad (2)$$

in which $\alpha_n(m^o)$ is the frequency of earthquakes on seismic source n above a minimum magnitude of engineering significance, m^o; $f_n(m)$ is the probability density function of event size on source n between m^o and a maximum earthquake size for the source, m^u; $f_n(r/m)$ is the probability density function for distance to earthquake rupture on source n, which may be conditional on the earthquake size; and $P(Z>z/m,r)$ is the probability that, given a magnitude m earthquake at a distance r from the site, the ground motion exceeds a value z. In practice, the double integral in Equation 2 is replaced by a double summation with the density functions $f_n(m)$ and $f_n(r/m)$ replaced by discrete representations of their corresponding cumulative functions. As shown in Figure 3 (step 4), the result is a hazard curve expressing the annual probability that various levels of the ground motion parameter will be exceeded.

2.3.1.5 Evaluation and Propagation of Uncertainty

The basic calculation described above results in a seismic hazard estimate for a single characterization of seismic sources, associated recurrence and maximum magnitude evaluations, and a single ground-motion attenuation relation. Thus, the result of this calculation is a single hazard curve (Figure 3, step 4) that represents the aleatory uncertainty (randomness) inherent in the natural phenomena of earthquake generation and seismic wave propagation. The values of the parameters that quantify the aleatory uncertainty are formally elicited from experts who have reviewed all relevant available data. There is also epistemic uncertainty in the characterizations of seismic sources and ground-motion attenuation because of incomplete knowledge of earthquake processes, limited data, and permissible alternative interpretations of the available data. Alternative interpretations that are supported by available data are formally elicited from experts, who weight the interpretations according to their individual assessment of the degree to which each interpretation explains the data. The range of each expert's interpretations and the range of interpretations from expert to expert expresses the epistemic uncertainty. The hazard assessment methodology explicitly incorporates both aleatory and epistemic uncertainties into the hazard calculations.

As described in Appendix C, two approaches can be employed to incorporate epistemic uncertainties into the seismic hazard assessment. They are referred to here as the logic tree approach and the Monte Carlo approach.

The logic tree formulation requires the evaluation of discrete alternatives for each input to describe the variability. The alternatives are weighted on the basis of assessments using standard earth science methods and approaches. This approach is flexible enough to capture all alternative interpretations that are permitted by the data. The final result of the application of the logic tree approach is a distribution of seismic hazard curves, typically represented by a mean hazard curve and selected percentiles (Figure 3, step 5).

The Monte Carlo approach to epistemic uncertainty propagation makes use of multiple subjective probability distributions for the various parameters of the hazard input evaluations. The computation samples from these distributions using Monte Carlo simulation techniques to arrive at mean and percentile hazard curves. When using this approach, uncertainty in seismic source zonation is represented by weighted alternative maps; uncertainty in recurrence is characterized by subjective probability distributions on the recurrence parameters; and uncertainty in ground motion evaluations is characterized by a set of alternative ground motion relationships and their associated weights.

2.3.2 Assessment of Fault Displacement Hazard

A process similar to the five steps described above for assessing vibratory ground motion hazard is also used to assess the hazard of fault displacement:

Step 1: Determine the spatial distribution of seismic sources based on identified Quaternary faults within and near the site and on other site characterization data. Evaluate the uncertainty in the locations of the seismic sources.

Step 2: For each seismic source, describe the rate of occurrence and relative size distribution of future seismicity. In addition, evaluate the maximum magnitude for each source. Characterize the uncertainty in recurrence relations and in evaluations of maximum magnitude.

Step 3: Evaluate or determine relations that express how fault displacement within the GROA varies with earthquake magnitude. Also, evaluate the relation between primary and secondary faulting. Characterize the uncertainty in these relations.

Step 4: Integrate over each combination of inputs determined in steps 1 through 3 to calculate a hazard curve expressing the annual probability that a given value of fault displacement will be exceeded. Carry out the integration for all combinations of inputs to incorporate the variability of input evaluations.

Step 5: Express the results of step 4 as a distribution of fault displacement hazard curves that can be represented by a mean curve and curves for particular percentiles of the distribution.

These steps are described below; more detailed discussion is presented in Appendices A and C.

2.3.2.1 Evaluation of Seismic Sources

The identification and characterization of seismic sources (step 1) for fault displacement hazard are similar to that for vibratory ground motion hazard:

- Seismogenic faults are identified and their geometries evaluated
- Probabilities of activity are assessed
- Dependencies with other sources are described.

Fault-specific sources which correspond to mapped faults are expected to be the norm for modeling fault displacement hazard. However, volumetric sources may be used to express an interpretation that faulting can occur anywhere within an extended fault zone (see Section A2.2). The probability of activity for each seismic source and dependencies between sources will be determined in the same fashion as for vibratory ground motion hazard. Seismic source characterization for the assessment of fault displacement hazard will also include an evaluation of the possibility that new faults (i.e., displacement in previously intact rock) and unmapped faults could produce significant fault displacement within the GROA.

Consistent with NUREG-1451 (NRC 1992), all Type I faults—those with a potential to affect repository design or performance—will be identified in the course of seismic source assessment. The level of detail in fault mapping at the site is expected to be sufficient to locate and characterize all Type I faults

2.3.2.2 Evaluation of Earthquake Recurrence and Maximum Magnitude

The evaluation of earthquake recurrence and maximum magnitude for the assessment of fault displacement is identical to that for the assessment of vibratory ground motion. Recurrence and maximum magnitude will be determined on the basis of seismic, geologic, and tectonic information, and uncertainty in the evaluations will be assessed and documented.

2.3.2.3 Evaluation of Fault Displacement Within the Geologic Repository Operations Area

The translation from earthquake occurrences to fault displacements is comparable to the problem of evaluating the ground motions due to earthquake occurrences. Earthquake magnitude is empirically related to co-seismic displacement and can be used to estimate the amount of slip on a primary fault during a particular earthquake. An evaluation will also be made of the amount and distribution of secondary fault displacement. As discussed in more detail in Appendix C, relationships for the distribution, sense, and amounts of co-seismic slip at particular locations are complex, and a variety of methods are available for making this assessment. All data relevant to the behavior of faults in the Yucca Mountain vicinity will be used in the displacement hazard assessment. These data include information on the displacement history of local faults during the Quaternary period, the distribution and geometric relationships of faults in the GROA, evaluations constraining the tectonic and geometric relationships between faults, and analogies to documented cases of co-seismic rupture within similar tectonic regimes.

2.3.2.4 Probabilistic Hazard Calculations for Fault Displacement

As for vibratory ground motion, the probabilistic methodology developed by Cornell (1968) forms the basis for fault displacement hazard calculations. The mathematical formulation presented in Section 2.3.1.4 also applies to fault displacement, with appropriate substitutions:

- In Equation 1, Z is redefined as fault displacement and the exceedance value, z, is also specified as a fault displacement.

- In Equation 2, $P(Z>z|m,r)$ is redefined as the probability that, given a magnitude m earthquake at a distance r from the site, the fault displacement exceeds a value z at the site of interest. This probability includes an evaluation of the occurrence of secondary faulting. For fault displacement, m^0 is a minimum magnitude below which surface fault displacement of engineering significance is not expected.

As for vibratory ground motion, the result of the calculation is a hazard curve expressing the annual probability that various values of fault displacement will be exceeded.

2.3.2.5 Evaluation and Propagation of Uncertainty

Evaluation and propagation of uncertainty for fault displacement are carried out identically as for vibratory ground motion (see Section 2.3.1.5). Either the Monte Carlo or the logic tree approach can again be employed. The final result of either approach is a distribution of fault displacement hazard curves, typically represented by a mean hazard curve and percentile curves.

2.4 DISCUSSION

The results of the probabilistic seismic hazard assessment will be examined using sensitivity analyses. The variation of the results with respect to changes in key parameters will be evaluated both to identify those inputs that more strongly affect the results and to focus any additional site characterization activities, if required, to reduce the uncertainties in these parameters. Disaggregation of results at reference annual hazard exceedance probabilities will identify those seismic sources that dominate the hazard. Extensive documentation of inputs and their uncertainty, the seismic hazard results themselves, and the sensitivity analyses will together facilitate regulatory evaluation of the seismic hazards at Yucca Mountain, the adequacy of seismic design, and the long-term performance of the repository with respect to waste containment and isolation.

In addition to the results of the probabilistic seismic hazard assessment, the DOE will also consider the results of deterministic evaluations of the seismic hazard in choosing the final seismic design bases for vibratory ground motion and fault displacement. Deterministic assessments are for postulated, specific earthquake scenarios, in contrast with probabilistic assessments, which integrate the hazard from all potential earthquakes with their specified probabilities of occurrence. The DOE intends to perform deterministic evaluations of the hazard from Type I faults and candidate Type I faults that lie within 5 km of the Yucca Mountain site. These evaluations will include assessments of maximum earthquake magnitudes and maximum paleoseismic fault displacements, if any. The DOE plans to evaluate where the results of the deterministic evaluations fall within the probabilistic hazard results and then to assess the adequacy of the probabilistically derived design bases in light of this comparison.

2.5 SUMMARY

The DOE methodology to assess vibratory ground motion and fault displacement hazards incorporates all relevant site characterization data and provides probabilistic results that are required for preclosure seismic design and for assessment of the long-term performance of the repository with respect to waste containment and isolation. The methodology is based on procedures developed and refined over the past two decades that have broad acceptance in the scientific and regulatory communities. Inputs to the methodology are based on field investigations, seismic monitoring, and analyses of site characterization data. Uncertainty in inputs, including both randomness and diversity in interpretations, is directly incorporated into the assessment, allowing the total uncertainty of the results to be evaluated explicitly. The resulting probabilistic hazard estimates will be compared with deterministic hazard assessments when the final seismic design bases are developed.

APPENDIX A

EVALUATION AND CHARACTERIZATION OF SEISMIC SOURCES FOR YUCCA MOUNTAIN

APPENDIX A

EVALUATION AND CHARACTERIZATION OF SEISMIC SOURCES FOR YUCCA MOUNTAIN

A1.0 INTRODUCTION

A seismic source is a construct developed for probabilistic seismic hazard analysis as a means of approximating the locations of sources of seismic waves and fault displacements (e.g., SSHAC 1995). It is defined as a region of the earth's crust that has relatively uniform seismicity characteristics that are distinct from those of the adjacent crust. These characteristics are described by a defined process (usually Poissonian) for the temporal occurrence of earthquakes and probability distributions for maximum magnitude and earthquake recurrence (frequency of occurrence of earthquakes having various magnitudes). Uncertainties in the source size and spatial location are described by discrete probability distributions (i.e., sets of weighted alternatives). A probability of activity (or existence) is assigned to each seismic source. The emphasis here is on sources of tectonic earthquakes (i.e., sudden differential movement accommodated on faults or folds within the brittle crust) because they can release the most seismic energy closest to the site and are associated with fault movement and displacement of the ground surface. However, the potential for volcanic earthquakes near Yucca Mountain must also be evaluated because of the record of Quaternary basaltic volcanism near the site. In addition, given the proximity of Yucca Mountain to the NTS, the size and distribution of future UNEs must be evaluated. As detailed below, probabilistic seismic sources will be defined for tectonic and volcanic earthquakes, and the locations and yields of potential future UNEs will be deterministically evaluated.

This appendix identifies the parameters and discusses the procedures that will be used to evaluate and characterize seismic sources. Seismic source evaluation and characterization include identifying all seismic sources that could affect the design or performance of a repository, determining the maximum magnitude and range of magnitudes associated with each source, defining the location and three-dimensional geometry of each source, evaluating the recurrence rates of various magnitudes for each source, and identifying the uncertainties associated with all of these parameters for each source.

The remainder of Appendix A is organized around the following three steps: 1) recognition and spatial depiction of recently active faults or regions that could be sources of future seismicity; 2) assessment of the maximum magnitudes of potential earthquakes on each source; and 3) assessment of recurrence rates for earthquakes of various sizes.

A2.0 SEISMIC SOURCE ASSESSMENT: SOURCE RECOGNITION, LOCATION, AND GEOMETRY

In the following paragraphs, the approach to identifying seismic sources is presented for different categories of seismic sources. These include Quaternary faults, zones of historical seismicity, buried and hidden sources, sources related to detachment faulting, underground nuclear explosion sources, and volcanic earthquake sources. The discussion focuses on the data and parameters necessary to evaluate and characterize the activity and geometry of candidate seismic sources.

A2.1 FAULT-SPECIFIC SEISMIC SOURCES

In much of western North America, including the Yucca Mountain region, individual faults can be identified and treated as distinct seismic sources. Most large historical earthquakes have occurred on recognized or mappable faults or folds (e.g., *The Tectonic Environments of Seismically Active and Inactive Areas Along the San Andreas Fault System* [Allen 1968] and *Seismological and Paleoseismological Techniques of Research in Active Tectonics* [Allen 1986]). Accordingly, the geological, seismological, and related geophysical investigations at Yucca Mountain have emphasized the collection of information to determine the location, temporal activity, size, subsurface geometry (orientation, length and down-dip extent), and sense of slip of individual faults.

The scale of feature and level of detail for study varies as a function of distance from the site. Relative to nearby faults, more distant faults must generate larger or more frequent earthquakes to produce the same contribution to seismic hazard. Therefore, nearby faults generally require more detailed and comprehensive field investigations.

Results from the probabilistic seismic hazard analysis will be used to assess the adequacy of the level of detail of the investigations. Initial investigations were based on comprehensive literature reviews, field reconnaissance, and considerations of alternative tectonic models. Sensitivity analyses will be used to identify those faults that contribute most strongly to the probabilistic hazard at the site and to evaluate the sensitivity of the hazard results to uncertainties about those faults. The results of the sensitivity analyses and the feasibility of reducing the uncertainty through further investigations will be considered in deciding whether more detailed investigations are warranted.

A2.1.1 Fault Activity

An active fault is one that slips and produces earthquakes (i.e., is seismogenic) in the present (Quaternary) tectonic stress regime. One method of assessing the activity of a fault is by evaluating its association with historical and instrumentally recorded seismicity. To facilitate this evaluation, a catalog of earthquakes will be compiled from historical and instrumental sources, and fault plane solutions will be compiled or determined for appropriate events. Uncertainties in event location, size, and direction of slip will be assessed and incorporated in evaluations of activity.

Other than historical observations, the geologic record and paleoseismic evidence provide the most reliable evidence of fault activity. This technique employs interpretations of aerial photography to identify faults, and trench excavations to map fault displacements, measure fault orientations, and collect datable fault-related deposits. Any fault large enough or close enough to affect repository design or performance, should it produce an earthquake will be characterized, consistent with NRC staff guidance in NUREG-1451 (NRC 1992). Faults and geologic structures that have experienced recurrent motion during the Quaternary period (approximately the last 2 million years) are inferred to have potential for future earthquakes and to require investigation and characterization. Conversely, faults that can be shown to lack Quaternary displacement do not require further investigation because this is considered sufficient time for fault movement if the fault has any potential to slip within the present tectonic stress regime.

Additional criteria for assessing fault activity include association with observed seismicity, structural relationship with a known active fault, and orientation relative to the contemporary stress regime (e.g., NRC 1992). Seismicity data can be useful in recognizing active or buried faults. Nevertheless, because the historic earthquake record near Yucca Mountain encompasses a time period (approximately 100 years) much shorter than the recurrence intervals for surface faulting earthquakes in the site vicinity (tens of thousands of years or longer), the absence of seismicity does not necessarily indicate that a fault is inactive.

For faults expressed on the surface but where Quaternary deposits, paleosols, or geomorphic surfaces are not present, and for faults encountered underground, structural relationships and an understanding of the regional tectonics may be used to infer the likelihood of a fault being active. A fault of unknown activity may be determined to have a non-zero probability of being active based on a structural model in which movement on a known active fault could cause movement on the fault in question. (The faults need not intersect for a kinematic link to exist.) This approach requires an understanding of the three-dimensional geometry of the faults and of the contemporary crustal stress regime.

In theory, the susceptibility of a fault to movement can be assessed based on its orientation relative to the existing tectonic stress field. In most cases, there is large uncertainty regarding the magnitude and orientation of the regional stress field, the nature of spatial variations in the stress field, and how faults, which typically have experienced a complex stress history, respond to these factors. However, inferences about the regional stress field based on the characteristics of Quaternary faults, earthquake focal mechanisms, and local stress measurements will contribute to a better understanding of the tectonic setting for the site region. An understanding of the tectonic setting of the site is essential to fault activity evaluations, particularly where direct evidence concerning the Quaternary history of faulting for a candidate seismic source is limited.

Based on the types of information discussed above, the potential activity of each fault will be evaluated to determine its probability of activity. For faults with demonstrated late Quaternary movement, the probability of activity will be assessed as 1.0. For other faults, for which the evidence of late Quaternary activity is uncertain, probabilities of less than 1.0 may be assessed.

In addition to the assessment of the likelihood that each candidate seismic source is active, any dependencies between seismic sources will be assessed. Of particular interest, fault-specific seismic sources that are interpreted to have a potential for simultaneous rupture will be identified. The probability that slip on one fault will be accompanied by slip on another will be elicited from the seismic source experts and factored into the hazard calculations. Equivalently, the seismic source experts may identify and assess the likelihood of multiple-faulting scenarios; each scenario description would identify all faults interpreted to rupture simultaneously.

Note that the assessment of multiple-faulting scenarios must rely more on geometric considerations and historical analogs of distributed ruptures elsewhere in the Basin and Range than on the paleoseismic record at Yucca Mountain. The paleoseismic record is consistent with past episodes of simultaneous rupture on several of the local faults (e.g.,Pezzopane, et al. 1996b), but paleoseismic constraints cannot distinguish faulting that occurred simultaneously from faulting that occurred days or weeks (and, oftentimes, thousands of years) later.

A2.1.2 Fault Geometry

Elements of interest in fault geometry are the mapped location, the direction and angle that the fault dips, and the down-dip extent of the fault. An evaluation of the fault's dip within the seismogenic crust is important for evaluating the potential down-dip width of a fault rupture and, for nearby faults, the distance from the fault plane to a site of interest. Knowledge of the down-dip width of a fault is important because seismic moment and earthquake magnitude are proportional to the area over which slip occurs on the fault. The distance from the fault plane to the observer is important because ground motion generally attenuates with distance.

Tectonic models proposed for the Yucca Mountain region involve substantially different fault geometries. End-members of the various models are described by either steeply dipping faults that continue to the base of the seismogenic crust or sub-horizontal detachment faults that become listric at shallow depths and that are sometimes broken by younger steep faults.

Fault dip measurements at the surface or in the near-surface commonly are extrapolated to seismogenic depths, but this approach involves significant uncertainty. Balanced geologic cross-sections will provide useful constraints on subsurface dips. If seismicity is associated with a fault, the uncertainty in subsurface geometry may be reduced by the orientation of earthquake fault plane solutions and the distribution of earthquake hypocenters. Seismic reflection profiles may provide additional constraints, imaging shallow-dipping geologic structures best. However, steeply dipping to vertical faults can be impossible to image as reflectors. In addition, dipping reflectors that are imaged may be older non-seismogenic faults or other geologic discontinuities that may not be directly related to seismogenic faults.

Assessments of the down-dip extent of faults usually rely on estimates of the thickness of the seismogenic crust. The best indication of seismogenic crustal thickness may be the focal depth distribution of instrumental seismicity (Sibson 1982, 1984). For example, more than 95 percent of the hypocenters in the southern Great Basin near Yucca Mountain are located in the upper 15 km of the crust, and mainshock foci are commonly 8 to 16 km in depth (Rogers et al. 1991). On the basis of instrumental seismicity records, the seismogenic crustal thickness near Yucca Mountain is estimated to be between 10 and 15 km.

For the case of simultaneous ruptures on multiple faults, the geometry of each fault interpreted to be involved in multiple faulting scenarios must be identified. The assessment of subsurface geometry is particularly important in characterizing multiple faulting scenarios. Faults that are interpreted to be listric to or to merge with other faults may be candidates for simultaneous rupture. In addition, the depth at which a fault merges with another fault is important because the down-dip extent (i.e., width) of the fault is an important determinant of its potential to release stored elastic strain energy and radiate seismic waves. A fault that merges with another fault at shallow depths (2-3 km or less) will contribute little to vibratory ground motion if it ruptures simultaneously. On the other hand, the possibility of such secondary faulting might control the fault displacement hazard on the secondary fault.

A2.1.3 Sense of Fault Slip

Assessments of the horizontal and vertical components of displacement and of fault dip are required to determine the sense of slip and net displacement on a fault. If the sense of slip is known (e.g., from slickensides) and the amount of displacement for one of the components is known (e.g., from measurements of vertical throw), then the other component of slip and the amount of net slip can be calculated. The slip sense of a fault source is important for seismic hazard analysis because it can affect both the level and duration of ground motion. Numerical modeling and empirical evidence indicate that, for a given magnitude and distance, ground motion levels associated with normal faulting might be less than those associated with strike slip faulting and likely are less than those associated with reverse faulting (see Section B2.3.1). The sense of slip is also important because it must be known to determine the total slip on a fault, which controls slip rate estimates, and seismic hazard generally scales linearly with slip rate. The particular issue of concern at Yucca Mountain is estimating the proportion of horizontal slip on what appear to be predominantly dip-slip faults, because horizontal slip is more difficult to recognize in the paleoseismic record. The sense of slip for each fault source will be evaluated using available information, including that from paleoseismic investigations, geomorphic studies, geologic mapping of kinematic indicators such as slickensides, earthquake focal mechanisms, and tectonic models.

A2.2 SEISMIC SOURCE ZONES

Seismic source zones, as used here, denote volumetric seismic sources[1]. Commonly, source zones are defined to associate spatially diffuse historical seismicity with specific geologic structures or to define a seismic source in areas where causative faults have not been identified. Source zones can be used to delineate regions where known or suspected faults are inferred to project and to encompass a broad range of uncertainties in the geometry and activity of the source. In the western United States, source zones are used frequently as "background" source zones to characterize random, small-to-moderate magnitude earthquakes that do not rupture the ground surface. Seismic source zones have a specified probability of activity or existence and a spatially uniform distribution for maximum magnitude. Typically, source zones also have a spatially uniform earthquake recurrence (magnitude-frequency) distribution. However, the seismic hazard methodology allows recurrence parameters to vary within a seismic source zone, if the analyst so chooses. Usually, this flexibility is used to express an interpretation that the spatial pattern of seismicity, over the time frame of interest, will not be purely random but, rather, will be similar to the pattern of historical seismicity.

Volumetric seismic sources may be useful at Yucca Mountain for characterizing: 1) seismicity from discrete seismogenic structures of uncertain location (e.g., buried or hidden sources, such as detachment faults, 2) "background" sources of small-to-moderate magnitude earthquakes, and 3) regions of young magmatism interpreted to be sources of volcanic earthquakes.

In principle, volumetric sources can also be used to model fault displacement hazard as well as vibratory ground motion hazard. A volumetric source could be used, for example, to express an interpretation that undiscovered faults capable of surface displacement could be located anywhere within the source zone. However, it is expected that the level of detail in fault mapping at the site, both on the surface and underground, will allow the locations and characteristics of Type I faults (NRC 1992) to be specified. If a Type I fault is not manifested by a single, primary fault trace but, rather, as a zone of faulting, a volumetric source zone might be used to represent the volumetric extent of the fault zone.

A2.3 BURIED AND HIDDEN SOURCES

Buried seismic sources are seismogenic structures that have been mapped or imaged in the subsurface, but terminate below the surface and are not exposed. In contrast, a structure which has not been mapped or imaged but may be covered by overlying deposits is considered a hidden source. Buried or hidden sources are inferred in areas that lack recognizable faults or fault-related structures at the surface, but that exhibit seismicity or contemporary deformation. Where hidden sources are suspected, a combination of subsurface structural interpretations will be coupled with evidence for young tectonic deformation in an attempt to identify and characterize the potential seismic sources. Seismic reflection and balanced cross-section techniques are capable of identifying certain structures that are potentially seismogenic, given the contemporary tectonic regime. Also, in particular circumstances these subsurface interpretative techniques can be used to assess the degree of fault activity and the rate of fault slip, which are important to the assessment of recurrence rates. An important consideration in assessing the earthquake potential of buried faults is their geometry and depth within the crust. The location and dimensions of a

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1 In the literature, seismic source zones are commonly referred to as "areal" seismic sources because, on a map, they circumscribe an area. This terminology is avoided here because non-vertical fault-specific seismic sources (i.e., dipping faults) also circumscribe areas in plan view.

buried structure are important to the assessment of the maximum magnitude that the structure may be capable of generating (discussed further in section A3.0).

In recent years, there has been considerable interest in the existence of low-angle detachment faults and the role they play in the tectonic setting at Yucca Mountain (e.g., EPRI 1993). The detachment models consider that faults near Yucca Mountain lie above, and are related to, one or more low-angle normal faults at relatively shallow depths with various interpretations as to the underlying mechanism that forces the detachment to slip. It is expected that a seismic source zone approach will be useful in characterizing postulated detachment faults because the spatial distribution of the source is very broad, the pattern of faulting is complex, and the seismogenic characteristics of detachment faults are sensitive to the wide variety of interpretations.

A2.4 VOLCANIC EARTHQUAKES

Another earthquake category relevant to seismic hazard analysis at Yucca Mountain is that of volcanic earthquakes. Included here are earthquakes that can be associated with injection or movement of magma or the triggering and release of regional tectonic strain as a result of volcanic eruptions. Although volcanic earthquakes are commonly smaller than tectonic earthquakes, they will be included in the seismic hazard assessment at Yucca Mountain because of the record of Quaternary basaltic volcanism in Crater Flat.

The spatial and temporal distribution of volcanic events have been the focus of considerable study at Yucca Mountain (e.g., Crowe et al. 1992; Perry and Crowe 1992; Valentine et al. 1992; and CRWMS M&O 1996a). Observations show that volcanism has evolved from silicic ash-flow tuffs erupted from the northern Yucca Mountain region in the middle to late Tertiary to much smaller eruptions of basaltic lava, ash, and scoria from centers southwest of Yucca Mountain in the Quaternary. Interpretations of geochemical evidence suggest that volcanism near Yucca Mountain is becoming more basaltic, which is typically less explosive, and smaller in volume, indicating lower magma flux rates. Although volcanism appears to be waning, the Lathrop Wells volcanic center and the Crater Flat volcanic field have been active in the Quaternary, and are close enough to Yucca Mountain to constitute potential sources for volcanic earthquakes or for eruptive triggers that could release regional strain as tectonic earthquakes. Seismic source zones will be defined to represent these centers of Quaternary volcanism, and others that may be recognized in ongoing studies.

The largest magnitudes of volcanic earthquakes are usually much smaller than the largest tectonic earthquakes, possibly because the rocks that are involved in volcanic earthquakes are hot and weak and cannot store much strain energy. Events observed to be associated with the movement of magma are commonly in the range of M 4 to M 5 or less. However, M 5 to M 7 events have been recorded in the vicinity of larger, more mature volcanoes, such as near Mount Saint Helens (e.g., Weaver et al. 1987) and Hawaii. Although volcanic events in the range of M 6 or greater are considered improbable near Yucca Mountain, the possibility that volcanic eruptions or magma injection could trigger a tectonic earthquake larger than M 6 will be evaluated.

The distinguishing magnitude-frequency distribution for many volcanic regions is characterized by *b*-values closer to 2, as opposed to *b*-values near 1 for regions with tectonic events. In other words, volcanic regions are characterized by a much higher ratio of smaller magnitude to larger magnitude events. Commonly, the temporal pattern of volcanic earthquakes is that of an earthquake "swarm." Typically there are no main events in swarms—all shocks are rather small and similar in magnitude. Swarms start with a few events, their number gradually increasing until reaching a maximum, and then dropping off gradually to background levels. Swarms have been interpreted to be a result of magma movement, and, as mentioned above, are characterized by earthquakes with magnitudes less than about 5.

The estimation of volcanic-earthquake recurrence rates from historical data is difficult because no recorded earthquakes near Yucca Mountain or in the southern Great Basin region have been identified as volcanic events, except for events along the eastern Sierra Nevada near Mammoth and Inyo Craters, which are associated with silicic magmatism. For the Yucca Mountain hazard assessment, the estimation of recurrence rates of volcanic earthquakes most likely will be tied to estimated rates of future volcanic eruptions. The rates of formation of new volcanic centers and eruptions at established volcanic centers will be used to evaluate the recurrence of volcanic events and the probabilities that eruptions could trigger larger tectonic earthquakes. These rates have been estimated in a probabilistic volcanic hazard analysis of the site (CRWMS M&O 1996a) and are available for use in the seismic hazard assessment.

Important data sets for assessments of the location, magnitude, and recurrence rates of volcanic earthquakes will be regional and local Quaternary geologic maps, rates of formation of new volcanic centers, locations and rates of past volcanic eruptions, and interpretations of regional and local tectonic and volcanic processes.

A2.5 SUMMARY OF APPROACH TO SEISMIC SOURCE ASSESSMENT

Seismic sources that contribute to vibratory-ground-motion and fault-displacement hazards at Yucca Mountain will be identified and characterized. The specific faults that require detailed characterization (Type I faults) will be determined based on factors including, but not limited to, fault length and location relative to Yucca Mountain, displacement of Quaternary deposits, direct relationship with seismicity, structural relationship to other Quaternary faults, orientation within the contemporary stress regime, and considerations of alternative tectonic models.

Each seismic source will be assessed to determine its probability of activity. Active sources will be assigned a probability of 1.0, inactive sources a probability of 0.0. A probability between 0.0 and 1.0 will be assessed for sources that are potentially active but for which direct evidence of activity is absent or inconclusive. Dependencies between seismic sources will also be evaluated. In particular, the likelihood of multiple-faulting scenarios will be assessed. Seismic sources may include buried or hidden faults and mapped faults not covered by Quaternary deposits. Important data sets for this evaluation will be regional and local Quaternary fault mapping, fault trenching and paleoseismic data, tectonic geomorphic studies, regional and local geophysical studies (e.g., regional seismic reflection, high-resolution seismic, gravity, electrical and magnetic studies), tectonic models, historical seismicity data, tectonic stress information, and geodetic data.

The three-dimensional geometries of seismic sources near the site will be evaluated in terms of their map location, subsurface geometry, and down-dip extent within the seismogenic crust. Discrete surfaces will be used to represent mapped Quaternary faults, while volumetric zones will be used to characterize buried and hidden faults, background seismicity, and volcanic sources. Alternative interpretations of source geometries and their relative consistency with the data will be evaluated and documented. Important data sets for evaluating source geometries will be geologic mapping, local-scale fault exposures, geophysical interpretations (e.g., seismic reflection profiles), seismicity data (e.g., regional focal depths, focal mechanisms), and tectonic models.

The sense of slip will be evaluated for each fault source. Important data sets for evaluating the sense of slip will be paleoseismic investigations, geomorphic studies, geologic mapping of kinematic indicators such as slickensides, earthquake focal mechanisms, and tectonic models.

The interpretation of seismic sources and the calculation of seismic hazard is an iterative process. The seismic source characterization experts who participate in the probabilistic seismic hazard assessment will provide comprehensive and well-documented interpretations of seismic sources. With this input, the seismic hazard at the site will be calculated, sensitivity studies will be conducted, and the results will be provided to the experts to allow them to fully understand the sensitivity of the results to various parameters. The experts may then reevaluate their interpretations considering this feedback and the rest of the information base.

A3.0 MAXIMUM EARTHQUAKE MAGNITUDE EVALUATION

The idea that each seismic source is associated with a maximum magnitude earthquake is a key assumption in seismic hazard analysis. The maximum earthquake is considered to be the magnitude of the largest earthquake that can be associated with a specific source, given the current tectonic regime.

Maximum earthquake magnitudes are based typically on either the maximum physical dimensions of the source or the size of the largest historical earthquake associated with the source or analog sources, or both. The frequency of occurrence of the maximum earthquake on a particular source is typically hundreds of years to several hundreds of thousands of years. Consequently, the historical seismicity record is usually too short to encompass the maximum event associated with a specific seismic source. This is especially true for the Yucca Mountain region, where the historical seismicity record is roughly one hundred to one thousand times shorter than the average recurrence interval for surface-rupturing earthquakes on faults near the site.

Maximum magnitudes will be calculated for each seismic source using empirical magnitude-rupture parameter regressions and the rupture lengths, rupture areas, and the maximum and average displacements determined from geologic and paleoseismic data. Rupture dimensions will be assessed via multiple approaches to lend stability to the magnitude evaluations, and uncertainties in the fault rupture parameters will be documented. Fault segmentation assessments will be based on available paleoseismic and fault behavioral data. Maximum magnitudes will be assessed considering multiple approaches and the relative resolving power of the approaches and their respective data sets. Maximum magnitudes will be evaluated for each source and will be expressed as a probability distribution that incorporates uncertainties in the geologic and paleoseismic data.

A3.1 METHODS BASED ON FAULT RUPTURE DIMENSIONS

Seismic moment is proportional to the fault rupture dimensions (length and down-dip width, or area) and the amount of fault displacement, and empirical observations show that earthquake magnitude is a function of seismic moment (e.g., Hanks and Kanamori 1979). The scaling of magnitude with moment suggests that magnitude can be related to rupture dimensions and, in fact, empirical data from surface-rupturing earthquakes show strong statistical correlations between the rupture dimensions and earthquake magnitude (e.g., Bonilla et al. 1984). These correlations, in turn, suggest that maximum magnitude can be related to maximum rupture dimensions. Empirical relationships between rupture dimension and magnitude have been refined and updated (Wells and Coppersmith 1994) and, along with the relationship between seismic moment and moment magnitude, serve as a basis for assessing maximum earthquakes in a wide variety of design situations (e.g., Schwartz et al. 1984).

Currently, the most comprehensive and up-to-date rupture dimension-magnitude regressions are by Wells and Coppersmith (1994). These regressions improve those of previous studies through an approach that is based on moment magnitude (M_w or just M) rather than surface wave magnitude (M_s) or local magnitude (M_L). Moment magnitude is the only magnitude scale that is directly related to the source rupture dimensions and displacement. Moment magnitude, as discussed in the next section, is the preferred parameter for characterizing earthquake size because of its widespread use and unambiguous attributes.

A3.1.1 Seismic Moment and Moment Magnitude Relationships

Seismic moment (M_o) is a measure of the energy radiated by the earthquake source, and is directly related to the source dimensions and the amount of slip by the equation:

$$M_0 = \mu A D \quad \text{(A-1)}$$

in which μ is the shear modulus (usually taken as 3 x 10^{11} dyne cm^{-2}), A is the rupture area (length multiplied by down-dip width), and D is the average fault displacement (e.g., Hanks and Kanamori 1979). An earthquake's seismic moment can be established from geologic and geodetic studies (assuming a value for the down-dip width of faulting) because surface rupture displacements and rupture lengths are quantities that can be estimated from field measurements. Also, a seismogram analysis can be used to determine the seismic moment, which allows comparisons of seismic moments measured in the field to those measured from earthquake waveforms.

As noted, seismic moment is empirically related to magnitude, which is the most common measure of earthquake size. However, many different magnitude scales exist (e.g., Kanamori 1983), each measuring a different frequency band of the source spectrum, and all saturating at some point with increasing source size. In contrast, moment magnitude M_w (or M) is defined in terms of the seismic moment through the equation

$$\log M_0 = 1.5 M_w + 16.1. \quad \text{(A-2)}$$

M_w does not saturate with increasing source size and has been shown to provide values that are consistent with those of other magnitude scales over a wide range of magnitudes (Hanks and Kanamori 1979; Kanamori 1983). Moment magnitude, therefore, is the preferred parameter for characterizing earthquake magnitudes at Yucca Mountain.

Seismic moment and moment magnitude assessments at Yucca Mountain will be made based on measurements of surface displacements and rupture dimensions as discussed below. Assessment of maximum magnitude incorporates an understanding of the fault rupture dimensions, regional tectonic environment, similarity to other faults in the region, and regional seismicity records. Uncertainties involved in the evaluation of these fault parameters are discussed in the following sections.

A3.1.2 Fault Segmentation and Distributed Faulting Evaluations

Maximum magnitude estimates rely on a determination of the maximum dimensions of fault rupture in a single event. Although occasionally an earthquake rupture traverses multiple segments of a single fault, studies of co-seismic fault ruptures worldwide have shown that larger faults typically do not rupture their entire length during individual earthquakes. Rather, they rupture individual segments and, through time, these segments may rupture repeatedly through several seismic cycles. This repeated behavior indicates that barriers to rupture propagation commonly are persistent through time (Aki 1979; 1984]). Fault segmentation models provide the means for identifying portions of fault zones that are likely to rupture during individual earthquakes (Schwartz and Coppersmith 1986; Schwartz 1988a). For many faults, the locations of segments and the boundaries between segments appear to be physically controlled. To the extent that the paleoseismic investigations lead to identifications of the timing and extent of past ruptures on faults in the vicinity of Yucca Mountain, segmentation evaluations will be an important part of the seismic source characterization.

The identification of future rupture segments is often difficult, and methodologies for using segmentation modeling to evaluate the dimensions of future ruptures are in the early stages of development. Multiple approaches have been employed to develop criteria for evaluating segmentation, including paleoseismic investigations (e.g., Schwartz 1988a) and observations of historical surface ruptures (e.g., Knuepfer 1989). The best types of data that provide information on segmentation are those that quantify differences in behavior along the length of a fault during its most recent seismic cycle and previous cycles. In addition to observations of historical events, paleoseismic data regarding the timing of past events, displacements per event, displacement distributions along the faults, and fault slip rates all inform interpretations of fault segmentation and earthquake recurrence (e.g., Schwartz 1988a). Further information that can be used to recognize fault segments includes significant changes in fault strike, fault trace complexity, the cumulative amount and sense of slip, and the presence of transverse geologic structures (e.g., Knuepfer 1989). The presence of multiple features at segmentation boundaries is a good indicator of the termination point for future ruptures, as opposed to the existence of a single feature (Coppersmith 1991).

Paleoseismic trenching and geomorphic analysis can be used to assess the amount of time that has passed between the present and the most recent large earthquake on a fault, which is termed the elapsed time. The elapsed time since the most recent event is useful in identifying fault segments that may rupture independently. When combined with recurrence interval data, elapsed time can provide the basis for calculating conditional probabilities of the occurrence of future earthquakes on a fault (see Section A4.5.2). Application of elapsed time in the hazard analysis at Yucca Mountain could be most useful in assessing activity and understanding fault segmentation.

Evaluations of the extent of faulting in future events at Yucca Mountain must also consider the likelihood of distributed faulting (i.e., simultaneous rupture on proximate faults). The normal faults at Yucca Mountain are narrowly spaced and exhibit an anastomosing pattern in plan view, suggesting that they are structurally interconnected (e.g., Pezzopane, et al. 1996b). Paleoseismic determinations of the timing of past events on local faults are permissive of simultaneous rupture (e.g., Pezzopane, et al. 1996b). In addition, historical episodes of distributed faulting in the Basin and Range are not unusual (e.g., Pezzopane and Dawson 1996). Therefore, it seems likely that distributed faulting scenarios will be identified and given some weight in the compilation of seismic sources. The segments of each fault that slip in each scenario must be explicitly identified. The moment magnitude associated with a multiple rupture scenario will be calculated using the sum of the moments from each participating fault segment.

To summarize, segmentation models will provide a physical basis for the selection of rupture lengths in the calculation of maximum earthquakes at Yucca Mountain. Magnitude assessments and segmentation models will rely on paleoseismic data that are developed at numerous sites along the faults. Differences in timing of the most recent event and older events will be compared with changes in fault slip rates, fault geometries, and structural expressions, to recognize the boundaries between segments that could be considered barriers to rupture propagation. The assessment of fault rupture lengths and their uncertainties and associated magnitude estimates will consider the potential for simultaneous rupture of segments of proximate faults in distributed faulting scenarios.

A3.1.3 Fault Rupture Length Relationships

The most common approach used to determine the size of an earthquake that can be generated by a specific fault is through a comparison of surface rupture length and earthquake magnitude (e.g., (e.g., Bonilla et al. 1984; Wesnousky 1986; Slemmons et al. 1989; Reiter 1991; Wells and Coppersmith 1994). The preferred method is to identify segments of the fault that appear to have ruptured as units in single earthquakes and to use their lengths with the magnitude-rupture length regression to determine moment magnitudes. This approach relies heavily on paleoseismic data that describe the timing of paleo-earthquakes, which will be available for the faults that control the seismic hazard at Yucca Mountain. As discussed earlier, individual and multiple segment rupture scenarios will be considered in the magnitude evaluations. The fault lengths in these scenarios will be correlated with moment magnitude using empirical relationships.

A3.1.4 Fault Rupture Area Relationships

Fault rupture area, the product of the length and down-dip extent of the rupture, is more closely related to seismic moment and, hence, earthquake magnitude, than rupture length alone. An approach based on fault rupture areas may be especially useful for assessing the maximum magnitudes of postulated detachment faults and buried sources at Yucca Mountain. Empirical relationships (e.g., Wyss 1979; Bonilla et al. 1984; Somerville and Abrahamson 1991; Wells and Coppersmith 1994) have been established to describe the relationship between rupture area and magnitude for historical events. For a given rupture length, different down-dip widths of faults may rupture, depending largely upon fault type and tectonic environment. Methods for assessing down-dip extent were discussed in Section A2.1.2 on fault geometry. In addition, compilations of length-to-down-dip-width ratios (aspect ratios) for historical earthquakes (e.g., Purcaru and Berckhemer 1982) may be used to determine down-dip rupture width for a given rupture length.

A3.1.5 Fault Rupture Displacement Relationships

Seismic moment and earthquake magnitude are also directly related to the amount of displacement or slip during the rupture. Displacement data from historical surface-faulting earthquakes have been used to develop empirical relationships between maximum surface displacement and magnitude (Bonilla and Buchanan 1979; Bonilla et al. 1984; Slemmons et al. 1989; Wells and Coppersmith 1994) and between average surface displacement and magnitude (Wells and Coppersmith 1994). The magnitude-displacement relationships are useful because they allow magnitudes to be estimated for prehistoric earthquakes for which displacements have been estimated from geologic studies (e.g., Schwartz 1988b; Machette et al. 1992).

Commonly, maximum and average displacements are obtained from studies of offset geologic materials as exposed in trenches placed across the surface traces of mapped faults and from studies of variations in the surface geomorphic expression of faults. Net displacement is determined from the vector sum of the horizontal and vertical slip components measured at a single location. Average displacement is determined from several measurements of the net displacement along the length of the fault, and maximum displacement is the largest of these values.

Displacements for Quaternary faults near Yucca Mountain will be evaluated from paleoseismic studies. Maximum and average net displacements and their uncertainties will be assessed for each geologically recognizable event on each fault, and the values obtained will be used with empirical relationships to determine magnitudes of prehistoric earthquakes.

A3.2 METHODS BASED ON HISTORICAL SEISMICITY

A second category of methods for assessing maximum earthquakes involves the consideration of the size of historical earthquakes that are associated with sources of interest or with sources in an analogous tectonic setting. Geologic and seismologic studies have shown that, in most cases, the maximum earthquake associated with a source rarely occurs during the period of historical observation. This is the expected case for Yucca Mountain, a region with a brief seismic record relative to other areas in North America and with no large historical earthquakes near the site. Hence, for any given seismic source relevant to the site, it is highly unlikely that the historical seismicity record contains the maximum event. However, the historical seismicity record will be reviewed and the magnitude of significant earthquakes in similar tectonic environments will be considered.

A3.3 SUMMARY OF APPROACH TO EVALUATE MAXIMUM EARTHQUAKE MAGNITUDES

A maximum earthquake will be assessed for each source and will be expressed as a probability distribution that incorporates uncertainties in the geologic and paleoseismic data. The moment magnitude of maximum earthquakes will be calculated for each relevant source using empirical relationships between magnitude and rupture dimensions. Multiple approaches to the magnitude evaluations will be used to lend stability to the results; regressions between magnitude and rupture length, rupture area, and the maximum and average displacements will be utilized to the extent that these parameters are available from geologic and paleoseismic data. Fault segmentation assessments will be based on all available paleoseismic and fault behavioral data. Uncertainties in the fault rupture parameters will be expressed in terms of alternative values, the geologic basis for preferred and alternative values will be documented, and the uncertainties will be properly accounted for and incorporated into the seismic hazard analyses.

Important data for the maximum earthquake evaluation will include regional and local Quaternary geologic maps, local instrumental seismicity data, seismic reflection profiles and structural cross-sections that depict the down-dip extent and geometry of faults, displacements and timing data of past earthquakes from paleoseismic and fault behavioral studies, interpretations of segmentation and alternative tectonic models, empirical correlations between rupture dimensions and magnitude, and compilations of regional historical seismicity and seismicity from tectonically analogous regions.

A4.0 EARTHQUAKE RECURRENCE EVALUATION

Probabilistic seismic hazard analysis requires the specification of the recurrence (frequency of occurrence) of earthquakes of various magnitudes. Each seismic source, whether a fault or volumetric source zone, requires its own recurrence relationship.

Studies of the historical seismicity of large regions have shown that the number of earthquakes is exponentially distributed with earthquake magnitude (Gutenberg and Richter 1954). The Gutenberg-Richter earthquake recurrence or magnitude-frequency relationship is expressed as:

$$\log N(M) = a - bM \qquad \text{(A-3)}$$

in which N is the number of earthquakes of a given magnitude M or larger per unit time, a is the logarithm of the number of earthquakes of magnitude zero or greater, and b is the slope of the curve characterizing the relative proportion of large earthquakes to small earthquakes. This magnitude distribution model is often termed a constant or linear b-value model or a truncated exponential model. The magnitude distribution is truncated at the value of the maximum magnitude that is associated with the seismic source.

Because seismicity in large regions usually exhibits an exponential magnitude-frequency relationship, it is reasonable to evaluate earthquake recurrence rates for large volumetric source zones on the basis of the historical seismicity record. However, as early as the 1960s, it was recognized from geologic data (e.g., Allen 1968; 1975) that the seismicity on an individual fault does not exhibit the exponential magnitude distribution that is typical of large regions. Extrapolating the magnitude distribution of recorded seismicity on faults often does not produce events as large as experienced historically or documented in the geologic record (Youngs and Coppersmith 1985). Integration of geologic and seismological studies of faults in the western United States and around the world has shown that the sizes and frequency of surface-rupturing earthquakes on specific faults are typically much greater than recorded seismicity alone would indicate (e.g., Wesnousky et al. 1983; Schwartz and Coppersmith 1984). An approach that uses the paleoseismic record of late Quaternary faulting to determine the rate of infrequent, large, "characteristic" earthquakes is known to reduce the uncertainties inherent in defining the seismicity rate based on the short-term historical earthquake record (e.g., Schwartz and Coppersmith 1986; Wesnousky 1986). Hence, observed seismicity is useful for determining the recurrence rates of small- to moderate-sized events which occur randomly throughout larger regions, but seismicity records are insufficient to characterize the recurrence curve for a given source at greater magnitudes up to the maximum. For Yucca Mountain, geologic data must be used to determine the repeat times for characteristic events.

Specific considerations in the use of historical and paleoseismic data for earthquake recurrence evaluations are discussed next.

A4.1 HISTORICAL SEISMICITY DATA

Methods for analyzing earthquake catalogs to determine recurrence rates are fairly well established. Current practice calls for developing a common magnitude measure for all events, removal of dependent events (foreshocks and aftershocks), and analysis of catalog completeness as a function of magnitude, location, and time. Examples of empirical criteria for foreshock-aftershock sequence size are given in Arabasz and Robinson 1976, Gardner and Knopoff 1974, and Uhrhammer 1986. The time periods during which independent events of various magnitudes are completely reported in the catalog can be specified using the method proposed by Stepp (1972). Usually the truncated exponential recurrence model is used for large source zones (e.g., Cornell and Van Marke 1969) and recurrence parameters are developed from the seismicity data using a maximum likelihood formulation (e.g., Weichert 1980).

A4.2 PALEOSEISMIC RECURRENCE DATA

The time period between geologically recognizable earthquakes on a particular fault is the paleoseismic recurrence interval. The geologic record captures the occurrence of earthquakes by recording direct stratigraphic displacements within the fault zone; uplift, subsidence, or other tectonic deformation; or secondary effects related to seismic shaking, such as liquefaction and landslides. Typically these data are gathered from trench excavations across fault-related deposits and structures that are preserved at or near the ground surface. The information obtained from trenching studies usually reflects both the number and timing of the maximum or near-maximum earthquakes that ruptured the ground surface. Actual time intervals between successive events can be determined where datable materials are present, although in most cases only average recurrence intervals can be assessed.

Fault-specific recurrence models are developed by combining recurrence data with measurements of the size of the event (i.e., displacement per event). As discussed by Schwartz (1988a), the geological evaluation of earthquake recurrence rests on the ability to recognize past events, evaluate the size of each event, and date the interval between events. Because the major faults near Yucca Mountain are visible at the surface and in trench excavations, it is expected that site characterization studies will provide this information.

A4.3 FAULT SLIP RATE DATA

Fault slip rates are determined from the net amount of slip on a fault that has occurred during a measured period of time. Slip rates reflect the long-term, or average, activity of a fault. Although faults with high slip rates commonly generate large-magnitude earthquakes, faults with low slip rates may do the same, but at longer recurrence intervals. Fault slip rates offer an advantage over historical seismicity data by spanning several seismic cycles of large earthquakes on a fault.

Paleoseismic slip rates are used with the seismic moment relationship to determine average earthquake recurrence rates. The basic assumption in this use of slip rate is that it reflects the rate at which strain energy accumulates along a fault and is released episodically in earthquakes (e.g., Brune 1968). The seismic moment relationship ($M_o = \mu AD$) is used to convert slip rates into earthquake recurrence rates. The integrated effects of multiple earthquakes along a fault can be expressed as the seismic moment rate through the equation:

$$\dot{M}_o = \mu AS \tag{A-4}$$

in which D, the displacement associated with a single earthquake, is replaced with S, the slip rate associated with repeated earthquakes; as before, μ is the shear modulus and A is the area of the fault surface undergoing slip. The use of seismic moment and seismic moment rate provides an important link between fault slip rate data and historical seismicity data (e.g., Wesnousky et al. 1984). Recurrence rates determined from slip rates (seismic moment rates) for larger earthquakes will be used to complement recurrence rates for moderate-magnitude events calculated from historical seismicity data.

A4.4 HAZARD IMPLICATIONS OF DIFFERENT RECURRENCE MODELS

The earthquake recurrence relationship, in effect, partitions the seismic moment rate into earthquakes of various magnitudes. As noted above, the most commonly interpreted relationships are the truncated exponential and the characteristic. Traditional methods for translating fault slip rates into recurrence relationships were based on exponential recurrence (e.g., Anderson 1979). However, for recurrence curves based on fault slip rates, the characteristic earthquake formulation (Youngs and Coppersmith 1985) may be more appropriate than the exponential because such curves are inherently fault-specific. For the same slip rate, use of the characteristic rather than exponential recurrence model significantly reduces the recurrence rate of moderate to small magnitude earthquakes and modestly increases the rate of the larger events. (In some cases, slip on a fault may be produced almost entirely by the large events, with the small and moderate events occurring on splays or barriers that do not contribute to measurable slip on the main trace of the fault.) The difference between the truncated exponential and the characteristic earthquake models can affect the calculated seismic hazard at a site, depending on whether the moderate-magnitude events or the large events contribute most to the hazard (Youngs and Coppersmith 1985). It is expected that both models will be evaluated for use at Yucca Mountain to lend stability to the assessment and to encompass the inherent uncertainties.

When the fault slip rate or moment rate is fixed, the calculated hazard may be sensitive to the choice of maximum magnitude. Increasing the maximum magnitude, for example, will increase the recurrence rate of the largest earthquakes but significantly decrease the recurrence rate of smaller events. This is because the largest earthquakes account for the major part of the total seismic moment rate; adding a single large earthquake requires the subtraction of many smaller events to maintain the same moment rate. The net result may be an increase or a decrease in the calculated hazard of exceeding a particular level of a peak ground motion parameter, depending on the proximity of the seismic source to the site, the period (frequency) range that is associated with the ground motion parameter, and the functional form and variance of the ground motion attenuation relationship. The potential sensitivity of hazard estimates to maximum magnitude means that the choice of fault segmentation models may be important to the hazard assessment. Earthquake recurrence models and fault segmentation models will be treated in depth in the probabilistic seismic hazard workshops, and the seismic source assessment experts will be required to thoroughly justify and document all of their interpretations.

A4.5 OTHER RECURRENCE ISSUES

A4.5.1 Temporal and Spatial Clustering

Earthquake recurrence models that typically are used in probabilistic seismic hazard analysis assume that earthquakes occur randomly and that the average recurrence interval between earthquakes is relatively constant in time (i.e., earthquake recurrence is modeled as a Poisson process). However, recent studies of faults in a variety of tectonic settings appear to show a spectrum of recurrence behaviors ranging from quasi-periodic to temporally clustered. Temporal clustering of a fault or source is manifested by the generation of several large-magnitude earthquakes, followed by a period of quiescence that is considerably longer than the recurrence intervals during the cluster period. In addition, spatial clustering of earthquakes has been observed, where adjacent fault segments fail within a relatively brief time period. Temporal or spatial clustering could affect the seismic hazard at Yucca Mountain and, hence, will be considered in the hazard assessment.

Temporal and spatial clustering is recognized behavior for some faults in the Basin and Range province (e.g., Wallace 1987)—individual fault zones in relatively close proximity are active for periods of hundreds to possibly thousands of years, but then are inactive for tens of thousands of years. The Wasatch and Lost River fault zones are characterized by ruptures that sometimes break individual segments or groups of adjacent fault segments as well as earthquakes that rupture several segments along the overall zone (e.g., Schwartz 1988a; Machette et al. 1991). It appears that active plate boundary-related faults display more quasi-periodic behavior (e.g., Sieh et al. 1989; Fumal et al. 1993) than do intraplate faults, which are more typical of the faults near Yucca Mountain. For example, pronounced temporal clustering occurs on the Meers fault in Oklahoma. The fault was seismically quiescent for a relatively long time period and then entered an active phase of repeated late Pleistocene and Holocene earthquakes (e.g., Crone and Luza 1990). Coppersmith (1988) has documented evidence for temporal and spatial clustering in the central and eastern United States.

Temporal clustering may affect the accuracy of recurrence rates that are based on fault slip rates. When a fault slip rate is used, it is generally assumed that it represents an average rate of earthquake occurrence over the time period that the slip rate was calculated. If, however, the fault is presently within an active cluster period, it may have a recurrence rate higher than the average. Conversely, if the fault is in a quiescent period, the recurrence rate would be lower than the average. If the timing of past events near Yucca Mountain can be determined with enough accuracy and precision to evaluate the degree of clustered behavior, if any, this information will be factored into the hazard analysis.

A4.5.2 Real-Time Recurrence Models

The most commonly used spatial-temporal earthquake recurrence model is that proposed by Cornell (1968) in which earthquakes are assumed to occur randomly and independently throughout a seismic source with occurrence times that follow a Poisson process. In the Poisson temporal occurrence model, the probability of a specified number of events occurring during any given time period is a function only of the length of the time period and the average number of events per unit time. Because events occur independently in the Poisson model, it is memoryless (i.e., the time of occurrence of the next event is independent of the elapsed time since the prior one) and the magnitude of the next event does not depend on the magnitude of any past events. (The magnitude of the next event is a random variable that follows the chosen magnitude distribution model.)

While the Poisson process has been shown to reasonably model the occurrence of mainshocks in a large region, its lack of memory does not conform to the physical process believed to result in earthquakes on individual faults—one of gradual strain accumulation followed by sudden release. Detailed paleoseismic studies of several faults as well as historical seismicity from very active subduction zones indicate that the occurrence of larger events on a source tends to be more cyclical than random. These observations have led to the use of "real-time" temporal occurrence models that forecast the probability of earthquakes on a fault as a function of the time since the occurrence of the last earthquake that was large enough to renew (i.e., reset) the probabilistic memory of the fault. Typical use of a simple renewal model is to assess the probability of events within specified future time periods (e.g., Working Group on California Earthquake Probabilities 1988). Critical information needed to apply the renewal approach is the average recurrence interval, the variability (standard deviation) of the average interval, and the time elapsed since the most recent renewing event on the fault of interest.

Although renewal models conform better to the concept of strain accumulation and quasi-periodic release than does the Poisson model, because the data needed to evaluate the renewal model parameters typically are not available, real-time evaluations are not routinely used in seismic hazard analyses. However, Cornell and Winterstein (1988) compared hazard results for renewal processes and the Poisson process and found that, in most cases, the Poisson-process assumption results in a reasonably conservative representation of the hazard. Although renewal processes will be considered for application at Yucca Mountain, the Poissonian model will likely be used because it is simple to apply and may be more appropriate for cases in which the hazard is controlled by several faults (Reiter 1991).

A4.6 SUMMARY OF EARTHQUAKE RECURRENCE APPROACH AND RELEVANT DATA

Earthquake recurrence relationships will be developed for each seismic source that is a potential contributor to the seismic hazard at the Yucca Mountain site. Both truncated exponential and characteristic earthquake models will be considered, based on evaluations of historical seismicity and, for individual faults, paleoseismic recurrence intervals and slip rates. Memoryless, time-independent, and spatially uniform Poisson temporal occurrence models are expected to be used for each seismic source. However, the use of simple renewal models for temporal earthquake occurrence will be considered, as will the possibilities of temporal earthquake clustering and spatial earthquake clustering.

A5.0 UNDERGROUND NUCLEAR EXPLOSIONS

Although no UNEs have been conducted at the NTS since October 1992, and there are no current plans to resume testing, if the United States were to resume critical underground nuclear weapons tests the tests almost certainly would take place at the NTS. Thus, UNEs need to be considered in the seismic hazard analysis for Yucca Mountain. The primary considerations in the source characterization of underground nuclear explosions relate to the magnitude and closest distance of the primary explosion from the Yucca Mountain site. Secondary considerations include effects that are triggered by the explosion, such as aftershocks and surface fault displacements.

A5.1 PRIMARY UNDERGROUND NUCLEAR EXPLOSION SOURCES

UNE sources can be included in a probabilistic seismic hazard assessment if their future distribution in space, time, and magnitude (or yield) can be specified. As discussed below, constraints can be placed on the locations and yields of future nuclear weapons tests. However, there have been no UNEs at the NTS since 1992, and a moratorium on UNES currently is in effect. Although the NTS is being maintained in a state of readiness to resume testing, any assessment of the likelihood that underground nuclear weapons testing will resume would be highly speculative. Therefore, the DOE has adopted a deterministic, rather than probabilistic, approach to characterizing the seismic hazard from UNEs. Specifically, the constraints on UNE locations and yields will be identified and empirical ground motion attenuation relationships will be used to assess potential UNE ground motions at Yucca Mountain. Based on UNE ground motion studies to date (summarized by Walck 1996), the DOE expects that naturally occurring tectonic earthquakes, rather than UNEs, will control the seismic design criteria for repository facilities that are important to safety.

Evaluation of UNE sources will take into account the political and physical limitations on their size and location. Testing prior to the moratorium was limited to a yield of 150 kilotons by the Threshold Test Ban Treaty and the Treaty on Underground Nuclear Explosions for Peaceful Purposes (e.g., Vortman 1979). Physical limitations on the location and size of tests result from geologic and logistical considerations and from the potential for damage to off-site facilities from ground motions. Based on the latter constraint, Yucca Flat, Buckboard Mesa and Pahute Mesa have yield limits of 250 kilotons, 700 kilotons and 1,100 kilotons, respectively (Vortman 1979). The yield limit for Mid Valley, a potential future test area, is likely to be similar to that for Yucca Flat. These limits are well above the current yield limits specified by treaty. In an evaluation of potential UNE ground motions at Yucca Mountain, Subramanian et al. (1990) concluded that the worst-case ground motions would result from a 700-kiloton explosion at a distance of 22.8 km in Buckboard Mesa.

A5.2 SECONDARY UNDERGROUND NUCLEAR EXPLOSION SOURCES

To characterize secondary seismic sources, it is necessary to describe induced tectonic strain release caused by UNEs. Co-explosion strain release takes place in the form of aftershocks, distributed strain of the ground, and fault displacements.

For aftershocks, the size distribution of the events (including the maximum magnitude in relation to the magnitude of the primary event), and the temporal decay of the aftershocks, will be characterized based on historical studies. It is observed that 95 percent of the triggered aftershocks occur within 14 km of the detonation point, and the majority of these occur within 4 km (e.g., Vortman 1991). Aftershocks fall off to the background level within a period of several weeks, and the strongest aftershock is usually at least 2 magnitude units smaller than the size of the primary explosion (e.g., Vortman 1991). Triggered surface fault displacements have been observed up to 5 km from an explosion (Bucknam 1969), but are generally limited to the local area of the explosion (e.g., Covington 1987).

APPENDIX B

EVALUATION AND CHARACTERIZATION OF VIBRATORY GROUND MOTIONS AT YUCCA MOUNTAIN

APPENDIX B

EVALUATION AND CHARACTERIZATION OF VIBRATORY GROUND MOTIONS AT YUCCA MOUNTAIN

B1.0 INTRODUCTION

The objective of this appendix is to describe the methodology that will be used to assess ground motions at the Yucca Mountain site. The methodology includes the explicit evaluation of uncertainty in ground motion values. The ground motion products that can be generated using this methodology include peak acceleration and velocity, response spectral ordinates at specified periods, power spectral density functions, and ground motion time histories representative of specific spectra. The methodology includes the contributions of source, path, and site effects to ground motions. It considers the effects that are recognized as important contributors to ground motion characteristics on rock and stiff alluvium. In the following description of the methodology, source, path, and then site effects are discussed. The methodology makes use of region- and site-specific ground motion recordings and information on local wave propagation characteristics.

B2.0 EVALUATION OF SOURCE AND PATH EFFECTS ON GROUND MOTIONS

The ground motion generated by an earthquake or an UNE depends on the magnitude and other properties of the seismic source, on the properties of the earth's crust along the wave propagation path between the source and the observer, and on the properties of the site (i.e., the seismic-wave transmission properties of the shallow crust beneath the observer). Source and path effects on ground motion are modeled by ground motion attenuation relationships, which express how a ground-motion descriptor such as peak acceleration depends on the size (and possibly other properties) of the seismic event and on the distance between the seismic source and the observer. The DOE's approach to evaluating source and path effects is described next; the evaluation of site effects is discussed in Section B3.0.

B2.1 AVAILABLE DATA AND INFORMATION

A number of strong motion recordings are available from the Yucca Mountain site to provide a basis for developing a site-specific characterization of ground motions. The data include recordings of both earthquakes and UNEs, both at the surface and at depth in boreholes. Surface recordings exist for both rock and alluvial sites and for topographic conditions ranging from flat to steep. The earthquakes for which on-scale ground motion recordings are available in the site region include the Landers and Big Bear earthquake sequences of June 28, 1992, the Little Skull Mountain earthquake sequence of June 29, 1992, the Southern Utah earthquake of September 2, 1992, the Rock Valley earthquake sequence of May 15, 1993, and the Eureka Valley earthquake sequence of May 17, 1993. There is also a data base of strong motion recordings of hundreds of underground nuclear explosions obtained at NTS stations, including stations at Yucca Mountain. The Yucca Mountain stations include 11 stations inside or within a few km of the perimeter of the proposed repository, four of which also have downhole recordings. The earthquake and explosion recordings can be used in site-specific numerical evaluations of ground motions. They also provide a large amount of data for the empirical characterization and numerical assessment of wave propagation effects and site response.

Important available studies include a study by Spudich et al. (1997) of ground motions in extensional tectonic regimes and a determination of the spectral decay parameter κ (kappa) for sites at and near Yucca Mountain, based on recordings of aftershocks of the 1992 Little Skull Mountain earthquake (Su, et al. 1996).

The data base of strong motion recordings of earthquakes in western North America has grown rapidly over the past decade. These recordings provide a basis for the development of empirical ground motion attenuation relations and for the validation of ground motion attenuation models developed by numerical evaluations. Some of the empirical ground motion attenuation relations derived from this data base in recent years are summarized and compared by Idriss (1993) and Abrahamson and Shedlock (1997).

B2.2 APPROACH TO GROUND MOTION EVALUATIONS

For the probabilistic seismic hazard analysis, ground motion models will be selected or developed by a panel of ground-motion experts. Each expert will consider all ground-motion estimation methods that are supported by available data and will individually select and weight the models to be used in the hazard calculations, following a thorough evaluation of the data and of competing models in a series of formally facilitated workshops. The experts have the latitude to select or weight models differently in different magnitude-distance-frequency bins. Thus, in the hazard calculations, ground motion models may have different weights at close distances than at far distances or different weights at low frequencies than at high frequencies.

The ground motion evaluations will utilize both empirical and theoretical ground motion models. The empirical models will be selected or developed from analyses of a large set of earthquake and explosion strong motion recordings from Yucca Mountain, the western United States, and other analog regions. Theoretical models will incorporate physically based site-specific mathematical representations of seismic sources, seismic wave propagation, and local site effects on ground motion.

To the degree that observational data are available that are representative of the source, propagation path, and site conditions for Yucca Mountain, the DOE anticipates that the experts will utilize empirical relationships. Available empirical relationships will be considered and tested for their applicability to the Yucca Mountain region and modified if required. Empirical methods will be supplemented by theoretical or hybrid empirical-theoretical methods. For some faults in the immediate vicinity of Yucca Mountain, it may be necessary to incorporate near-source effects on ground motion. If evaluations indicate that such effects are significant, theoretical approaches will be used to assess them.

For the empirical evaluations, existing relationships will be considered for their appropriateness to the Yucca Mountain region. If necessary, these relationships will be modified using available data to more accurately reflect local wave propagation characteristics. To determine the needed modification, ground motion assessments based on regression analyses of empirical data will be augmented by statistical analyses of suites of strong motion recordings that have been selected to match the magnitude, closest distance, site conditions, and other site-specific aspects (such as faulting mechanism) of earthquakes or explosions that control the seismic hazard at Yucca Mountain. The primary data base of strong motion recordings will include recordings from sites with geological and seismic wave velocity characteristics comparable to those at the Yucca Mountain site, but a larger data base of recordings from sites with a broader range of characteristics will be required to evaluate effects discussed below such as the magnitude dependence of dispersion or dependence of ground motions on style of faulting.

Theoretical considerations in the choice of empirical ground motion models include predicted differences between the wave propagation properties of the earth's crust at the Yucca Mountain site and at sites in California due to differences in Q and in the crustal seismic velocity structure. The comparison with California is important because California earthquakes predominate the database upon which most published attenuation relationships for the western United States are based. Another theoretical consideration is possible differences between dynamic (root mean square [RMS]) stress drops of Basin and Range normal faulting earthquakes and earthquakes in compressional tectonic regimes (Schneider, et al. 1996).

The empirical ground motion relationships will describe the dependence of peak acceleration, peak velocity, and response spectral ordinates on earthquake or explosion magnitude and closest distance to the source. Separate relationships will be considered for vertical and horizontal motions. The dependence of ground motions on the type of faulting will be taken into account as defined by the available data. Other effects will be incorporated into the ground motion relationships if they significantly affect the assessed hazard. For example, separate relationships may be used for earthquakes occurring at normal depths (greater than several kilometers), and for UNEs and very shallow earthquakes. For dip-slip faulting, the difference between ground motions on the footwall and hanging wall may be included. Attenuation relations may be adjusted at close distances to account for near-fault directivity effects at the longer periods. Treatment of these effects will depend on their contribution to the assessed vibratory ground motion hazard at sites of interest.

The dispersion in ground motions about their median value will be described as a function of magnitude, distance, and period. The predictions of empirical relationships will be compared to ground motions from Basin and Range earthquakes and earthquakes from other regions that are representative of the earthquake source and wave propagation conditions in the Yucca Mountain site region. Modifications to the empirical relationships will be made based on this comparison, if warranted by the data.

Theoretical methods will be used to supplement the evaluations of ground motion based on empirical relationships. Despite the large number of strong motion recordings obtained during the past decade, the empirical data set contains only a limited range of geometrical orientations of the earthquake sources in relation to near-fault recording stations. While empirical relationships have the advantage of being based on a large set of records that are applicable to the site in a general way, they do not reflect the geometrical orientation of the faults near the site or the local seismic wave velocity structure. Theoretical methods incorporate site-specific descriptions of the earthquake or explosion source and the wave propagation path and characteristics of the site (i.e., the shallow part of the path beneath a site of interest). Theoretical model inputs also include the fault geometry, sense of slip, and rupture dimensions and average slip as a function of seismic moment (or, equivalently, the static stress drop as a function of seismic moment).

Theoretical approaches vary in the degree to which they rely purely on theory. Purely theoretical approaches use entirely physically based mathematical representations of the seismic source and of propagation path and site effects. Hybrid empirical-theoretical approaches use recorded data to model source and path functions or to otherwise constrain free model parameters (e.g., ASCE

1993). The selection of the approaches used will take into consideration the kinds and quality of data available to constrain the ground motion evaluation parameters, the characteristic features of ground motions recorded at the site, and the adequacy of the evaluations in describing these ground motion characteristics over the frequency range of interest at the site.

In the theoretical evaluations, recorded data will be used to check the assumptions on which the theoretical assessment is based. For example, if surface waves dominate the ground motions from UNEs and very shallow earthquakes, then the ground motion model will need to include surface waves. If a one-dimensional velocity model cannot explain the observed surface waves, then two-dimensional or three-dimensional models will be evaluated to describe the wave propagation characteristics of shallow paths. Having thus established the appropriateness of the ground motion formulation, it will next be tested in its ability to explain the data. This comparison with the data will be used to refine the selection of parameters that describe the source, path, and site, and also to assess the uncertainty associated with the use of the formulation.

A stochastic point-source ground motion model (sometimes referred to as the band-limited white noise model) (e.g., Silva 1993; CRWMS M&O 1994) will be used to supplement the empirical models. This model characterizes strong ground motions as stochastic in time, with a Fourier amplitude spectrum specified by a simple, deterministic seismological model of the source, path, and site. Although simple, the model generally provides good estimates of strong ground motions.

Although the stochastic point-source ground motion model generally performs well, its applicability in near-source regions is limited in that it assumes that seismic waves radiate from a point in the earth's crust. In the near-source region of large earthquakes, aspects of a finite source including rupture propagation, directivity, and source-receiver geometry can be important. Therefore, the DOE will also use one or more finite source models to investigate the importance of these factors.

In finite source models, the fault rupture surface is discretized into a set of fault elements. The seismic radiation from the fault elements will be described by either empirical source functions derived from strong motion recordings or by constrained theoretical calculations. The effect of the wave propagation path will be described by Green's functions, which can be determined either empirically or theoretically. The selection of empirical or theoretical approaches to describing the source and wave propagation effects will consider the frequency range of the ground motions being assessed and on the quality and appropriateness of available empirical source functions and Green's functions. Empirical approaches are preferred if appropriate data are available. If necessary, different methods will be used for long period ground motions, which can be predicted well using deterministic source-and path-effect models, and for high frequency ground motions, the details of which cannot be deterministically predicted, but which can be well modeled as a stochastic process.

B2.3 SPECIFIC SOURCE- AND PATH-EFFECT VARIABLES

In some cases, uncertainties in ground motion relationships can be reduced by explicitly taking into account additional source- and path-effect variables that affect ground motion.[1] Some of these variables are described next.

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1 By adding new model parameters, aleatory modeling uncertainty is recast as epistemic parametric uncertainty. The overall uncertainty can then be reduced if data are available to evaluate the additional parameters.

B2.3.1 Effect of Style of Faulting

Currently available information indicates that the predominant style of faulting at Yucca Mountain is normal faulting. At present, there are no widely used empirical ground motion attenuation relations that have been developed explicitly for normal faulting earthquakes. This is an issue because of some indications that normal faulting may, on the average, cause lower ground motion levels than reverse and, perhaps, strike-slip faulting, and because ground motion attenuation relationships commonly used for the western United States are based mostly on recordings of strike-slip and reverse faulting earthquakes. The case for normal faulting causing lower ground motion than reverse faulting is fairly strong. Numerical modeling and empirical evidence indicate that, for a given magnitude and distance, ground motion levels associated with reverse or thrust faulting are slightly higher than ground motions associated with normal and strike-slip faulting (e.g., McGarr 1984; Campbell 1991). It should be noted, though, that Joyner and Boor (1988) found that empirical attempts to correlate fault type with ground motion amplitudes do not support clear-cut conclusions. However, the case is bolstered by recent physical modeling studies (Brune 1996a; Brune 1996b) which indicate that dynamic wave effects occur in the hanging walls of shallow-angle normal and reverse faults that lead to systematically higher ground motion from thrust faulting than from normal faulting. The case for normal faulting ground motion being less than that from strike-slip faulting is less clear. Westway and Smith (1989), for example, find that ground acceleration during normal faulting earthquakes with magnitudes >5 is similar to that of reverse or strike-slip faulting events. However, Brune and Anooshepoor (1997) note that the static normal and shear stresses along a fault in an extensional tectonic regime must approach zero at the surface, limiting the ability of normal faults to sustain the high shear stresses that are required for high seismic energy release.

The adequacy for use at Yucca Mountain of ground motion attenuation relationships that are based mostly on strike-slip and reverse faulting earthquakes in the western United States will be evaluated by examining the residuals of these relationships with respect to data recorded from normal faulting earthquakes and from earthquakes (both normal and strike-slip) that have occurred in extensional tectonic regimes (Spudich, et al. 1997) Other source parameters which influence ground motion levels, such as stress drop, will also be examined to understand the relation between ground motion from earthquakes in the Basin and Range (predominantly normal) and from those in California (predominantly strike-slip) (Doser and Smith 1989; Kanamori and Allen 1986).

B2.3.2 Footwall and Hanging Wall Effects

A difference in ground motion level is observed between ground motions recorded on the footwall and hanging wall of dip-slip faults (Abrahamson and Somerville 1994a; Abrahamson and Somerville 1994b). For distances between ten and twenty kilometers, the peak accelerations on the hanging wall tend to be larger than average and those on the footwall lower than average. The difference between hanging wall motions and footwall motions becomes less at closer distances, and is zero by definition at zero distance from the vertical projection of the top of the rupture plane. There are westward dipping faults on both sides of the site. Therefore, the site is on the hanging wall for faults that outcrop to the east and on the footwall for faults that outcrop to the west. The pattern of hanging wall and footwall effects is recognized in empirical data and confirmed by numerical evaluations. If required to explain significant aspects of ground motion at Yucca Mountain, the relationship between footwall and hanging wall motions will be estimated using a combination of empirical data guided by numerical evaluations that take into account the specific orientation of faults near the site.

B2.3.3 Effect of Rupture Directivity on Near-Fault Ground Motions

Directivity (also called "fault fling") refers to the effect on ground motion of the propagation of the rupture front along the fault. Directivity effects are manifested as systematic differences in observed ground motion as a function of the angle between the source-to-observer vector and the direction of rupture propagation.[2] The classic directivity effect is that observers that lie in the direction of propagation record ground motions of shorter duration and higher amplitude than observers located opposite to the direction of rupture propagation. The effects of directional propagation of rupture are largest at lower frequencies, in the period range equivalent to the rupture process time (e.g., Kashara 1981). At higher frequencies, directivity effects exist but are complicated by rupture incoherence, scattering, and refraction.

The large accumulation of strong motion recordings over the past decade includes a substantial number within 10 km of large earthquakes. These data indicate that the principal near-fault effect of directivity on high-frequency ground motion is that the amplitudes of the vertical motions become comparable to those of the horizontal motions, whereas they are less than the horizontal motions at greater distances. Rupture directivity effects are not generally observed in high-frequency peak-acceleration data recorded adjacent to the fault rupture, but become more evident when the recording site is located off the end of a strike-slip fault.

In contrast to the case for high frequencies, at longer periods (about one second and longer), directivity effects are very evident in strong motion data recorded adjacent to faults (Somerville and Graves 1993) The propagation of the rupture toward the site causes a large long-period pulse of motion in the direction normal to the fault that occurs near the beginning of the record. The time compression effect of rupture directivity, which is partly responsible for the large amplitude, also causes the motion to have a shorter duration compared with that at other locations. Somerville, et al. (1995) quantified the differences between fault-normal and fault-parallel response spectra based on an empirical analysis of recorded strong motion data. They showed that the ratio between fault-normal and fault-parallel motions becomes larger than unity at a period of 0.5 seconds and increases with increasing period, increasing magnitude, and increasing proximity to the fault. The Somerville, et al. (1995) study incorporated data from the 1994 Northridge, California earthquake but not the 1995 Kobe, Japan earthquake. Updating their study to include the latter event, Somerville, et al. (1997) conclude that directivity effects become significant at a period of 0.6 seconds and generally increase with increasing period.

The effects of rupture directivity on ground motions having periods longer than 0.6 seconds will be accommodated by making adjustments to response spectral attenuation relations that describe the average of the horizontal components of motion. The adjustments, which are period-, magnitude-, and distance-dependent (Somerville, et al. 1995; 1997), convert the average horizontal component to the fault-normal and fault-parallel components. These ground motion components can then be combined vectorially, if desired for analytical convenience, to produce ground motions that are oriented in longitudinal and transverse directions with respect to the horizontal axis or repository structures.

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[2] Even without rupture propagation, ground motions will vary azimuthally because of the P-and S-wave radiation patterns of a point dislocation in an elastic medium. However, radiation patterns have not been incorporated into attenuation relationships because of the complicating effects of scattering and refraction caused by variations in wave propagation velocities (Joyner and Boore 1988).

The amplitudes and durations of the recorded ground motions from the 1992 Little Skull Mountain earthquake exhibit directivity effects; because of the proximity of this event to the site, the records from this earthquake in particular have been used to evaluate and validate ground motion models for Yucca Mountain (Abrahamson and Becker 1996). If required, more site-specific estimates of the effect of rupture directivity will be derived from calculations that use the specific fault geometry and faulting mechanism of faults near the Yucca Mountain site, using a numerical method such as that described by Hartzell and Heaton (1983).

B2.3.4 Effect of Distribution of Slip

Earthquake ground motions in the near-fault region are affected by the details of the slip distribution over the fault plane. Patches over which higher slip occurs are called "asperities" and radiate a disproportionate amount of seismic energy (e.g., Hartzell and Heaton 1983). Patches which do not rupture are called "barriers" and will generate high-frequency "stopping phases" if the rupture terminates abruptly (Papageorgiou and Aki 1983a; 1983b). A number of ground motion models have been run for six different "scenarios" involving the occurrence of plausible earthquakes on Quaternary faults near Yucca Mountain (Schneider, et al. 1996). Most of these models explicitly incorporate the distribution of slip on the fault, and the results of these models will be considered in selecting near-fault ground motion values in ground motion attenuation relationships.

B2.3.5 Vertical Ground Motions

Peak vertical accelerations are approximately equal to peak horizontal accelerations in the near-fault region, while peak vertical velocities are about two-thirds of the horizontal. The spectral shape of the vertical component is correspondingly different from the horizontal, showing a shift to higher frequencies, and this shift is distance-dependent. These near-fault features of vertical ground motions will be incorporated into the evaluation of vertical ground motions.

B2.4 SUMMARY OF APPROACH TO EVALUATING SOURCE AND PATH EFFECTS

Ground-motion experts will individually evaluate source and path effects on ground motions at Yucca Mountain, employing both empirical and theoretical approaches. Empirical relationships describing ground motion attenuation will be based on ground motion records from Yucca Mountain and from analog locations in the western United States and elsewhere. Each expert will choose or develop relationships that include dependencies on the component of ground motion (horizontal or vertical), type of faulting, directivity, and systematic differences between hanging-wall and footwall motions, to the degree that these dependencies are significant and can be defined by available data. The empirical relationships will be supplemented by theoretical or hybrid theoretical-empirical numerical methods to characterize the ground motion more completely and to assess ground motion uncertainties. Considering available ground motion records and information on the seismic wave transmission characteristics of the site and region, the experts will choose or develop numerical models that incorporate either empirical or theoretical source functions and propagation-path Green's functions. The overall uncertainty associated with numerical model predictions will be evaluated considering uncertainties in physical representations of the earthquake source, uncertainties in propagation-path parameters, and the sensitivity of model outputs to inputs.

B3.0 EVALUATION OF SITE EFFECTS ON GROUND MOTION

Site effects are the modifying influence on ground motion of local shallow geologic structure and topography. As seismic waves, incident from below, approach the ground surface, their amplitude increases because of the effect of the free surface and because the seismic impedance of the rock (ratio of applied stress to resulting particle velocity) normally decreases as depth decreases. In addition, if the near-surface geologic materials form layers having sharp impedance contrasts, seismic waves will be trapped in these layers, reverberate, and amplify ground motion amplitudes at certain resonant frequencies. Surface and subsurface topography can result in the focusing or de-focusing of seismic waves with resultant increases or decreases in amplitudes.

The phenomena just described lead to a frequency-dependent site response and frequency-dependent reduction of ground motion amplitudes with depth. The reduction of ground motion amplitudes at repository depths is expected to be significant, as illustrated by nearby recordings of an aftershock of the June 29, 1992 Little Skull Mountain earthquake. For the September 7, 1992 aftershock at an epicentral distance of 3.5 km, Anderson et al. (1993) found a 2-Hz horizontal response spectral reduction factor of about 0.65 between the top of Little Skull Mountain and a tunnel 100 meters beneath the surface; for the vertical motions, the corresponding reduction factor was 0.5. Similar results were obtained from local seismic events (eight earthquakes and two cultural sources) recorded at the surface and at a depth of 332 m in borehole UE25a-3 located in the Calico Hills about 12 km east of Yucca Mountain. A mean reduction factor of approximately 0.66 was observed between surface motion and subsurface (332 m) motion over the bandwidth 0.2 Hz to 20 Hz (King 1982).

The DOE will factor appropriate site response factors into ground-motion estimates that are used as a basis for the design of structures, systems, and components that are important to safety. In this section the data needs for characterizing site effects are discussed and potential methods are presented for incorporating site effects and their variability into evaluations of ground motion.

B3.1 DATA NEEDS AND AVAILABLE DATA

The large number of earthquake and UNE recordings from the Yucca Mountain site (e.g., Pezzopane et al. 1996a) provides a basis for characterizing site effects empirically. The data include records obtained both at the surface and at depth in boreholes. The downhole recordings show the amplification of seismic waves as they approach the ground surface, providing empirical information which is needed for the design of underground openings. Surface recordings are available for both rock and alluvial sites and for topographic conditions ranging from flat to steep.

As noted, the empirical data set includes UNE records that have been obtained at the surface and downhole at several Yucca Mountain sites. UNEs are shallow seismic sources and, therefore, usually generate higher surface wave amplitudes than comparably sized earthquake sources. However, Durani and Walck (1996) have modeled the first few seconds of downhole UNE vertical and radial motions (i.e., ground motions from UNE body waves) at Yucca Mountain reasonably well using a simple one-dimensional body-wave propagator matrix method. The resulting P-wave and S-wave shallow velocity models can be used to numerically propagate earthquake ground motions and assess amplitude variations with depth. Borehole seismometers have been installed at Yucca Mountain (at borehole UZ-16), and accelerometers are being installed in the ESF. As they become available, earthquake records from these instruments will be used to assess depth-of-burial effects directly.

Information about the physical properties and the wave propagation characteristics of the earth's crust at shallow depths beneath the site will be input to a theoretical numerical model of site response. In theoretical models, site response is calculated by numerically propagating incident seismic waves through a model of the shallow seismic velocity structure at the site. Information has been collected on the crustal seismic velocity structure in the Yucca Mountain region, seismic wave attenuation due to geometrical spreading, anelastic attenuation (Q), the spectral decay parameter κ (kappa) (Abrahamson and Becker 1996), and on the nonlinear properties of tuff deposits (Stokoe, et al. 1997). This information will be supplemented by the collection of geotechnical information at the sites of specific surface facilities. Vertical seismic profiling has shown that there is considerable lateral variability in the shallow shear-wave velocity structure over the site area (CRWMS M&O 1996b). The DOE, therefore, will install site-specific boreholes to obtain local shear-wave velocity measurements for surface ground motion calculations.

B3.2 APPROACH TO SITE RESPONSE EVALUATION

Incorporation of site effects into ground motion estimates is a two-step process. First, the regional ground motion attenuation properties must be identified. Second, ground motion estimates must then be corrected for the effects of near-surface velocity contrasts and gradients and, possibly, for nonlinear response of near-surface rock and soil at high strain levels. The probabilistic seismic hazard assessment will provide ground motion descriptions that apply to a hypothetical outcrop of the rock of the geologic horizon in which waste would be emplaced—the Topopah Springs welded tuff unit, 300 m below the surface of the mountain. The hypothetical rock outcrop motions will reflect the regional ground motion attenuation characteristics. For surface facilities, these motions must then be corrected for the influence of the overlying rock and fill (if any). For subsurface facilities, depth-of-burial corrections must be applied.

Correction of hypothetical rock outcrop motions for the effects of near-surface velocity gradients and for the depth of burial of subsurface facilities will also incorporate both empirical and theoretical results. Recorded surface and subsurface ground motions will be used to calibrate numerical theoretical models of local site response, which will be used to extend the empirical results to different locations and to different burial depths. It is likely that site response and nonlinear effects can be estimated using standard one-dimensional (1-D) velocity models. However, if comparisons with recorded data indicate that the site's structural complexity or lateral heterogeneity is such that a 1-D velocity model is inadequate, more complex 2-D or 3-D models can be employed.

In deterministic analyses of ground motions at the site from a postulated earthquake at a particular location, site response can be "built into" the ground motion model if suitable earthquake records are available. For example, site recordings of small earthquakes that have hypocentral locations and focal mechanisms that are similar to those of the earthquake being modeled can be used as empirical Green's functions (Hartzell 1978) if such records exist. The advantage of this approach is that the recorded motions inherently reflect whatever local site effects are present. No additional corrections for site response are required except, possibly, for nonlinear response of near-surface materials at high strain levels.

B3.3 SPECIFIC SITE-EFFECT VARIABLES

B3.3.1 Nonlinear Behavior of Shallow Geologic Materials

The DOE will evaluate the potential effects on strong earthquake ground shaking of the nonlinear response of near-surface geologic materials at the locations of surface facilities that are important to safety. With increasing cyclic strains, geologic materials exhibit strain softening—reduction of the shear modulus—and an increase in material damping. The effect on ground motion generally is to reduce peak particle accelerations and the seismic energy that are transmitted to surface structures and to shift the energy that is transmitted from higher to lower frequencies.

For a number of samples of the tuff that outcrops at the site, the DOE has obtained measurements of shear modulus and damping and their dependencies on strain level and confining pressure (Stokoe et al. 1997). These measurements will enable the effect of nonlinear response of the soft rock at Yucca Mountain to be modeled. The DOE anticipates using the equivalent linear elastic model (Seed and Idriss 1967), which has been incorporated into the SHAKE computer code (Schnabel et al. 1972). The equivalent linear method of analysis and true nonlinear analysis methods have been summarized by Finn (1988).

B3.3.2 Topographic Site Effects

The topography of the Yucca Mountain site may be steep enough to affect earthquake and UNE ground motions. The western flank of Yucca Mountain drops about 180 meters over a horizontal distance of about 300 meters, giving a shape ratio of 0.6. On its much less steep eastern flank, there is a drop of about 270 meters over a horizontal distance of about 2,250 meters, giving a shape ratio of 0.12. Based on the empirical data compiled by Geli et al. (1988), the slope of the western flank is expected to produce significant topographic effects, while the slope of the eastern flank is not.

UNE recordings at the surface and downhole at Yucca Mountain provide an opportunity to evaluate empirically the influence of topographic effects on ground motions. UNE seismograms are dominated by surface waves, but shear waves are also present, and the influence of topographic effects on both shear waves and surface waves will be evaluated to the extent permitted by the data. Topographic effects can be numerically simulated using a finite difference model (e.g., Frankel and Leith 1992) or a boundary integral equation scheme (e.g., Bouchon and Barker 1996).

Topographic effects need not be explicitly modeled to be accounted for. An alternative, legitimate approach is to treat topographic effects implicitly, as a source of aleatory uncertainty in model predictions. This is accomplished by specifying the model parameters such that the dispersion in the model predictions is consistent with the observed intra-event (site-to-site) scatter of ground motions recorded at sites that encompass the range of topographic conditions at Yucca Mountain.

The ground motion experts will select or develop ground motion models that explicitly and/or implicitly account for topographic effects at Yucca Mountain.

B3.4 SUMMARY OF APPROACH FOR EVALUATING SITE RESPONSE

The DOE will develop ground motion descriptions that apply to a hypothetical outcrop at Yucca Mountain of the tuff that exists at proposed repository depths; these outcrop motions will be corrected for application to the surface and subsurface locations of structures, systems, and components that are important to safety. The site response and depth-of-burial corrections will employ both empirical and theoretical methods. Comparisons between ground motions recorded at surface sites, and between surface motions and those at depth in boreholes, will be used to calibrate theoretical models of the site response. Deterministic analyses of ground motions at the site from postulated earthquakes at particular locations may employ a hybrid theoretical-empirical approach in which recordings of small earthquakes at the site are used as empirical Green's functions, which inherently reflect local site effects. The results of dynamic response analyses of the tuff that outcrops at Yucca Mountain will be used to model the nonlinear response of the near-surface tuff to high-amplitude incident seismic waves. Ground motion models will be selected or developed that explicitly and/or implicitly account for topographic effects.

B3.5 ASSESSMENT OF UNCERTAINTY IN GROUND MOTION MODELS

As described in Section 2.3 of this report, uncertainty in ground motion values comprises aleatory uncertainty due to randomness in the underlying process of earthquake rupture and seismic wave propagation, and epistemic uncertainty resulting from incomplete knowledge about those processes. Aleatory and epistemic uncertainties are present in both empirical and numerical models of ground motion. In the following, we describe methods of assessing epistemic and aleatory uncertainty, first in empirical approaches and then in numerical approaches.

Empirical ground motion relationships are mathematical formulations selected to fit specific sets of recorded data. Epistemic uncertainty arises because the data sets admit multiple interpretations of the underlying ground motion relationships. In addition, there is uncertainty in the selection of the most appropriate or representative data sets to use for modeling ground motion at a particular site. This epistemic uncertainty will be incorporated by using more than one empirical ground motion relationship.

Regarding the randomness in ground motion, the use of a random effects model has provided estimates of earthquake-to-earthquake (inter-event) and within-earthquake (intra-event) contributions to variance (Abrahamson and Youngs 1992) and has demonstrated that total variance decreases with increasing earthquake magnitude (Youngs et al. 1995). For peak acceleration, this decrease is more pronounced for horizontal motions than for vertical motions. There is also a dependence of variance on period, with variance tending to increase at the longer periods. These dependencies of variance on magnitude, period, and component of motion will be taken into account in the assessment of randomness in the empirical attenuation relations.

With respect to uncertainty in theoretical approaches, a rigorous procedure for assessing the uncertainty in ground motion values derived from theoretical models has been developed by Abrahamson et al. (1990). There are two contributions to this uncertainty. The first contribution, which consists of modeling uncertainty, represents the variance between recorded and calculated ground motions in situations where the basic information required for calculating the motions (such as earthquake source parameters, seismic velocity structure of the path, and site conditions) is known. This contribution to uncertainty will be evaluated from the discrepancy between recorded ground motions of past earthquakes and ground motions calculated using the known source, path and site descriptions that pertain to these events. The second contribution, which consists of parametric uncertainty, represents uncertainty in the source parameters of future earthquakes that may affect the site in question, and the uncertainty in the path and site effects at that site. This second contribution will be characterized by developing probability distributions for the source, path, and site parameters.[3]

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[3] Both the modeling and parametric uncertainties contain epistemic and aleatory uncertainty. Unknown bias in the model predictions because of limited data is epistemic modeling uncertainty. Differences between model predictions and recorded ground motion amplitudes, when the parameters required by the model are known, are the result of physical processes not included in the model; these differences are effectively random and represent aleatory modeling uncertainty. Imperfect knowledge about the true probability distributions of the parameters associated with future events is epistemic parametric uncertainty. The event-to-event variation in the parameters of future events, given their true distributions, is aleatory parametric uncertainty.

The variance in ground motions described by empirical ground motion attenuation relationships is derived from the variability in recorded data for a given category of sites. The variance thus reflects not only the variance at a given site from event to event, which is relevant at a specific site, but also the variability in response from site to site, which is only appropriate for a specific site when there is no information available about the site response. Hence, to correct an attenuation relationship for site response, the estimate of variance in the empirical attenuation relation should be replaced with an estimate derived from site-specific data.

The correction of ground motion variance can be significant because, for larger magnitude earthquakes, it is found that the intra-event contribution to the variance is larger than the inter-event contribution (Youngs et al. 1995). In other words, most of the variability in ground motions (from site to site and event to event) is attributable to varying path and site effects. This indicates that, if the path and site response characteristics at a given site are known, the variance in the ground motion estimates may be reduced substantially.

A practical consideration in correcting ground motion variance estimates for larger magnitude events is that both intra-event variance and inter-event variance decrease with increasing magnitude (Abrahamson 1988; Youngs et al. 1995). Hence, if the variance of the site response is derived from small magnitude earthquakes, it may not be applicable to larger earthquakes. All these factors will be assessed and incorporated into the site response assessment.

The uncertainty in site response estimates will be partitioned into modeling uncertainty and parametric uncertainty, as discussed above. Site response modeling uncertainty will be evaluated from differences between recorded surface motions and surface motions that have been calculated using a numerical wave propagation procedure, recorded downhole motions, and a description of the velocity structure between the downhole and surface recorders. Parametric uncertainty will be estimated by varying the parameters of the structure description and the parameters that describe the incident wave field, such as its orientation, wave composition, phasing, and frequency content.

APPENDIX C

SEISMIC HAZARD ASSESSMENT PROCEDURES

APPENDIX C

SEISMIC HAZARD ASSESSMENT PROCEDURES

C1.0 INTRODUCTION

Section 2 of this report presents a summary of the methodology to assess seismic hazard for vibratory ground motion and fault displacement. This Appendix provides additional information on the assessment procedures. These procedures are drawn from studies representing the state-of-the-practice; most of the major elements have been used previously by the nuclear industry, the DOE, and the NRC.

The seismic hazard assessment methodology described in this Appendix requires a large amount of data to evaluate and characterize the uncertainty on the interpretations input to the hazard calculation. To minimize data uncertainty, an extensive program aimed at collecting a range of high quality data is required. These data will be developed by the ongoing Yucca Mountain site characterization program.

C2.0 VIBRATORY GROUND MOTION HAZARD ASSESSMENT

The basic methodology for seismic hazard assessment is that developed by Cornell (1968). This methodology comprises five basic steps as shown in Figure C-1. The first four steps are described next and the fifth step is discussed in Section C4.

C2.1 STEP 1: SEISMIC SOURCE INPUTS

The first step in the assessment of vibratory ground motion hazard is the identification and evaluation of seismic sources. Seismic sources are characterized by a probability of activity and a probability density function that describes the distribution of earthquakes in distance for each seismic source; this depends on source location and geometry. Dependencies between sources, if any, are also part of the seismic source input. The interpretations of seismic sources are developed as discussed in Appendix A.

Table C-1 summarizes the types of data that are used to develop interpretations of seismic sources. The interpretations will seek to explain the data sets fully, and alternative interpretations will be developed as permitted by the data. The development of multiple alternative interpretations provides a description of the epistemic uncertainty in the source descriptions. The seismic hazard computational procedure is capable of accepting input source interpretations of any degree of complexity needed by earth scientists to fully characterize seismic sources and their associated uncertainty.

Table C-1. Data Used to Identify Alternative Seismic Sources and Characterize Uncertainty

Aerial photography and satellite imagery
Historical seismicity maps and cross-sections
Quaternary fault maps, literature reviews, and reconnaissance investigations
Detailed paleoseismic investigations of local Quaternary faults
Focal mechanisms, hypocenter distributions, and historical earthquake data
Heat-flow, magnetic, and gravity anomaly maps
Seismic reflection and refraction investigations and borehole logs
Detachment fault maps, ages
Geodetic leveling, trilateration, and global-positioning satellite (GPS) surveys
Crustal stress measurements
Fault kinematic indicators such as the orientations of slickensides
Tectonic geomorphology investigations for evidence of deformation or stability
Tectonic models of local and regional structures
Fault segmentation studies
Correlations between nuclear explosion yield and moment magnitude
Evaluations of the locations and yields of underground nuclear explosions
Maps of Quaternary volcanic centers

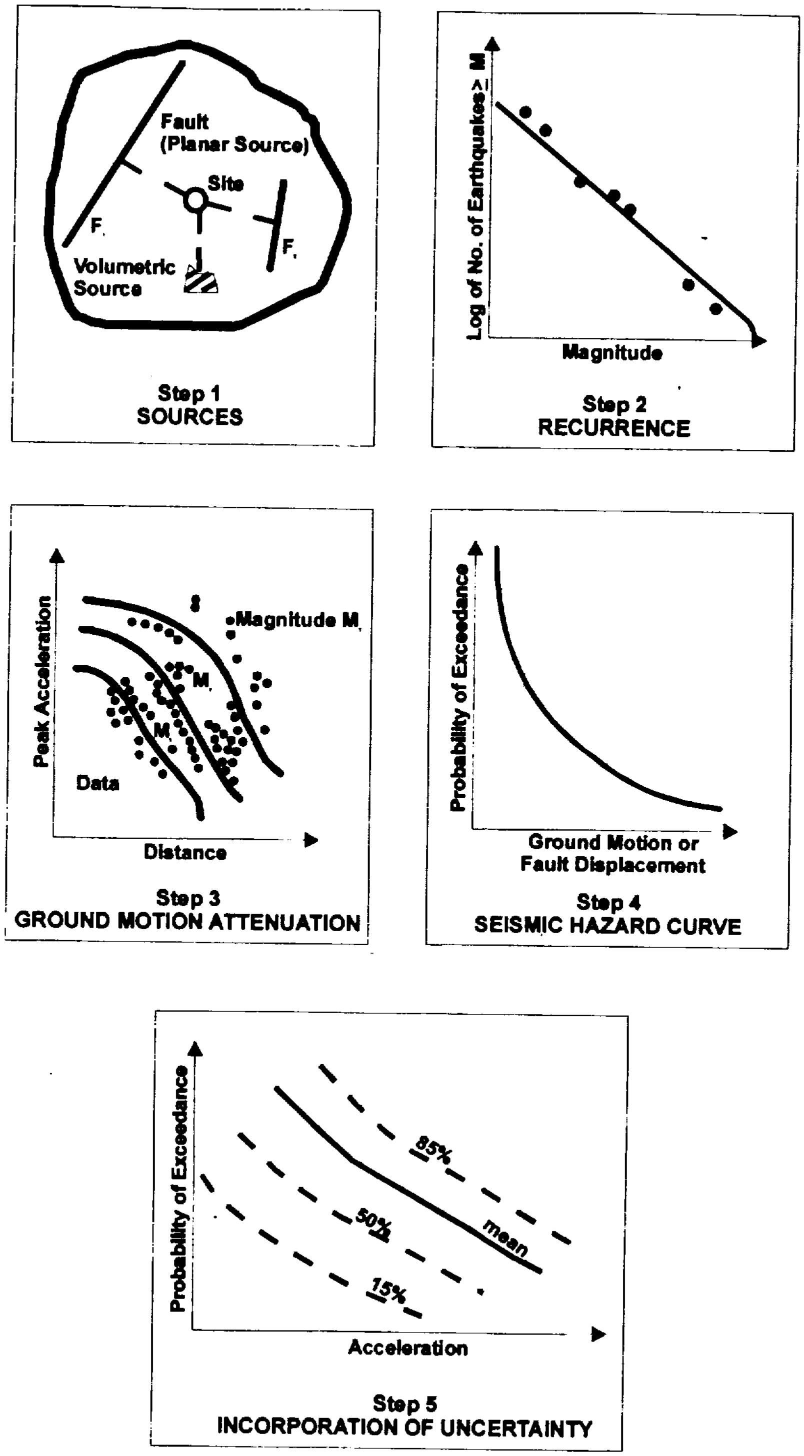
C2.2 STEP 2: EARTHQUAKE RECURRENCE

For each source zone, the rate and relative distribution of earthquakes with respect to size, including maximum magnitude, are represented by a density function on magnitude as illustrated in Figure C-1, Step 2. A Poissonian-in-time, exponential-in-magnitude recurrence relationship is normally appropriate for volumetric seismic sources. For fault-specific seismic sources, the applicability of the characteristic-earthquake magnitude recurrence relationship must be considered. Evidence of temporal clustering can be accommodated through the use of time-dependent temporal occurrence models. The seismic-source-characterization experts for the probabilistic seismic hazard analysis will identify appropriate magnitude-recurrence relationships for each seismic source and will determine whether the available data warrant the implementation of non-Poissonian (time-dependent) temporal occurrence models.

The parameters of the recurrence relationship will be developed from available geologic slip rate data, historical seismicity, and seismic moment rate estimates, as described in Appendix A. The types of data used to assess the parameters of the earthquake recurrence relationship for each source are summarized in Tables C-2 and C-3. Table C-2 more specifically addresses the rates of occurrence and Table C-3 addresses the determination of maximum earthquake magnitude.

Table C-2. Data Used to Evaluate Seismic Recurrence Rates and Their Uncertainties

Paleoseismic studies of Quaternary fault slip rates and recurrence intervals
Historical seismicity catalogs
Quaternary fault maps and literature compilations of paleoseismic investigations
Surface and at-depth structural relationships between faults
Contemporary crustal deformation measurements—geodetic leveling, trilateration, and global-positioning satellite (GPS) surveys—and resulting seismic moment rate estimates
Tectonic geomorphology investigations for evidence of deformation or stability
Tectonic models of local and regional structures
Testing frequency and yield estimates of future underground nuclear explosions
Volcanic eruption rate estimates and rates of formation of new volcanic centers
Magnitude-frequency distributions for volcanic earthquakes



(modified from Reiter, 1991)

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Figure C-1. Basic Steps of the Methodology to Assess Vibratory Ground Motion Hazard

Table C-3. Data Used to Evaluate Maximum Magnitudes and Their Uncertainties

Estimates of overall fault length and fault segment length of Quaternary faults
Determinations of fault dip and down-dip fault width
Focal depth estimates of earthquakes
Estimates of total displacement and displacement per event on Quaternary faults
Fault rupture models of primary and secondary fault ruptures
Surface and at-depth structural relationships between faults
Seismic source characteristics of local and regional faults and nuclear explosions
Fault displacement and moment magnitude data
Rupture dimensions and moment magnitude data
Fault segmentation data
Yield estimates of future underground nuclear explosions

C2.3 STEP 3: GROUND MOTION ATTENUATION RELATIONSHIPS

The ground motion attenuation relationships, as formulated in the seismic hazard methodology, give the probability distribution of ground motion that results at a site from a given earthquake at a given location. The ground motion assessment procedure, which is presented in detail in Appendix B, includes both empirical and theoretical components.

The inherent stochastic nature of the earthquake rupture and propagation phenomenon leads to aleatory uncertainty in the assessed ground motion. The ground motion measure at a site, therefore, is modeled as a random variable. In Equation C-1, the characterization of the ground motion Z is made in terms of a probability distribution function of Z as a function of the dependent parameters m (magnitude) and r (the distance from the earthquake source to the site). When representing the horizontal component of ground motion, various authors have defined Z as the randomly oriented horizontal component, the larger of the two horizontal components, the arithmetic mean of the two horizontal components, or the geometric mean of the two horizontal components. The DOE plans to calculate the hazard for the randomly oriented horizontal component. The distance measure, r, is commonly defined as the closest distance to the vertical projection of the ruptured area onto the surface of the earth, the closest distance to the rupture surface, or the closest distance to the seismogenic (high stress) portion of the rupture. The DOE will use the distance measures that correspond to the attenuation models that are chosen by the ground motion attenuation experts in the probabilistic seismic hazard analysis. Thus, several different distance measures may be used in the hazard calculations.

As applied in the seismic hazard methodology, the probability distribution of Z given m and r is required. This is obtained by formulating a relationship between the median value of Z as a function of m and r, and providing a description in the form of a lognormal distribution of the uncertainty in Z, given m and r[4]. For example, if Y represents the logarithm of the ground motion parameter, and $Y(m,r)$ is a function of m and r which gives a value for the mean of $\ln(Z)$, then the uncertainty in Z is described by:

[4] Because ground motion parameters are observed, typically, to have a lognormal distribution, regression analyses are performed to develop relationships that predict mean values and standard deviations of the logarithm of the ground motion values as functions of earthquake magnitude and distance and, possibly, other parameters. Taking the exponent of the mean value of the logarithmic distribution provides an estimate of the median value of the ground motion parameter.

$$\ln(Z) = Y(m,r) + E \tag{C-1}$$

where E is a random variable with zero mean and some standard deviation. The function $Y(m,r)$ and its associates, which can also be a function of other parameters such as frequency, stress drop, or fault type, is referred to as the ground motion attenuation representation. Characterization of that representation for the Yucca Mountain site is discussed in Appendix B. For a given value of m and r, the integrand in Equation C-4, $P(Z>z|m,r)$, is equal to the value of the complementary cumulative normal probability function:

$$P(Z>z|m,r) = 1 - \Phi\left(\frac{\ln(z) - y(m,r)}{\sigma}\right) \tag{C-2}$$

where σ is the logarithmic standard deviation of the ground motion parameter.

The data to be used in assessing ground motion relationships at Yucca Mountain include available recordings of ground motions, information on the characteristics of the seismic sources that may affect the Yucca Mountain site, and a description of the propagation paths for the seismic energy from those seismic sources to the site. Table C-4 lists types of data that will support the determination of applicable ground motion relationships.

Table C-4. Data Used to Evaluate Ground Motions and Their Uncertainties

Source locations and geometries (surface projections, fault dips, and down-dip widths)
Surface and underground recordings of earthquakes and nuclear explosions
Ground motion records from local or regional areas on both rock and alluvial sites with flat to steep topography
Strong ground motion data from other parts of the U.S. and the world where source and attenuation characteristics are similar
High-gain, portable, and broadband records in analog and digital formats
Seismic velocity and density measurements of local geology
Seismic reflection and refraction studies of local geology and crustal structure
Seismic wave propagation models calibrated to physical properties of local geology

C2.4 STEP 4: VIBRATORY GROUND MOTION HAZARD CURVE

The seismic hazard curve shown as Step 4 in Figure C-1 represents the seismic hazard result, which is obtained by an integration of the source, recurrence and ground motion attenuation inputs. For a particular source interpretation, recurrence description, and ground motion attenuation relation, one hazard curve is calculated. The seismic hazard curve shows the calculated annual probability at which various levels of a ground motion parameter will be exceeded.

Earthquake recurrence is defined by two stochastic variables, X and M. X is the number of earthquakes occurring per unit time (e.g., per year), and M is the magnitude of an earthquake, given that one occurs. Each source is characterized by an *X* and *M*. The hazard computation incorporates the following assumptions:

- As stochastic variables within a seismic source:
  - *X* and *M* are independent.
  - X is represented typically as a stationary Poisson process, but may be modeled as a time-dependent (e.g., renewal) process.
  - *X* is spatially uniform.
  - There is a minimum magnitude m^0 of engineering concern; magnitudes less than m^0 are not considered in the calculation.

- Between seismic sources:
  - *X*'s are independent.
  - *M*'s are independent.
  - *X*'s and *M*'s are mutually independent

The probability that at a given site a ground motion parameter, *Z*, will exceed a specified level, *z*, during a specified time period, *T*, is given by the expression:

$$P\ (Z > z) = 1.0 - e^{-\nu(z) \cdot T} \leq \nu(z) \cdot T \qquad \text{(C-3)}$$

in which $\nu(z)$ is the average frequency during the time period, *T*, that the ground motion parameter *Z* exceeds *z* at the site, as a result of earthquakes on all sources in the region. The inequality at the right of Equation C-3 is valid regardless of the probability model for earthquake occurrence, and $\nu(z)\cdot T$ provides an accurate and slightly conservative estimate of the hazard for probabilities of 0.1 or less.

The frequency of exceedance, $\nu(z)$, is a function of the size and location of future earthquakes and of the level of ground motions they may produce at the site. It is computed by the expression:

$$\nu(z) = \sum_{n=1}^{N} \alpha_n(m^0) \int_{m=m^0}^{m^u} \int_{r=0}^{\infty} f_n(m) \cdot f_n(r|m) \cdot P(Z>z|m,r)\ dr\ dm \qquad \text{(C-4)}$$

in which *N* is the number of seismic sources, $\alpha_n(m^0)$ is the frequency of earthquakes on source *n* larger than a minimum magnitude of engineering significance, m^0; $f_n(m)$ is the probability density function for event size on source *n* between m^0 and a maximum event size for the source, m^u; $f_n(r|m)$ is the probability density function for the distance to the earthquake rupture on source *n*, which is usually conditional on the earthquake size; and $P(Z>z|m,r)$ is the probability that, given a magnitude *m* earthquake at a distance *r* from the site, the ground motion exceeds level *z*. For computations, the double integral in Equation C-4 is replaced by a double summation with discretized density functions $f_n(m)$ and $f_n(r|m)$.

The frequency of exceedance, $\nu(z)$, is displayed as a hazard curve (Figure C-1, Step 4), typically normalized for a one-year period (i.e., $T = 1$) to express the annual probability of exceedance of the ground motion parameter.

For most seismic environments, the Poisson temporal occurrence model is appropriate (see Section A4.5.2). However, if any of the seismic source characterization experts in the Yucca Mountain hazard assessment choose a time-dependent temporal model (e.g., a nonhomogeneous Poisson model or a renewal model), the probability of exceedance of a value z over the entire period $T > 1$ will be obtained by integration over that period of time.

C3.0 FAULT DISPLACEMENT HAZARD ASSESSMENT

The seismic hazard methodology for Yucca Mountain includes an assessment of the hazard of differential fault displacement. Because of the stochastic nature of fault displacement and significant uncertainties associated with the assessment, the hazard assessment approach is probabilistic. Possible approaches to the assessment of the probabilistic fault displacement hazard at Yucca Mountain have been documented (Coppersmith and Youngs 1992; Coppersmith et al. 1993). The seismic-source-characterization experts will evaluate these published approaches and augment them as necessary.

The probabilistic fault-displacement-hazard methodology explicitly incorporates the uncertainties associated with the locations, sizes, and rates of earthquake occurrences, as well as the locations and amounts of displacement given an earthquake occurrence. Much of the analysis follows well-established procedures for assessing vibratory ground motion hazard. As for the assessment of vibratory ground motion hazard, the fault displacement hazard methodology consists of five steps. The first four steps are discussed here; the fifth step is presented in Section C4.

C3.1 STEP 1: SEISMIC SOURCE INPUTS

Seismic sources will be identified and described by their location, three-dimensional geometry, and sense of slip, and their probabilities of activity and dependencies will be assessed (see Appendix A). It is expected that the level of detail in fault mapping at the site, both on the surface and underground, will allow the locations and characteristics of Type I faults (McConnel et al. 1992) to be specified with confidence. These Type I faults will be modeled as fault-specific sources of fault displacement hazard. Volumetric seismic sources may be identified, in addition, to account for the possibility of secondary faulting on small, unmapped faults or the formation of new faults in previously intact rock.

C3.2 STEP 2: EARTHQUAKE RECURRENCE

The principal basis for assessing the frequency of primary fault displacement likely will be fault slip rate. As described in Appendix A, the slip rate and fault dimensions are used together to estimate the seismic moment release rate along the fault, and the moment rate is then partitioned into earthquakes of various magnitudes up to the maximum magnitude according to a magnitude recurrence (size distribution) model, such as the truncated exponential model or characteristic earthquake model.

In principle, paleoseismic data on recurrence intervals and the amount of displacement per event on a particular fault can be used to estimate directly the likelihood of exceeding various displacement levels, without going through the intermediate step of establishing a magnitude recurrence model. At a minimum, such data enable important consistency checks with magnitude recurrence models and displacement hazard estimates. As discussed next, available paleoseismic data will be incorporated into the evaluation of the displacement hazard on primary faults.

C3.3 STEP 3: FAULT DISPLACEMENT RELATIONSHIPS

Analogous to the development of ground motion attenuation relationships in the assessment of vibratory ground motion hazard, the assessment of fault displacement hazard requires the development of relationships that describe the amount, sense, and location of primary and secondary fault displacement, given the occurrence of a magnitude *M* earthquake on a primary fault. A primary fault is defined as a fault with dimensions large enough to be seismogenic and whose surface rupture is directly related to the seismogenic displacement at depth. A secondary fault is defined as having limited dimensions and surface displacement that is related to secondary strain release, rather than directly related to co-seismic slip. The fault displacement relationship describes the pattern, amount, and probability of differential fault displacement for the primary faults and secondary faulting around the primary faults.

The expected pattern of primary and secondary faulting associated with earthquakes in the Yucca Mountain region will be assessed, in part, on the basis of empirical observations of Basin and Range ruptures. The patterns of surface ruptures associated with historical earthquakes in the Basin and Range Province have shown a wide range of behaviors, from relatively simple ruptures along simple, well-defined primary faults, to highly complex ruptures with a wide zone of secondary faulting. Any identified relationships between the width of the zone of secondary deformation and location on the hanging wall or footwall, sense of slip, and earthquake magnitude will be incorporated.

The amount of fault displacement associated with primary faults will be assessed in a variety of ways. Paleoseismic data regarding the amount of displacement associated with individual paleoseismic events will be incorporated into the assessment. Empirical relationships between earthquake magnitude and maximum and average displacement per event will be used for those faults lacking data on paleoseismic slip per event. Kinematic indicators (e.g., slickensides) of the sense of fault slip and regional tectonic models will provide constraints on the relative amounts of horizontal and vertical slip.

The expected amount of displacement associated with secondary faults will be estimated from available detailed geologic data, empirical relationships between the relative amounts of primary and secondary slip, and analogies to other Basin and Range surface ruptures. The analysis will consider the possible differences in the locations or amounts of displacement at the surface versus at the depth of the repository. Relationships will be investigated between the width of the zone of secondary deformation and location on the hanging wall or footwall, sense of slip, and earthquake magnitude.

The data used to assess the fault displacement hazard and uncertainty in the hazard characterization are summarized in Table C-5.

Table C-5. Data Used to Evaluate Fault Displacements and Their Uncertainties

Detailed maps of local Quaternary faults
Detailed paleoseismic investigations of local Quaternary faults
Fault rupture models of primary and secondary fault ruptures
Seismic reflection studies to determine fault locations and geometries
Seismic source characteristics of local and regional faults and nuclear explosions
Rupture displacement and moment magnitude data
Fault kinematic indicators such as the orientations of slickensides and fault striae
Focal mechanisms, hypocenter distributions, and historical earthquake catalogs
Tectonic models of local geologic structures
Fault segmentation data
Models of triggered slip associated with regional earthquakes and nuclear explosions
Testing frequency and yield estimates of future underground nuclear explosions
Crustal stress measurements

C3.4 STEP 4: FAULT DISPLACEMENT HAZARD CURVE

The end product of the fault displacement hazard assessment will be hazard curves that express the probability of exceeding various amounts of displacement at different surface and subsurface locations at the site and a set of rules for estimating the hazard at intermediate locations. The hazard curves will explicitly incorporate the contribution to faulting hazard from any secondary faulting or dependent faulting.

C4.0 TREATMENT OF UNCERTAINTY

Step 4 of Figure C-1 represents the hazard curve that would be obtained if all of the parameters that describe the seismic sources, the recurrence relationships, and the ground motion attenuation or fault displacement relationships were known with certainty. However, fault displacement hazard, as well as vibratory ground motion hazard, is subject to epistemic uncertainty as well as aleatory uncertainty. Therefore, the fault displacement hazard is expressed by a distribution of hazard curves, as shown in Figure C-1, Step 5, that expresses uncertainty caused by lack of knowledge. Usually the mean, median, and selected percentiles of the distribution of hazard curves are plotted.

C4.1 REPRESENTATION OF UNCERTAINTY

It is the state-of-the-practice to express the uncertainty in each step of the hazard calculation with a probability density function for each of the uncertain parameters. These probability distributions can be either discrete or continuous, depending on the method chosen to propagate the uncertainty.

C4.1.1 Uncertainty in Seismic Source Inputs

Generally, epistemic uncertainty in the seismic sources is represented by alternative interpretations permitted by the data. Alternative interpretations may be given in the form of weighted alternative geometries for the seismic sources, each with its probability of activity, or by weighted alternative seismic source maps. The source geometries include length, location, depth, and dip. Weights will be based on how well the alternative geometries explain the available data. A discrete probability distribution of seismic source maps is constructed by enumeration of all the possible combinations of sources. It is important to note that, even with the most detailed site characterization achievable, some uncertainty in the seismic source interpretations will remain.

C4.1.2 Uncertainty in Earthquake Recurrence and Maximum Magnitude

Epistemic uncertainty in the recurrence rate of earthquakes can be represented either by a joint distribution function of the a and b parameters of the Gutenberg-Richter relation (see Section A4.0) or by a joint distribution of the actual rate of occurrence for each magnitude. A probability distribution for the maximum magnitude is also needed. These probability distributions can be either discrete or continuous.

C4.1.3 Uncertainty in Ground Motion Attenuation and Fault Displacement Relationships

A set of weighted ground motion attenuation and fault displacement relationships is used to represent epistemic uncertainty. The alternative ground motion attenuation relationships represent alternative approaches for assessing ground motion (e.g., empirical and theoretical), as well as alternative methods within a general approach (see Appendix B). The alternative fault displacement relationships represent different methods of evaluating the distribution and amount of rupture displacement on primary and secondary faults. The logarithmic standard deviation of the ground motion measure (σ in Equation C-2) is an aleatory parameter whose value is uncertain. A set of weighted values is used, therefore, to express the epistemic uncertainty in σ.

C4.2 PROPAGATION OF UNCERTAINTIES

The propagation of uncertainties is accomplished by one of two different techniques that produce equivalent results. In the logic tree approach, the hazard is calculated for every combination of hazard-input parameters. In the Monte Carlo approach, simulations are performed for sample inputs drawn from the probability distributions of all the uncertain parameters.

C4.2.1 The Logic Tree Approach

Figure C-2 shows an example logic tree. Each node on the tree represents possible alternatives that reflect the uncertainty in the particular parameter or representation that is symbolized by the node. Each alternative has a branch starting from the node. For example, one node could represent fault length with alternative interpretations of 40 km or 60 km. In this case, two branches would come off the node, each with an associated probability. These probabilities would be developed based on evaluations of the available data. The logic tree can be developed to include any number of alternative interpretations needed to represent the uncertainty adequately. Typically, logic trees are used to express epistemic uncertainty, as in the example just given. In principle, however, the discrete or discretized probability distributions of random variables, which represent aleatory uncertainty, can also be expressed by logic trees.

When all parameters (nodes) are evaluated and their uncertainty represented by alternative interpretations (branches) the logic tree is complete. Each unique path through the tree represents a combination of uncertain parameters supported by the data. Going from the starting point of the tree at the left of Figure C-2, following a single path to an ending point at the right, constitutes a single selection of parameters as described in Steps 1 through 3 of Figure C-1. For each combination a hazard calculation is performed (Step 4, Figure C-1). The weight attached to this hazard curve is the product of the weights of the branches on the path. By performing a calculation for all the paths through the logic tree, a complete probabilistic description of the

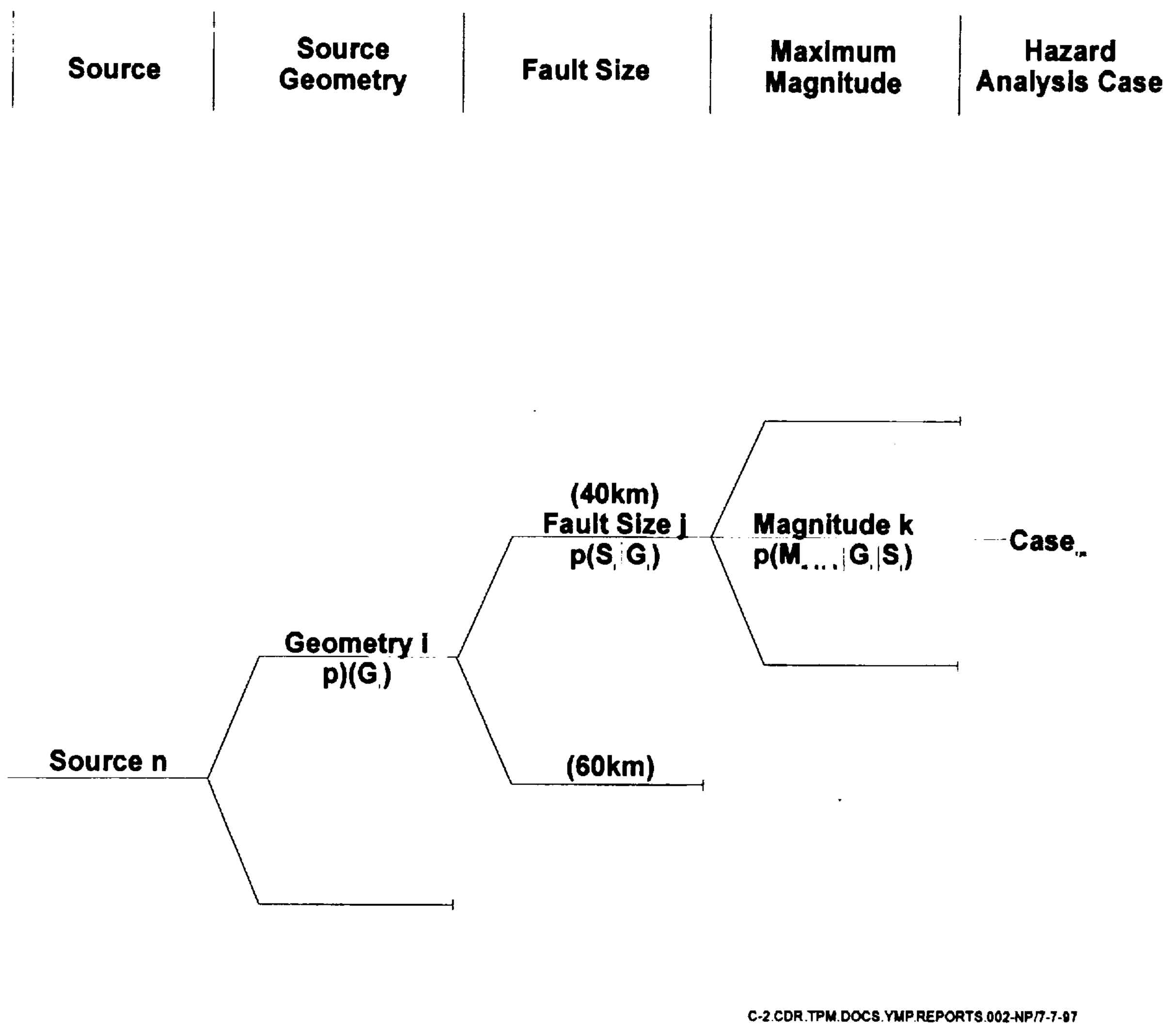

Figure C-2. Example Logic Tree Showing Uncertainties in Source Geometry, Fault Size, and Maximum Magnitude for a Given Fault Source *n* hazard is obtained from which various statistics are calculated, including the mean value of the hazard, the median, and other percentile values.

C4.2.2 The Monte Carlo Approach

In this approach, each simulation is similar to one path of a logic tree, but instead of identifying specific paths, all the possible paths implied by the probability distribution functions of the uncertain parameters are incorporated by randomly drawing the value of the parameters from their respective probability distribution functions. Correlation between parameters is included when necessary. The mechanics of the method are shown in Figure C-3. In one simulation, a zonation map made of one set of seismic sources is selected from the discrete probability distribution of maps (Step 1, Figure C-1); then for each source in the selected map, a recurrence curve is selected from the probability distribution of recurrence parameters (Step 2), and a ground motion attenuation model is selected from the discrete probability distribution of models (Step 3). The hazard is calculated for the simulation. After many simulations (thousands) the set of hazard results calculated represents a sample of all the possible estimates of the hazard from which a mean, median, and percentile values are calculated.

C5.0 SENSITIVITY ANALYSIS, DISAGGREGATION, AND DOCUMENTATION

C5.1 SENSITIVITY ANALYSIS AND DISAGGREGATION

Sensitivity analyses form a basis for the hazard analyst to determine the importance of the different parameters input to the calculation. Sensitivity analyses will be performed for the following:

Seismic sources

- Seismicity parameters
- Maximum and minimum magnitude
- Ground motion attenuation
- Fault displacement relationship.

PSHA provides an estimate of the integrated probability of exceeding specified levels of a ground motion parameter (such as peak acceleration) from earthquakes of varying magnitudes, from seismic sources at various distances. The hazard results can be disaggregated to determine the fractional contribution of potential earthquakes in specified magnitude and distance bins, to identify those earthquake magnitudes and distances that dominate or control the hazard at the site. If desired, contributing earthquakes can also be sorted into additional bins that indicate how many standard deviations the target ground motion level is above the median predicted level for the given magnitude and distance (McGuire 1995). The DOE intends to disaggregate the hazard results using an approach similar to those described in McGuire (1995) and in Regulatory Guide 1.165 (NRC 1997) (see Section D1.4). The hazard results will be disaggregated over the range of periods that are determined to be relevant to repository design. The following disaggregated results will be provided:

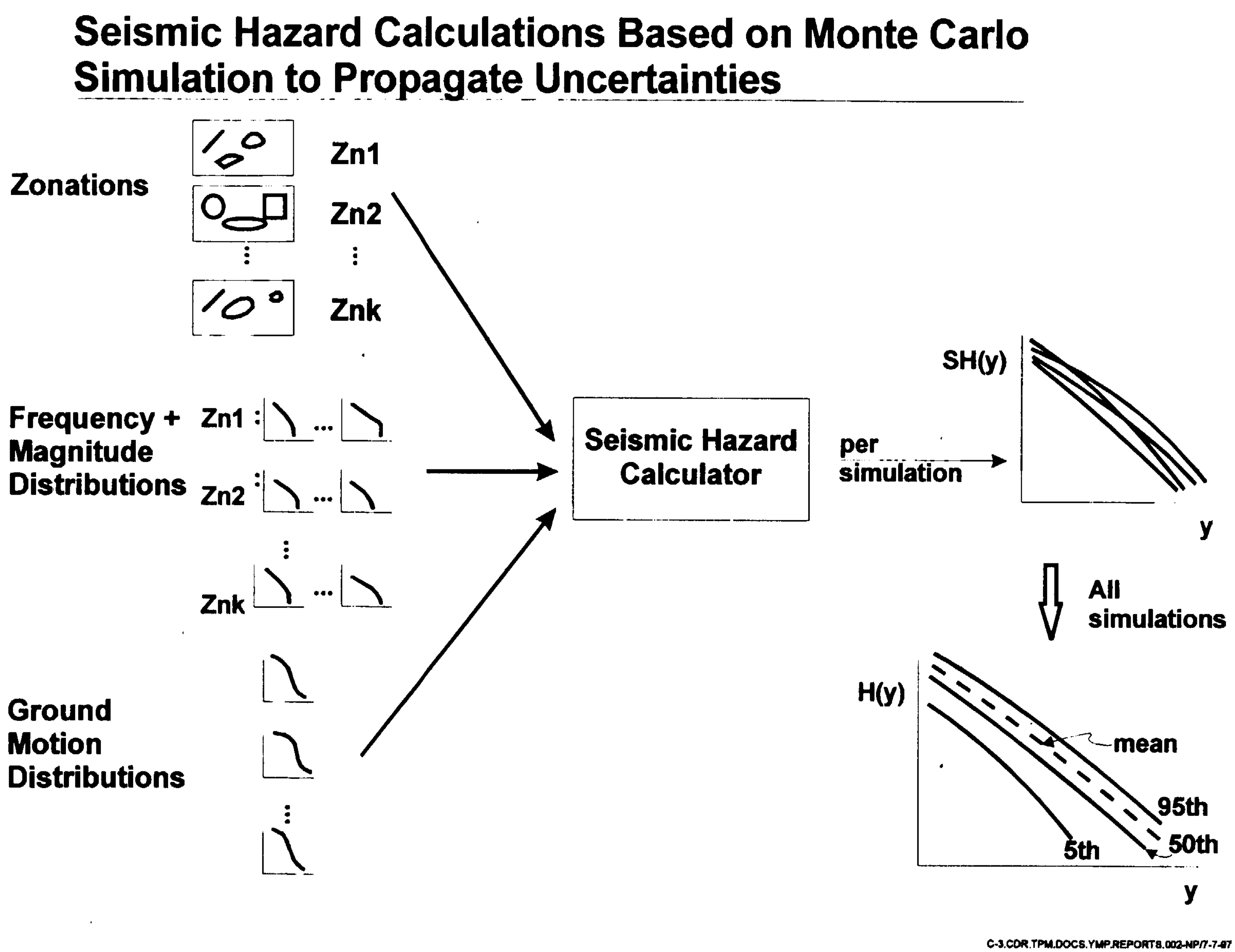

Figure C-3. Schematic Representation of the Monte Carlo Method of Propagating Uncertainties

- The contribution to the total hazard by bins of distance, magnitude, and ground motion variance
- The mean and, possibly, modal magnitude and distance values that correspond to the total hazard
- The hazard by seismic source
- The mean magnitude and distance that correspond to the hazard contributed by each seismic source.

The sensitivity analyses and disaggregation results have two important uses. By identifying the input parameters to which the hazard results are most sensitive, further work can be concentrated to reduce the uncertainty on these parameters, if necessary. The disaggregation results and the sensitivity analyses, together, constitute a broad information base for determining the final seismic design loads and for regulatory review.

C5.2 DOCUMENTATION

An important part of a probabilistic seismic hazard analysis is the documentation of the data, interpretations, and analyses used to develop input to the hazard computations. Documentation will be sufficient to allow technical reviewers to understand the reasoning leading from various data sets to specific interpretations. Evaluation of parameter uncertainties will also be documented. Documentation of the results will include comparisons such as those between seismicity interpretations and the historical earthquake catalog, and between ground motion interpretations and catalogs of ground motion data. Documentation is an integral component of the methodology.

APPENDIX D

HISTORICAL CONTEXT OF THE PROPOSED SEISMIC HAZARD ASSESSMENT METHODOLOGY

APPENDIX D

HISTORICAL CONTEXT OF THE PROPOSED SEISMIC HAZARD ASSESSMENT METHODOLOGY

The methodology presented in this topical report is based on recent experience in the field of seismic hazard assessment. A number of the studies on which the methodology is based have been developed, reviewed, and/or endorsed by the NRC for the nuclear industry. Although there are key differences between a nuclear waste repository and a nuclear power plant facility, an important historical context is established by review and comparison with previous studies. This Appendix outlines seismic hazard assessment methodologies that have been presented in previous studies. The objectives of this Appendix are to demonstrate that the methodology described in this topical report builds on the experience gained from past studies and is consistent with the state-of-the-practice for assessing seismic hazards.

Elements of the seismic hazard assessment methodology presented in this topical report and in other recent and ongoing studies are summarized in Table D-1. Methodologies that incorporate probabilistic seismic hazard analysis (PSHA) were developed by the Lawrence Livermore National Laboratory (LLNL) and the Electric Power Research Institute (EPRI) in the 1980s; both methodologies have been reviewed and/or endorsed by the NRC and have been used extensively to evaluate nuclear power plant sites in the central and eastern United States. The LLNL and EPRI methodologies also have been reviewed by the Senior Seismic Hazard Analysis Committee (SSHAC). Funded by the DOE, EPRI, and NRC, the SSHAC provided guidance on how to perform a valid PSHA. As a result of the significant developments in seismic hazard assessment methodology during the past decade, the NRC revised the geologic and seismic siting criteria in 10 CFR 100 for application to future nuclear power reactors. The new rule requires that uncertainty regarding the vibratory ground motion hazard be addressed through a PSHA or other appropriate analysis.

Two studies have direct application to the PSHA methodology presented in this topical report. The American Society of Civil Engineers (ASCE) Subcommittee on Dynamic Analysis and Design of High Level Nuclear Waste Repositories has developed draft guidelines for high-level nuclear waste repositories. In addition, EPRI sponsored an Earthquakes and Tectonics Project that developed a methodology for evaluating fault displacement through the proposed Yucca Mountain repository.

Two programs approved or developed by the NRC are particularly relevant to the regulatory context of this topical report and are also described in this appendix. These programs are the reevaluation of the seismic design bases for the Diablo Canyon Nuclear Power Plant in California, and the Individual Plant Examination of External Events (IPEEE) program for severe accident vulnerabilities, which is required for licensed nuclear power plants.

Table D-1. Elements of the Seismic Hazard Assessment Methodology in Other Studies

	Elements of the Seismic Hazard Analysis Methodology					
Studies	Probabilistic	Site Specific	Explicit Uncertainty Treatment	Fault Displacement Hazard	Vibratory Ground Motion	Reviewed or Endorsed by NRC
LLNL Methodology	x		x		x	x
EPRI Methodology	x		x		x	x
SSHAC Study	x	x	x		x	x
10 CFR 100 Subpart B	x	x	x		x	x
Draft ASCE Guideline	x	x	x	x	x	
EPRI Earthquakes & Tectonic Study	x	x	x	x		
Diablo Canyon Power Plant	x	x	x		x	x
IPEEE	x	x	x			x
Methodology in this Topical Report	x	x	x	x	x	x

D1.0 SEISMIC HAZARD METHODOLOGIES OF OTHER STUDIES

D1.1 LAWRENCE LIVERMORE NATIONAL LABORATORY METHODOLOGY

In 1982, the NRC commissioned LLNL to develop a PSHA methodology and apply it to nuclear power plant sites in the United States east of the Rocky Mountains. The methodology was to evaluate and incorporate the uncertainty in the seismic hazard, including that due to diversity in scientific understanding. In January 1989, LLNL published the results of its study (Bernreuter et al. 1989). The study results were reviewed by the NRC, a committee of the National Research Council, and numerous private consultants. The study results also were compared to those of a parallel study conducted by EPRI (1988). The comparison showed generally good agreements in the median values of the seismic hazard, but there were significant differences at some sites in the assessments of the uncertainties.

In 1989, the DOE asked LLNL to develop site-specific assessments of the seismic hazard at the Savannah River Site in South Carolina as part of the New Production Reactor project. LLNL performed a complete review of the PSHA methodology previously developed and of the data acquisition process. This review indicated that better estimates of the uncertainty and better mean hazard values could be obtained by updating the modeling of the seismicity and ground motion attenuation uncertainty. The NRC subsequently sponsored LLNL to update the seismic hazard analysis for nuclear power plant sites east of the Rocky Mountains.

For the updated LLNL study, a Seismicity Panel and a Ground Motion Panel were formed to provide seismicity and ground motion inputs. Individuals representing a broad range of backgrounds, current employment, and expertise provided the means of sampling the diversity of scientific understanding. Recognizing that an individual cannot be expected to be knowledgeable about all issues relevant to seismic activity and ground motion, state-of-knowledge and feedback workshops were used to reach a common understanding of relevant data and information. Individuals were subsequently elicited to provide values of various parameters and the related uncertainties.

D1.2 ELECTRIC POWER RESEARCH INSTITUTE METHODOLOGY

Between 1983 and 1989, EPRI developed a PSHA methodology for the evaluation of seismic hazard and its uncertainty and applied it to nuclear power plant sites in the eastern and central United States. This industry-sponsored study was conducted in parallel with the LLNL/NRC study. By quantifying uncertainties in input parameters and efficiently propagating these uncertainties through the hazard analysis, a complete representation of seismic hazard, its total uncertainty, and the various contributions to this uncertainty were obtained.

The principal features of the EPRI methodology are (Toro et al. 1989, pp. 1-19):

1) It utilizes earth-science assessments considering the postulated causes of earthquakes and available data and translates these interpretations into evaluations of seismic sources, seismicity parameters, and maximum magnitudes.

2) It makes efficient use of the earthquake catalog and utilizes rigorous statistical approaches to assess seismicity parameters.

3) It documents uncertainties in the input parameters and propagates these uncertainties through the analysis. The result is a complete characterization of the hazard, its uncertainty, and the importance of different contributors to that uncertainty.

In the EPRI study, uncertainty was captured by using as inputs the tectonic interpretations developed by six Earth Science teams. Each team was encouraged to provide alternative tectonic interpretations, recurrence relationships, and maximum magnitudes, to represent the team's evaluation of scientific and data uncertainty. The contributors to uncertainty were represented in a logic-tree format and a hazard curve was computed for each terminal node on the tree. The probability associated with a terminal node (and with the corresponding hazard curve) is the product of the probabilities associated with all intermediate branches in the path from the root to the terminal node. Calculations of hazard curves for terminal nodes followed five steps: evaluation of seismicity parameters, calculation of hazard due to individual sources, evaluations of source combinations to express complex tectonic interpretations, combinations of source hazards, and calculation of summary statistics and sensitivity results (Toro et al. 1989, p.1-24).

D1.3 THE SENIOR SEISMIC HAZARD ANALYSIS COMMITTEE STUDY

Given the significant developments in PSHA methodology in the parallel LLNL and EPRI efforts during the 1980s), DOE, NRC, and EPRI jointly funded a project to review the EPRI and LLNL methodologies as well as other studies, and to provide guidance on performance of a state-of-the-art PSHA. For this project, a committee of experts, the Senior Seismic Hazard Analysis Committee (SSHAC 1995), was formed to direct the review and formulate the recommendations.

The mean hazard curves produced in the LLNL and EPRI studies differed significantly at a number of sites. (The median curves differed much less.) The SSHAC determined that the differences between the mean curves were caused not only by differences in the interpreted hazard inputs, but also by differences in the procedures by which the two studies dealt with the inputs. More generally, the SSHAC concluded that many of the major potential pitfalls in executing a successful PSHA are procedural rather than technical. For this reason, the SSHAC report heavily emphasizes procedural guidance.

For the most part, the Yucca Mountain PSHA will follow the SSHAC's procedural guidelines. In particular, several different roles for experts will be carefully explained and followed. These roles include those of the *technical facilitator/integrator*, *proponents*, and *evaluators*. The objective of the experts' interactions on each technical issue will be a representation of the legitimate range of technically supportable interpretations among the expert teams participating in the study and the relative importance or credibility that should be given to the differing hypotheses across that range. The Yucca Mountain PSHA will also incorporate a *participatory peer review*, as recommended by the SSHAC.

D1.4 NEW 10 CFR PART 100, SUBPART B METHODOLOGY

The NRC's new rule on reactor seismic siting criteria, 10 CFR Part 100, Subpart B, supplants the criteria in 10 CFR 100 Appendix A for the seismic and geologic siting of future nuclear power plants. (Appendix A criteria still apply to existing plants.) The new rule requires that uncertainties in the determination of the Safe Shutdown Earthquake (SSE) be explicitly addressed through an appropriate analysis, such as a probabilistic seismic hazard analysis or suitable sensitivity analyses.

In the new rule, the NRC endeavored to separate siting criteria from design criteria and to remove detailed guidance from the regulation. Siting criteria have been retained, but design criteria not associated with site suitability or establishment of the SSE have been moved to 10 CFR 50, Appendix S, *Earthquake Engineering Criteria for Nuclear Power Plants*. Part 100, Appendix A contains both requirements and detailed guidance on how to satisfy the requirements. This fact created problems in the past because geoscience assessments require considerable latitude in judgment and because geoscience information and concepts have evolved rapidly. Therefore, the level of detail in the new Part 100, Subpart B is reduced considerably and Part 50, Appendix S does not mandate a particular approach to establishing the SSE. Instead, the NRC has provided guidance in Regulatory Guide 1.165 (NRC 1997), on methods acceptable to the NRC staff for seismic site characterization and for the determination of the SSE.

One of the challenges in using the results of a PSHA to establish an SSE is determining a magnitude and distance for the SSE that properly reflects the uncertainty in a site's seismic environment (seismic sources, earthquake recurrence rates, maximum events and seismic wave attenuation relationships). The approach adopted in Regulatory Guide 1.165 (NRC 1997) is to disaggregate the probabilistic analyses results to determine the magnitude and distance of the *controlling earthquakes*. The approach can be briefly summarized as follows: First, a full seismic hazard analysis is completed for the site; the hazard curve is then entered at a target probability of exceedance to determine a ground motion level. The target probability of exceedance is based on the median probabilities of exceeding the SSEs of a set of more recently licensed nuclear power plants. (For reasons discussed in the second seismic topical report (YMP 1997), the DOE plans to use a probability level that is based on the mean probabilities of exceeding the SSEs of existing nuclear power reactors, rather than the median probabilities.) The fractional contributions of earthquake sources in different magnitude and distance bins to the hazard at the target exceedance probability and in defined frequency ranges are then used as weights in determining mean magnitudes and distances, which are interpreted as the magnitudes and distances of the controlling earthquake or earthquakes. For Yucca Mountain, the DOE will investigate whether mean or modal values provide the most robust and physically meaningful controlling earthquake magnitudes and distances. Using the controlling earthquake parameters, the ground motion attenuation relationships found to be most appropriate for the sites are then employed to compute site-specific response spectra and time histories for use in seismic design.

D1.5 AMERICAN SOCIETY OF CIVIL ENGINEERS GUIDELINES AND RECOMMENDATIONS FOR EVALUATION AND SEISMIC DESIGN OF HIGH LEVEL NUCLEAR WASTE REPOSITORIES

The ASCE Subcommittee on Dynamic Analysis and Design of High Level Nuclear Waste Repositories has prepared a draft document, *Seismic and Dynamic Analysis and Design Considerations for High Level Nuclear Waste Repositories* (ASCE 1993). The document presents guidelines for developing detailed approaches and criteria for assessing and defining dynamic loads that must be considered in the design of a high level nuclear waste repository and for developing detailed design procedures and technical criteria to ensure that the expected loads can be safely accommodated. The ASCE document contains a critical review of the available literature related to methods of seismic hazard assessment and analysis and evaluation of facilities similar to those in a high level nuclear waste repository. It discusses the overall philosophy of the seismic design and evaluation process that it recommends for design. Generic guidelines are provided for determining design vibratory ground motion and design displacements associated with fault ruptures.

The ASCE document recommends the use of a performance goal-based design and evaluation approach. In this approach, one starts with an explicitly defined performance goal for the facility being designed and "works back" to a target annual probability of exceedance for design-basis vibratory ground motions and fault displacements. For repository seismic design, the performance goals would be not-to-exceed values for the annual probability of seismically induced failure of SSCs that are important to safety. The DOE regards the performance-goal-based approach as a rational and implementable approach to seismic design and has adopted it for general use within the DOE complex (DOE 1994). However, the performance-goal-based approach is not designed to demonstrate compliance with NRC repository-design requirements in 10 CFR 60, which will be the basis for NRC approval of the repository seismic design. For the repository, therefore, the DOE has developed (YMP 1997) target annual exceedance probabilities for vibratory ground motions and fault displacements that are based on and in compliance with the NRC's definition of *design basis events* in 10 CFR 60. In addition, the DOE has developed repository seismic design acceptance criteria that, where feasible, were derived from the accepted seismic designs of more recently licensed nuclear power reactors (YMP 1997). Thus, the ASCE recommendations for a performance-goal-based approach to repository seismic design are presented here for completeness only. In general, the DOE is following the ASCE recommendations regarding the seismic hazard assessment portion of the seismic design process.

D1.5.1 General Philosophical Guidance on Seismic Design

The facilities in a high level nuclear waste repository will have varied performance requirements, some of which are unconventional. Also, some components of the facility may have postclosure waste containment and isolation goals. The design of such facilities will require consideration of very low probability seismic events. Primarily because of unconventional functional or performance requirements and the unusually long life of some facilities, the ASCE document recommends use of a performance goal-based seismic design and evaluation process that is capable of utilizing state-of-the-practice probabilistic-deterministic (composite) seismic hazard analysis methodologies. The document states that the DOE should develop a seismic design methodology and criteria document for the GROA based on the general design procedures presented in two DOE documents, UCRL-15910 (Kennedy et al. 1990) and DOE-STD-1020-94 (DOE 1994) and in recent technical papers by Kennedy (1993) and Nelson et al. (1993). The application of these procedures in the repository design would necessitate the development of repository-specific criteria and methodology documents addressing the following issues:

- Compatibility between seismic performance goals and design criteria of SSCs in a repository
- Performance categorization of safety-related SSCs in a repository
- Acceptance criteria and methodology for designing SSCs for seismic fault ruptures.

Once these issues were addressed specifically for the repository, a direct correlation would be established between the mandated quantitative safety goals and the use of applicable design codes and standards for various categories of SSCs in the repository. The ASCE document maintains that for a repository, such a method would have advantages over the conventional design methods in which the linkage between safety goals and design codes is not explicitly established.

D1.5.2 General Guidance on Seismic Hazard Assessment

The ASCE document recommends that elements of both deterministic and probabilistic approaches be combined for the seismic design of a repository, using the framework provided by the Panel on Seismic Hazard Analysis of the National Research Council (1988). This combined approach consists of performing a probabilistic analysis that integrates over all seismic sources and earthquake magnitudes that significantly contribute to the site hazard, and then identifying a single earthquake magnitude-and-distance pair that represents the ground motion hazard, for analysis and design. Using a probabilistic method, seismic sources, maximum earthquakes, other source parameters, and the associated ground motions are modeled as uncertain values. This representation is guided by knowledge about the earthquake environment around the site. The result is a seismic hazard curve and its uncertainty. With this hazard and uncertainty description and established performance objectives for the facility, an acceptable probability of exceedance for the seismic design is established.

The calculated seismic hazard at the established target probability level is then numerically disaggregated to reveal the relative contributions of earthquakes in different magnitude and distance ranges to determine the earthquake magnitudes and distances that dominate the hazard, or to identify dominant seismic sources. For the dominant (or controlling) earthquakes, deterministic analyses are then performed to evaluate the ground motion at the site, considering possible values and ranges of stress drops, fault rupture properties, wave propagation properties, and site effects.

Usually, a single earthquake magnitude-and-distance pair can be identified such that the deterministically derived ground motion spectrum approximately corresponds to the target annual probability of exceedance over the range of structural frequencies of engineering interest. This single design basis earthquake can then be used for the construction of time histories and for detailed time-domain response calculations.

D1.5.3 Guidance on Vibratory Ground Motion Determination

The major guidelines for the development and use of the hybrid probabilistic-deterministic approach recommended in the ASCE document are as follows:

1) Probabilities of earthquake effects should be calculated using "deductive" methods in which the operative tectonic mechanisms, the seismic source characteristics, and the associated site ground motion are deduced from a combination of observation and theory. For low probability events, this method is considered superior to "historical" methods that replicate the history of earthquake effects at a site using either instrumental records or calculations of what must have been the ground motions at the site during past earthquakes.

2) In areas where identifiable active faults are seismic sources, these must be delineated and accommodated in the source definition. These faults should be described in three dimensions (i.e., non-vertical dips should be modeled).

3) To represent earthquake magnitude distributions, the use of the "characteristic magnitude" has been recommended for major faults producing large earthquakes. The maximum magnitude for each fault or source must be specified as part of the distribution; where there is uncertainty in the maximum magnitude, this should be expressed explicitly.

4) If a long and complete history of earthquakes associated with a fault is not available, seismic slip rates on the fault should be used for estimating rate of occurrence. Slip rates may be inferred from paleoseismic data, offsets of dateable geomorphic features, or geodetic data. Even when historical and instrumental data are available, long term slip rates should be used as a check.

5) The method of calculating probabilistic seismic hazard is non-controversial and, therefore, the emphasis should be on determining and documenting the appropriate input for the hazard analysis, and on evaluating alternative interpretations of available data and models to reduce uncertainty.

6) The distinction between uncertainty caused by randomness and uncertainty in model inputs should be recognized and maintained. The uncertainty in inputs should be reflected by multiple hazard curves and should not be included in the multiple integrals in the hazard calculations, as is done to account for randomness.

7) Multiple experts should be used to obtain a range of seismic hazard results that accurately represent the scientific uncertainty.

8) A complete probabilistic seismic hazard analysis should make preliminary interpretations of input using multiple experts for seismic source, seismicity, and ground motion evaluations. The sensitivity of the preliminary results to input should be examined. A second set of input interpretations should then be made, concentrating on those areas of input most critical to the hazard results.

D1.5.4 Guidance on Fault Rupture Hazard Assessment

Historically, the most common approach for mitigating potential fault rupture hazards for critical facilities (e.g., nuclear power plants) has been to avoid locations having active faults. However, for the following two reasons, the ASCE document cites this approach as too restrictive and inappropriate for a repository:

1) The failure modes of a repository resulting from a fault rupture are significantly different from those of a nuclear power plant. The consequences of fault rupture are relatively insignificant compared to those for a nuclear power plant. For surface facilities, the potential consequences are limited to localized spillage (e.g., from the structural failure of a hot cell).

2) The long-term objective of isolating the waste from reaching the environment will be achieved primarily through geologic barriers. Potential seismic events are small contributors to the overall risk. Hence, a geologically and hydrologically desirable site should not be rejected because of low-probability fault rupture concerns.

The ASCE draft guideline provides some general guidelines for characterizing fault rupture hazards:

1) Hazards due to surface fault rupture can be mitigated by: 1) avoiding fault traces (i.e., establishing appropriate setback distances from the fault); 2) demonstrating that the nature and amount of deformation can safely be accommodated in the design of the facility; and/or 3) demonstrating that the probability of occurrence and possible adverse effects are acceptably low.

2) It should be assumed that future displacements will occur on existing faults and that the likelihood of future displacements will be related to the frequency of the most recent displacements. The tectonic forces that cause faulting may be considered constant over the geologically short time period of concern for the repository system. The Quaternary period may be accepted as a reasonable geologic time period for determining fault displacement hazards.

3) A combination of probabilistic and deterministic approaches should be used for evaluating fault hazards. This will allow detailed fault displacement parameters to be specified through deterministic studies, while providing a probabilistic framework within which to choose the design values that meet the established performance goals.

4) Two levels of investigation should be performed to determine fault rupture hazard: 1) geologic and geophysical studies to identify faults in the site area and to evaluate their potential for rupture; and 2) detailed investigations of proposed locations for safety related facilities to provide site-specific data for determining fault rupture design parameters.

5) The faults that extend to within 20 km of safety-related facilities should be studied unless a reasonable and conservative case can be made to further restrict the area of investigation based on site-specific geology and/or on the lack of consequences important to safety.

6) Two basic approaches can be used to predict the occurrence of fault displacement:

    a) Earthquake Recurrence Approach: Distributions are assessed for location, size, and frequency of earthquakes, and the potential displacements associated with individual earthquakes are evaluated; this approach is particularly useful for regions where fault displacements associated with paleoseismic events have not been directly measured.

b) Fault Displacement Approach: The location, sense of slip, and likelihood of fault rupture are assessed directly based on paleoseismic data that indicate the amount and timing of past surface displacement events at a specific site.

D1.6 ELECTRIC POWER RESEARCH INSTITUTE YUCCA MOUNTAIN EARTHQUAKES AND TECTONICS PROJECT

As part of its High Level Waste containment performance assessment work, EPRI sponsored a study to demonstrate a methodology for evaluating fault displacement through the proposed Yucca Mountain repository (Coppersmith et al. 1993). The EPRI study used a probabilistic approach, included an explicit uncertainty treatment, and described approaches to assessing fault displacement hazard specifically for the Yucca Mountain site.

During Phase 1 of the EPRI project, a methodology was developed and applied to demonstrate the feasibility of performing a risk-based evaluation of the containment performance of underground high level waste repositories (McGuire 1992). The objectives of the EPRI project were to develop an integrated methodology for early assessment of the waste containment performance of a repository at Yucca Mountain and to identify and prioritize crucial issues. The containment performance assessment methodology incorporates the external phenomena that may affect a repository during its lifetime (e.g., earthquakes, volcanoes, climate change), geohydrologic characteristics of the site (e.g., rock mechanics, infiltration rates), and engineered systems (e.g., canister designs). The result of the containment performance assessment is the probability of various levels of radionuclide release during a 10,000-year containment period. The Phase 1 study created a structure that can effectively deal with the uncertainties of each input element; however, the implementation was limited to demonstration of the methodology.

During Phase 2 of the EPRI project, the containment performance assessment methodology was expanded to incorporate additional elements and refined to more fully characterize existing elements (including fault displacement hazard). The Earthquakes and Tectonics Project was a further refinement of Phase 2. The objectives of the Earthquakes and Tectonics Project were twofold: 1) to quantify the uncertainties associated with earthquake and tectonics interpretations for use in containment performance assessments; and 2) to demonstrate methods for accomplishing the input evaluations, particularly including uncertainty.

Seven geologists and seismologists having widely recognized professional competence and experience collecting and analyzing earth sciences data in the southern Great Basin provided input interpretations. The group was balanced to contain individuals with diverse areas of technical expertise and institutional/organizational backgrounds (e.g., from government agencies, academic institutions and private industry), and to represent broad diversity of scientific understanding (scientific uncertainty). The specialists in the group were specifically asked to act not as representatives of technical positions taken by their organizations, but rather to provide their own technical interpretations and uncertainties.

The study was centered around two workshops (held in November 1991 and March 1992). Discussions held during the workshops provided opportunities to define and prioritize the significant issues, and to present relevant data and interpretations. Presentations on various technical issues included discussions of studies currently in progress, and the unpublished data obtained in these studies. The discussions helped to assure a common understanding of the issues being addressed and of the relevant existing data sets. Decomposition of the assessment issues, or structuring the analysis into component assessments instead of one complex assessment, was a major objective of the discussions. A general framework that indicated a basic approach for probabilistic analysis of fault displacement was provided and discussed by the participants, but the specialists evolved their own approaches for their final interpretations.

Providing alternative interpretations or ranges of parameters to express uncertainty on the specialists' evaluations was an integral part of the study. The individual assessments by each specialist were used to calculate the probability of fault displacement through the repository site. These individual results were then combined across all specialists, assuming equal weights, to arrive at the aggregated annual probability of displacements of greater than either 1 cm or 10 cm within the repository. The probabilistic distributions associated with these assessments represent the aggregate uncertainties across all the specialists.

The effects of potential future events on the performance of the repository were assessed in terms of the frequency of waste canister failure caused by fault displacement. Examination of the hazard results indicates that the variability in the computed frequency of canister failure is due primarily to uncertainty in the frequency of events and uncertainty in the length of rupture within the repository when displacement occurs on one of the identified sources. Finally, it is recognized that these results are preliminary. The results of continuing site characterization will greatly expand the existing relevant data base and are expected to provide insights that will significantly reduce scientific uncertainty.

D2.0 SEISMIC HAZARD ASSESSMENT APPLICATIONS IN A REGULATORY FRAMEWORK

D2.1 DIABLO CANYON NUCLEAR POWER PLANT LONG-TERM SEISMIC PROGRAM

From 1985 to 1988, Pacific Gas and Electric Company (PG&E) performed a reevaluation of the seismic design bases for the Diablo Canyon Power Plant, located on the south-central California coast. A large group of geologists, geophysicists, and engineers was retained by PG&E to address the technical aspects of the reevaluation. The investigations conducted included studies of geology, seismology, geophysics, and neotectonics; seismic source characterizations; ground-motion modeling and characterizations; soil-structure interaction assessments; seismic hazard analyses; seismic fragility analyses; probabilistic risk analyses; and deterministic evaluations. Many of the investigations and analyses completed for the Long Term Seismic Program are similar to the studies needed to assess seismic hazards at Yucca Mountain. The methodology described in this topical report is consistent with the methodology followed for the Diablo Canyon seismic reevaluation.

The reevaluation of the seismic design bases was specified in the Unit 1 Full-Power Operating License, issued by the NRC on November 2, 1984. The Diablo Canyon seismic reevaluation involved a comprehensive, multi-disciplinary program of data acquisition, analysis, and interpretation to assess the four elements of the license condition, including tectonic models, seismic source characteristics, ground motions, and the adequacy of seismic margins at Diablo Canyon. The NRC provided technical peer review of the data and findings through periodic field reviews and workshops to continuously evaluate the scope, progress, and preliminary results of the program. Following submittal of the Final Report of the Diablo Canyon Long Term Seismic Program (PG&E 1988) to the NRC, PG&E conducted a series of follow-up investigations and analyses in response to the data requests and questions raised by the NRC (PG&E 1989a-f). The NRC staff's conclusion (Safety Evaluation Report Supplement No. 34, June 1991) that the seismic margins for the Diablo Canyon Power Plant are adequate and the license condition had been met were approved by the Advisory Committee on Reactor Safety on October 10, 1991.

D2.1.1 Seismic Source Characterization

A comprehensive neotectonic and paleoseismic investigation program was conducted to evaluate and characterize both known and previously unidentified faults in the central California coast site region. More than twenty specific seismic sources were characterized in terms of source geometry (e.g., length, dip, segmentation) and behavior (e.g., recency, slip rate, displacement per event), including the Los Osos, San Simeon, Hosgri, Wilmar Avenue, San Luis Bay, Pecho, Olson, and Oceano faults. To investigate these faults and associated Quaternary deformation, an extensive program of geologic mapping, drilling, and trenching was conducted. Marine and fluvial terraces were mapped in detail along 90 km of the south-central California coast and dated using numerical, calibrated, and correlated dating techniques. Sixty-six trenches and natural exposures (totaling more than 2500 linear meters) were logged and interpreted to an average depth of 5 meters; 240 boreholes (ranging in depth from about 4.5 to 36 meters) were drilled and logged. In addition, more than 300 water-well, oil-well, and borehole records were compiled and analyzed. Approximately 15,000 km of seismic reflection data were analyzed or reviewed, and 990 km of new high-resolution and deep-penetration seismic reflection surveys were commissioned, and the data processed and analyzed.

The magnitude of the earthquake used to determine the seismic bases for the Diablo Canyon Power Plant was reevaluated based on the voluminous geologic, seismologic, and geophysical information developed and analyzed. To arrive at estimates of maximum earthquake magnitude on the Hosgri and other faults, a detailed study of the segmentation of the faults was conducted, and the results derived from multiple maximum magnitude approaches were considered. High-confidence estimates of maximum earthquake magnitude on the Hosgri fault zone and other faults were obtained as a result of these analyses.

D2.1.2 Evaluation of Ground Motions

The objectives of the ground motion studies of the Diablo Canyon study were to reevaluate the ground motions at the plant site based on the source characterization of the region, with full consideration of site-specific ground motion effects, and to provide appropriate forms of input ground motion data, including acceleration time histories, attenuation relationships, site-specific response spectra, and spatial incoherence functions, for various engineering analyses.

The seismic design criteria of the Diablo Canyon Nuclear Power Plant are controlled by the occurrence of large earthquakes on the nearby Hosgri fault system. At this close range, the database of recorded strong ground motions close to large earthquakes is quite sparse. Also, at close range, strong ground motions are sensitive to detailed features of the source such as the orientation of the fault plane (strike and dip) and the sense of slip (rake), rupture directivity, slip heterogeneity (asperities), and the geometrical location of the site in relation to the fault. These considerations led to the use of both numerical and empirical approaches to the evaluation of ground motions for the seismic reevaluation.

The empirical part of the program began with the development of an up-to-date strong motion data base. These data were used to develop ground motion attenuation relationships using multiple regression. Because of the sparsity of recordings close to large strike-slip earthquakes, the attenuation relations first were developed for thrust faults. The attenuation relations for strike-slip faulting were then derived from empirical and numerical studies of the ratio of reverse to strike-slip ground motions. The magnitude dependence of the dispersion of the empirical attenuation relations was shown to be a statistically significant characteristic of strong ground motions.

Three approaches were used to evaluate the deterministic site-specific response spectrum at Diablo Canyon. The site-specific criteria included the maximum earthquake magnitude, the closest distance to the source, the style of faulting, and the local site conditions. The three approaches were based on attenuation relations from regression analysis, statistical analysis of near-source strong motion recordings, and numerical assessments using site-specific fault geometry.

A procedure for simulating accelerograms close to large earthquakes was developed to generate realistic ground motion time histories at the plant site (Wald et al. 1988). In this procedure, the rupture surface of the simulated earthquake is discretized into small elements. For each fault element, the source time function is represented by a sequence of empirical source functions that simulates the slip function on the fault. The source contribution is convolved with a simplified Green's function appropriate for the particular geometry between the fault element and the site. Finally, the responses from all the fault elements are summed to yield the simulated accelerogram.

This simulation procedure accounts for the deterministic, stochastic, and empirical aspects of source and wave propagation effects on ground motions. Gross aspects of fault rupture were evaluated deterministically. Stochastic aspects were used to account for the irregularities in rupture velocity and slip velocity, as well as to minimize potential artifacts due to fault discretization. Finally, details of the radiated source spectrum, including frequency-dependent radiation pattern and un-modeled wave propagation phenomena such as scattering, were included empirically by using actual recordings of small earthquakes as empirical source functions.

The simulation procedure was validated against actual strong motion recordings before it was applied to the plant site. The validation demonstrated that the ground motion characteristics generated by this procedure, with constraints imposed by known source and propagation path properties, closely match those of actual recordings (Wald et al. 1988). The variance between the response spectra of the recorded and simulated accelerograms was used to quantify the uncertainty associated with the simulation procedure in situations in which the earthquake source model is known. In applying the simulation procedure to a specific site, there is the additional uncertainty (parametric uncertainty) associated with uncertainty in the source parameters of future earthquakes. By combining this parametric uncertainty with the modeling uncertainty, quantitative assessments of the overall uncertainty in the ground motions simulated at the site are obtained (Abrahamson et al. 1990). This is an important advance in numerical ground motion evaluations because it allows assessments to be made of the 84th percentile ground motions and permits the use of numerical ground motion evaluations in probabilistic seismic hazard studies.

As discussed in Appendix B, theoretical numerical approaches will be used in combination with empirical approaches to evaluate ground motions at Yucca Mountain. Experience at Diablo Canyon demonstrates how such numerical approaches can be successfully applied in a regulatory environment to provide information on near-fault ground motions.

D2.2 GUIDANCE FROM THE NRC FOR THE INDIVIDUAL PLANT EXAMINATION OF EXTERNAL EVENTS

Seismic events had to be considered in the NRC-mandated IPEEE to identify severe accident vulnerabilities. NUREG-1407 (NRC 1991) defines the acceptable methods to identify potential seismic vulnerabilities for the purpose of performing an IPEEE. The acceptable methods are a seismic probabilistic risk assessment or a seismic margins methodology. To perform a risk assessment for sites in the United States east of the Rocky Mountains, NUREG-1407 recommends the use of methodologies developed by LLNL and EPRI (see Sections D1.1-D1.3); for plants in the western United States, licensees are instructed to conduct their own studies. A seismic margins methodology is a deterministic analysis, and must be performed in accordance with standard practices.

For the Palo Verde Nuclear Generating Station, located near Wintersburg, Arizona, an investigation of seismic hazard at the site was conducted (Risk Engineering, Inc. 1993) and the results of this investigation were used to guide decisions regarding levels of seismic evaluation for the IPEEE program. Although the LLNL and EPRI seismic hazard analyses for the central and eastern United States could not be applied directly to the Palo Verde site, the methodologies of these studies were followed so that comparisons could be made between the hazard at the site and that at other nuclear power plant sites in the country. Multiple seismic source interpretations were considered to characterize uncertainty in the seismic hazard. Five teams of earth science experts (from J. M. Montgomery Consulting Engineers, Bechtel Corporation, Dames & Moore, Woodward-Clyde Consultants, and Geomatrix Consultants) identified and characterized the potential sources of seismicity. Ground motion attenuation functions were derived by multiple experts (Risk Engineering Inc. personnel, Dr. N. A. Abrahamson, and Dr. K. W. Campbell). Seismic hazard results were calculated and explicit hazard curves were produced for combinations of parameters. The uncertainties in the hazard derive from uncertainties in the input assumptions provided by the multiple experts regarding seismic sources, seismicity parameters, and ground motion attenuation equations.

APPENDIX E

REFERENCES

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REFERENCES

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APPENDIX F

ACRONYMS AND ABBREVIATIONS

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ACRONYMS AND ABBREVIATIONS

ASCE	American Society of Civil Engineers
CFR	Code of Federal Regulations
DOE	Department of Energy
EPRI	Electric Power Research Institute
GPS	Global Positioning Satellite
GROA	Geologic Repository Operations Area
IPEEE	Individual Plant Examination of External Events
LA	License Application
LLNL	Lawrence Livermore National Laboratory
NRC	Nuclear Regulatory Commission
NTS	Nevada Test Site
PG&E	Pacific Gas and Electric Company
PSHA	Probabilistic Seismic Hazard Analysis
SCP	Site Characterization Plan
SSHAC	Senior Seismic Hazard Analysis Committee
SSC	Structures, Systems, and Components
SSE	Safe Shutdown Earthquake
UNE	Underground Nuclear Explosion