March 31, 1995

MEMORANDUM TO: Goutam Bagchi, Chief
Civil Engineering and Geosciences Branch
Division of Engineering
Office of Nuclear Reactor Regulation

FROM: Michael Bell, Chief
Engineering and Geosciences Branch
Division of Waste Management
Office of Nuclear Material Safety
and Safeguards

SUBJECT: REQUEST FOR TOPICAL REPORT "METHODOLOGY TO ASSESS FAULT DISPLACEMENT AND VIBRATORY GROUND MOTION HAZARDS AT YUCCA MOUNTAIN" REVIEW.

We would like to have one of your staff review the attached topical report (TR) submitted by the Department of Energy (DOE), Yucca Mountain Project, to the NRC Division of Waste Management. This TR addresses the methodology DOE intends to use for determining the pre- and post-closure seismic parameters needed for the design of high-level waste repository facilities.

This TR is the first of three TRs that together will describe the seismic design process DOE plans to implement for the Yucca Mountain Geological Repository area.

We are sending this report for your review and comments to ensure that the methodology used by DOE is consistent with the methodology approved by the NRC for seismic design of other nuclear facilities.

We would appreciate receiving your comments by May 1, 1995. If you have any questions, please contact Dr. A. Ibrahim at 415-6651.

Attachment

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March 31, 1995

MEMORANDUM TO: Andrew Murphy, Chief
Structural and Geological Engineering Branch
Division of Engineering Technology
Office of Research

FROM: Michael Bell, Chief
Engineering and Geosciences Branch /s/
Division of Waste Management
Office of Nuclear Material Safety
and Safeguards

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March , 1995

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PAHB/DWM/NMSS

FROM: Michael Bell, Chief
ENGB/DWM/NMSS

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FROM: Michael Bell, Chief /s/
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This TR is the first of three TRs that together will describe the seismic design process DOE plans to implement for the Yucca Mountain Geological Repository area. It describes the methodology that DOE will use to develop seismic hazard inputs to its total system performance assessment, and, therefore, may be of interest to your staff.

We would appreciate receiving your comments by May 1, 1995. If you have any questions, please contact Dr. A. Ibrahim at 415-6651.

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YMP/TR-002-N

U.S. DEPARTMENT OF ENERGY

OCRWM

YUCCA MOUNTAIN

YUCCA MOUNTAIN SITE CHARACTERIZATION PROJECT

TOPICAL REPORT

METHODOLOGY TO ASSESS FAULT DISPLACEMENT AND VIBRATORY GROUND MOTION HAZARDS AT YUCCA MOUNTAIN

102

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Yucca Mountain Site Characterization Project

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

June 1994

U.S. Department of Energy
Office of Civilian Radioactive Waste Management
Las Vegas, NV 89109

Topical Report YMP/TR-002-NP:
Methodology to Assess Fault Displacement and Vibratory Ground Motion Hazards at Yucca Mountain

Robert M. Nelson, Jr., Acting Project Manager
Yucca Mountain Site Characterization Project

6/20/94
Date

Richard E. Spence, Director
Yucca Mountain Quality Assurance Division

6/23/94
Date

ABSTRACT

This topical report documents the methodology that will be used to assess fault displacement and vibratory ground motion hazards at Yucca Mountain. This methodology, along with that to be described in two subsequent topical reports, defines the process that will be used in the seismic design of the Geologic Repository Operations Area at the potential repository site. In addition, the methodology of this report will be used in the total system performance assessment of long-term waste isolation at the site. In the latter context, this methodology will be used in the evaluation of potentially adverse conditions that relate to ground shaking hazards and fault displacement hazards.

A five-step process is described for the assessment of the vibratory ground motion hazard. First, seismic sources are evaluated. Second, the maximum magnitude and rate of occurrence of each source are described. Third, ground motion/attenuation relations are developed for the site region. Fourth, a probabilistic hazard curve for vibratory ground motion is generated. Finally, multiple seismic hazard curves are developed to incorporate the various uncertainties documented in the analysis. A similar process is described 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 recurrence 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 performance goal-based 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.

METHODOLOGY TO ASSESS FAULT DISPLACEMENT AND VIBRATORY GROUND MOTION HAZARDS AT YUCCA MOUNTAIN

TABLE OF CONTENTS

1.0 INTRODUCTION 1
1.1 OBJECTIVE AND SCOPE 1
1.2 REGULATORY REQUIREMENTS 1
1.3 BACKGROUND AND MOTIVATION 3
1.4 OVERVIEW OF THE GROA SEISMIC DESIGN PROCESS 4
1.5 RECENT EXPERIENCE 6
1.6 ORGANIZATION OF THE REPORT 7

2.0 METHODOLOGY TO ASSESS VIBRATORY GROUND MOTION AND FAULT DISPLACEMENT HAZARDS 9
2.1 DESIRED ATTRIBUTES OF THE SEISMIC HAZARD METHODOLOGY 9
2.2 FRAMEWORK OF THE METHODOLOGY 11
2.3 DESCRIPTION OF THE METHODOLOGY 12

2.3.1 Assessment of Vibratory Ground Motion Hazard 12
2.3.1.1 Evaluation of Seismic Sources 13
2.3.1.2 Evaluation of Earthquake Recurrence and Maximum Magnitude 13
2.3.1.3 Evaluation of Ground Motion/Attenuation Functions 14
2.3.1.4 Probabilistic Hazard Calculations for Vibratory Ground Motion 14
2.3.1.5 Evaluation and Propagation of Uncertainty 15

2.3.2 Assessment of Fault Displacement Hazard 16
2.3.2.1 Evaluation of Seismic Sources 16
2.3.2.2 Evaluation of Earthquake Recurrence and Maximum Magnitude 17
2.3.2.3 Evaluation of Fault Displacement Within the GROA 17
2.3.2.4 Probabilistic Hazard Calculations for Fault Displacement 17
2.3.2.5 Evaluation and Propagation of Uncertainty 17

2.4 DISCUSSION 18
2.5 SUMMARY 18

APPENDIX A EVALUATION AND CHARACTERIZATION OF SEISMIC SOURCES FOR YUCCA MOUNTAIN A-1

A1.0 INTRODUCTION A-2

METHODOLOGY TO ASSESS FAULT DISPLACEMENT
AND VIBRATORY GROUND MOTION
HAZARDS AT YUCCA MOUNTAIN

TABLE OF CONTENTS

A2.0 SEISMIC SOURCE ASSESSMENT: SOURCE RECOGNITION, LOCATION, AND GEOMETRY . A-2
A2.1 FAULT-SPECIFIC SEISMIC SOURCES A-3

A2.1.1 Fault Activity A-3
A2.1.2 Fault Geometry A-4
A2.1.3 Sense of Fault Slip A-5

A2.2 SEISMIC SOURCE ZONES A-5
A2.3 BURIED AND HIDDEN SOURCES A-5
A2.4 SUMMARY OF APPROACH TO SEISMIC SOURCE ASSESSMENT AND RELEVANT DATA A-6

A3.0 MAXIMUM EARTHQUAKE MAGNITUDE EVALUATION A-7
A3.1 METHODS BASED ON FAULT RUPTURE DIMENSIONS A-7

A3.1.1 Seismic Moment and Moment Magnitude Relationships A-7
A3.1.2 Fault Segmentation Evaluations A-8
A3.1.3 Fault Rupture Length Relationships A-9
A3.1.4 Fault Rupture Area Relationships A-9
A3.1.5 Fault Rupture Displacement Relationships A-10

A3.2 METHODS BASED ON HISTORICAL SEISMICITY A-10
A3.3 SUMMARY OF APPROACH TO EVALUATE MAXIMUM EARTHQUAKE MAGNITUDE AND RELEVANT DATA A-10

A4.0 EARTHQUAKE RECURRENCE EVALUATION A-11
A4.1 HISTORICAL SEISMICITY DATA A-11
A4.2 PALEOSEISMIC RECURRENCE DATA A-12
A4.3 FAULT SLIP RATE DATA A-12
A4.4 OTHER RECURRENCE ISSUES A-13
A4.5 SUMMARY OF APPROACH TO EARTHQUAKE RECURRENCE EVALUATION AND RELEVANT DATA A-14

A5.0 UNDERGROUND NUCLEAR EXPLOSIONS A-14
A5.1 PRIMARY SEISMIC SOURCE A-15
A5.2 SECONDARY SEISMIC SOURCES A-15

A6.0 VOLCANIC EARTHQUAKES A-16

APPENDIX B

EVALUATION AND CHARACTERIZATION OF VIBRATORY
GROUND MOTIONS AT YUCCA MOUNTAIN B-1

METHODOLOGY TO ASSESS FAULT DISPLACEMENT AND VIBRATORY GROUND MOTION HAZARDS AT YUCCA MOUNTAIN

TABLE OF CONTENTS

B1.0 INTRODUCTION B-2

B2.0 EVALUATION OF SOURCE AND PATH EFFECTS ON GROUND MOTIONS B-2
- B2.1 DATA NEEDS AND AVAILABLE DATA B-2
- B2.2 GROUND MOTION RELATIONSHIPS FOR SEISMIC HAZARD ASSESSMENT B-3
- B2.3 ASSESSING VARIABILITY IN GROUND MOTION VALUES B-5
- B2.4 SPECIFIC ASPECTS OF GROUND MOTION EVALUATION B-6
  - B2.4.1 Effect of Local Geology B-6
  - B2.4.2 Effect of Style of Faulting B-6
  - B2.4.3 Effect of Rupture Directivity on Near-Fault Ground Motions B-7
  - B2.4.4 Vertical Ground Motions B-7
- B2.5 SUMMARY OF APPROACH TO GROUND MOTION EVALUATION B-7

B3.0 EVALUATION OF SITE EFFECTS ON GROUND MOTION B-8
- B3.1 DATA NEEDS AND AVAILABLE DATA B-8
- B3.2 SUMMARY OF SITE RESPONSE RESULTS REQUIRED FOR SEISMIC HAZARD ASSESSMENT B-8
- B3.3 ASSESSING VARIABILITY IN SITE RESPONSE B-9
- B3.4 SPECIFIC ASPECTS OF THE SITE RESPONSE EVALUATION B-9
  - B3.4.1 Effects of Shallow Velocity Gradient B-9
  - B3.4.2 Amplitude Variation Due to Depth of Burial B-10
  - B3.4.3 Effect of Nonlinear Soil Behavior B-10
  - B3.4.4 Effects of Topography B-10
- B3.5 SUMMARY OF APPROACH FOR EVALUATING SITE RESPONSE B-11

APPENDIX C SEISMIC HAZARD ASSESSMENT PROCEDURES C-1

C1.0 INTRODUCTION C-2

C2.0 VIBRATORY GROUND MOTION HAZARD ASSESSMENT C-2
- C2.1 STEP 1: SEISMIC SOURCE INPUTS C-2
- C2.2 STEP 2: EARTHQUAKE RECURRENCE C-3
- C2.3 STEP 3: GROUND MOTION ATTENUATION RELATIONSHIPS C-3
- C2.4 STEP 4: VIBRATORY GROUND MOTION HAZARD CURVE C-4

C3.0 FAULT DISPLACEMENT HAZARD ASSESSMENT C-5
- C3.1 STEP 1: SEISMIC SOURCE INPUTS C-5
- C3.2 STEP 2: EARTHQUAKE RECURRENCE C-6

METHODOLOGY TO ASSESS FAULT DISPLACEMENT
AND VIBRATORY GROUND MOTION
HAZARDS AT YUCCA MOUNTAIN

TABLE OF CONTENTS

C3.3 STEP 3: FAULT DISPLACEMENT RELATIONSHIPS C-6
C3.4 STEP 4: FAULT DISPLACEMENT HAZARD CURVE C-7

C4.0 VARIABILITY AND TREATMENT OF UNCERTAINTY C-7
C4.1 REPRESENTATION OF THE UNCERTAIN PARAMETERS C-7

C4.1.1 Variability in Seismic Source Inputs C-7
C4.1.2 Variability in Earthquake Recurrence and Maximum Magnitude C-7
C4.1.3 Variability in Ground Motion Attenuation or Fault Displacement C-8

C4.2 PROPAGATION OF UNCERTAINTIES C-8
C4.2.1 The Logic Tree Approach C-8
C4.2.2 The Monte Carlo Approach C-8

C5.0 SENSITIVITY ANALYSIS, DISAGGREGATION AND DOCUMENTATION C-9
C5.1 SENSITIVITY ANALYSIS AND DISAGGREGATION C-9
C5.2 DOCUMENTATION C-9

APPENDIX D DESIGN CONTEXT AND THE USE OF SEISMIC HAZARD ASSESSMENT RESULTS D-1

D1.0 INTRODUCTION D-2

D2.0 BACKGROUND AND EVOLUTION OF PERFORMANCE GOAL-BASED SEISMIC DESIGN METHOD D-2

D3.0 AN OUTLINE OF THE DOE'S PERFORMANCE GOAL-BASED DESIGN METHOD D-3

APPENDIX E HISTORICAL CONTEXT OF THE PROPOSED SEISMIC HAZARD ASSESSMENT METHODOLOGY E-1

E1.0 SEISMIC HAZARD METHODOLOGIES OF OTHER STUDIES E-2
E1.1 LAWRENCE LIVERMORE NATIONAL LABORATORY METHODOLOGY E-2
E1.2 ELECTRIC POWER RESEARCH INSTITUTE METHODOLOGY E-3
E1.3 THE SENIOR SEISMIC HAZARD ANALYSIS COMMITTEE (SSHAC) STUDY E-4
E1.4 PROPOSED 10 CFR PART 100, APPENDIX B METHODOLOGY E-4
E1.5 ANS COMMENTS ON PROPOSED 10 CFR PART 100, APPENDIX B METHODOLOGY . . E-5
E1.6 ASCE GUIDELINES AND RECOMMENDATIONS FOR EVALUATION AND SEISMIC DESIGN OF HIGH LEVEL NUCLEAR WASTE REPOSITORIES E-6

E1.6.1 General Philosophical Guidance on Seismic Design E-6
E1.6.2 General Guidance on Seismic Hazard Assessment E-7

METHODOLOGY TO ASSESS FAULT DISPLACEMENT
AND VIBRATORY GROUND MOTION
HAZARDS AT YUCCA MOUNTAIN

TABLE OF CONTENTS

E1.6.3 Guidance on Vibratory Ground Motion Determination E-7
E1.6.4 Guidance on Fault Rupture Hazard Assessment E-8

E1.7 EPRI YUCCA MOUNTAIN EARTHQUAKES AND TECTONICS PROJECT E-9

E2.0 SEISMIC HAZARD ASSESSMENT APPLICATIONS IN A REGULATORY FRAMEWORK E-11
E2.1 DIABLO CANYON NUCLEAR POWER PLANT LONG-TERM SEISMIC PROGRAM . . . E-11

E2.1.1 Seismic Source Characterization E-11
E2.1.2 Evaluation of Ground Motions E-12

E2.2 THE INDIVIDUAL PLANT EXAMINATION OF EXTERNAL EVENTS (IPEEE)
GUIDANCE FROM THE NRC E-13

APPENDIX F REFERENCES F-1

METHODOLOGY TO ASSESS FAULT DISPLACEMENT AND VIBRATORY GROUND MOTION HAZARDS AT YUCCA MOUNTAIN

LIST OF FIGURES

1 Basic Elements of the Seismic Hazards Program 8
2 Components of the Methodology to Assess Seismic Hazards Within the Framework of the Overall Seismic Hazards Program 19
3 Basic Steps of the Methodology to Assess Vibratory Ground Motion Hazard 20
C-1 Basic Steps of the Methodology to Assess Vibratory Ground Motion Hazard C-12
C-2 Example Logic Tree Showing Uncertainties in Source Geometry, Fault Size, and Maximum Magnitude for a Given Fault Source n C-13
C-3 Schematic Representation of the Monte Carlo Method of Propagating Uncertainties C-14

METHODOLOGY TO ASSESS FAULT DISPLACEMENT
AND VIBRATORY GROUND MOTION
HAZARDS AT YUCCA MOUNTAIN

LIST OF TABLES

C-1 Data Used to Identify Alternative Seismic Sources and Characterize Uncertainty C-10
C-2 Data Used to Evaluate Seismic Recurrences Rates and Their Uncertainties C-10
C-3 Data Used to Evaluate Maximum Magnitudes and Their Uncertainties C-10
C-4 Data Used to Evaluate Ground Motions and Their Uncertainties C-11
C-5 Data Used to Evaluate Fault Displacements and Their Uncertainties C-11
D-1 Structure, System, and Component (SSC) Seismic Performance Goals for Various Performance Categories in Typical DOE Facilities D-7
D-2 Seismic Performance Goals and Recommended Seismic Hazard Probabilities for SSCs in Typical DOE Facilities D-7
E-1 Elements of the Seismic Hazard Assessment Methodology in Other Studies E-14

METHODOLOGY TO ASSESS FAULT DISPLACEMENT AND VIBRATORY GROUND MOTION HAZARDS AT YUCCA MOUNTAIN

LIST OF ACRONYMS

ACI	American Concrete Institute
ANS	American Nuclear Society
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
CEUS	Central and Eastern United States
CFR	Code of Federal Regulations
DB	Design Basis
DBE	Design Basis Earthquake
DOE	Department of Energy
EBS	Engineered Barrier System
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
GROA	Geologic Repository Operations Area
HLW	High Level Waste
IPEEE	Individual Plant Examination of External Events
LA	License Application
LLNL	Lawrence Livermore National Laboratory
LTSP	Long Term Seismic Program
MCE	Maximum Credible Earthquake
NPH	Natural Phenomena Hazards
NPR	New Production Reactor
NRC	Nuclear Regulatory Commission
NTS	Nevada Test Site
OBE	Operating Basis Earthquake
PE	Probability of Exceedance
PG&E	Pacific Gas and Electric Company
PGA	Peak Ground Acceleration
PRA	Probabilistic Risk Assessment
PSHA	Probabilistic Seismic Hazard Assessment
PVNGS	Palo Verde Nuclear Generating Station
SAR	Safety Analysis Report
SCP	Site Characterization Plan
SEN	Secretary of Energy Notice
SHA	Seismic Hazard Assessment
SMM	Seismic Margins Methodology
SRS	Savannah River Site
SSHAC	Senior Seismic Hazard Analysis Committee
SSC	Structures, Systems, and Components
SSE	Safe Shutdown Earthquake
UBC	Uniform Building Code
UNE	Underground Nuclear Explosion

1.0 INTRODUCTION

Title 10 of the Code of Federal Regulations, Part 60 (10 CFR Part 60) requires that natural phenomena do 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 pre-closure period must be maintained, features that might affect GROA design and performance must be described and assessed, and potentially adverse conditions must be adequately investigated and evaluated. As part of 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 (SCP) (DOE, 1988). Subsequently, the DOE has updated its approach to incorporate scientific and technical advances in the assessment of seismic hazards and in seismic design. This Topical Report presents the DOE's proposed methodology to assess seismic hazards for review and acceptance by the Nuclear Regulatory Commission (NRC) staff.

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. When implemented, the methodology will provide results to support seismic design of the proposed high level nuclear waste repository at Yucca Mountain, Nevada. 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 some of the potentially adverse conditions. By submitting this Topical Report for formal review by the NRC staff it is the DOE's objective to obtain early approval of its methodology to assess seismic hazards.

This Topical Report is the first of three topical reports that together will describe the seismic design process the DOE plans to implement for the Yucca Mountain GROA (Figure 1). The current report contains a description of the methodology to assess seismic hazards. Two subsequent topical reports will describe the remaining steps of the proposed seismic design process. One will address the determination of appropriate seismic hazard levels for design. In accomplishing this objective, the report will establish seismic safety categories for GROA SSCs, associated seismic safety performance goals and risk reduction factors, and seismic design criteria to achieve the performance goals and risk reduction. The other subsequent report will describe the development of seismic design inputs (e.g., seismic response spectra, time histories and fault displacement levels) for the appropriate seismic hazard levels.

1.2 REGULATORY REQUIREMENTS

The applicable NRC regulatory requirements for the disposal of high level radioactive wastes in geologic repositories are found in Title 10, Code of Federal Regulations, Part 60 (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 (SAR) accompanying the LA, including the geologic repository operations area (GROA) design and performance. Seismic-related hazards are among the many features that must be assessed in the SAR 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 noted in the presentation contained 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 GROA[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 its Site Characterization Plan (DOE, 1988). In their review of that approach, the NRC staff identified a number of items for which they felt additional development and clarification were necessary (NRC, 1989). In addition, since publication of the SCP the NRC staff has developed guidance on investigations needed to identify and evaluate faults that are significant in assessing seismic hazards (McConnell et al., 1992). 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 (see Appendix E). These improved methods have now gained professional and regulatory acceptance. Hence, based on feedback from the NRC staff and on technical progress in the fields of seismic hazard assessment and seismic design, the DOE has at this time reevaluated its approach to assessing vibratory ground motion and fault displacement hazards and to determining loads appropriate for seismic design of the Yucca Mountain GROA.

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 and the occurrence of earthquakes, including the frequency of occurrence. The methodology explicitly incorporates input variability (e.g., randomness and diversity of data interpretation)[3]. It thereby allows uncertainties in the basic evaluations of seismic sources and other input parameters to be quantified and displayed as uncertainty in the final hazard results. The probabilistic evaluation provides a distribution of hazard curves showing the annual probability with which various levels of ground motion or fault displacement are exceeded. These results are needed input for assessment of long-term repository performance with respect to waste

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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 Site Characterization Plan (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 Randomness and diversity of interpretation (uncertainty) are together usually referred to as variability. Recently, in the interest of achieving greater clarity in usage, the terms "aleatoric uncertainty" and "epistemic uncertainty" have been proposed for randomness and diversity of interpretations, respectively. Together, these terms signify total uncertainty, or just uncertainty. Although these are higher order terms that more precisely characterize the components of uncertainty, they are not yet widely used in describing seismic hazard methodology. We will therefore use the more common terms randomness and uncertainty to characterize the components of variability.

containment and isolation. They also provide a strong, rational basis for determining seismic design loads within the framework of a risk-consistent seismic design process. The methodology relies upon an extensive program of field investigations, seismic monitoring, and analyses to provide the basic data on which evaluations of inputs to the seismic hazards assessment must be based. The methodology adopts generally established and accepted practice in the scientific and engineering communities for seismic hazards assessment supporting seismic design of critical facilities.

The results of the seismic hazards assessment will be used in the seismic design process and to evaluate the post-closure waste containment and isolation performance of the repository. Probabilistic hazard curves are required to implement a risk-based seismic design process and to allow the conservatism of the design process to be directly quantified by linking seismic hazard with seismic design criteria. Both the pre-closure and post-closure time frames are of interest to seismic designers. For the pre-closure period (about 100 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 post-closure 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 anticipated probabilistic nature of the Environmental Protection Agency (EPA) 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 post-closure 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).

1.4 OVERVIEW OF THE GROA SEISMIC DESIGN PROCESS

The seismic design process consists of three steps. Assessment of seismic hazards forms the first of these three steps (Figure 1). In the second step, seismic safety performance categories, associated performance goals and risk reduction factors, and seismic design criteria to meet the performance goals and risk reduction, are determined for GROA SSCs. From this information seismic hazard levels appropriate for design can be determined. In the third step, seismic design inputs (e.g., ground motion response spectra and time histories; fault displacement and exclusion zones) are developed for the established hazard levels. 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 in the following paragraphs.

The seismic design process provides assurance of no unacceptable risk to society from any adverse consequences caused by vibratory ground motion or fault displacement. Adverse consequences may be related to the unacceptable performance of SSCs that must perform as designed to protect public safety, the environment, or to assure the facility's mission, or that result in unacceptable property loss. Thus, seismic design must provide reasonable assurance that the likelihood of such failures or consequences is

[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 EPA standard is in the process of revision, it is anticipated that the new standard will also be probabilistic in nature. Of course, DOE will re-assess its methodologies when the EPA final standards applicable to Yucca Mountain are issued to ensure that its assumptions remain valid or, where necessary, to make appropriate corrections.

acceptably low. Quantitatively, reasonable assurance can be expressed as an annual probability of unacceptable SSC performance. Such probabilities are now termed "performance goals" by the engineering community[5], and this approach to seismic design is referred to as the performance goal-based seismic design process (e.g., Kennedy, 1992). The significant advance inherent in the performance goal-based seismic design process is that it links seismic hazard, seismic design requirements and acceptance criteria, and SSC safety significance into a unified process. The process also explicitly incorporates both uncertainties associated with the assessment of internal and external events that determine the magnitude of the seismic design loads and those associated with determining SSC fragilities or capacities.

In the performance goal-based seismic design process, the seismic design requirements and acceptance criteria for any particular SSC depend on the safety consequences of its failure. SSCs are categorized according to their safety significance, and numerical performance goals—probabilities of unacceptable performance that should not be exceeded—are established for each category.

The seismic design is deterministic and relies on evaluation and acceptance criteria that are based on national consensus standards and experience in regulating seismic design of nuclear facilities. The criteria are developed to provide greater risk reduction for safety categories for which the adverse consequences of failure are greater. Those SSC categories classified as more significant to safety will be designed to more stringent requirements and criteria. SSCs that fall into the category "not significant to safety," on the other hand, can be designed to less stringent criteria consistent with national consensus codes for ordinary structures. By using a graded approach, risk-consistent seismic designs are established for each safety category according to the category's importance to safety. This graded approach results in a risk-consistent seismic design across all SSCs.

An appropriately conservative seismic hazard level for design of an SSC safety category is given by the product of the seismic safety performance goal and the risk reduction factor for that category. Such a hazard level would form the basis for development of seismic design inputs such as peak acceleration or the amount of fault displacement. For example, if the goal for a given category is that unacceptable behavior will not occur with an annual probability exceeding 10^{-5}, and the risk reduction achieved by the seismic design criteria for that category is a factor of 20, then the appropriate seismic hazard level for design is 20 times 10^{-5} (or 2×10^{-4}). The results of the DOE methodology to assess vibratory ground motion and fault displacement hazards are in the probabilistic format required for use in the seismic design process based on seismic safety performance goals. It is through this process that the DOE will demonstrate the seismic safety of the Yucca Mountain GROA. Seismic safety performance categories, their associated quantitative seismic safety performance goals, risk reduction factors achieved by the seismic design criteria, and consequent seismic hazard levels for design are subjects that will be covered in detail in a subsequent topical report.

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5 The terms "performance goal" and "seismic safety performance goal", as used in this Topical Report, refer to the annual probability of unacceptable SSC performance that should not be exceeded for a given design performance category. The design process incorporating this concept is referred to as "performance goal-based design." These terms, which are commonly used within the engineering community in the context of design for natural phenomena hazards, are differently defined from and should not be confused with similar terms such as the "performance objectives" of 10 CFR Part 60, the "performance allocation" or "performance goals" discussed in the Site Characterization Plan, and the "performance assessment" process used to evaluate long-term waste containment and isolation.

1.5 RECENT EXPERIENCE

In developing the DOE methodology, recent experience in seismic hazards assessment has been taken into account. While licensing a geologic repository for high level nuclear waste has not previously been attempted, the experience gained in probabilistically assessing vibratory ground motion hazard at existing nuclear power plants over the past decade can be appropriately applied to this new task. Licensing proceedings for nuclear power plants highlighted the limitations of the deterministic approach that was used to assess seismic hazard in those cases. These limitations have led the NRC to initiate a process to revise Appendix A to 10 CFR Part 100. A draft version of this revision incorporates probabilistic procedures along with deterministic ones (see Appendix E).

One limitation of the traditional deterministic approach is its failure to incorporate complete information on frequency of occurrence[6]. To make decisions based on risk, frequency of occurrence is a necessary piece of information, because risk is directly related to likelihood of 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. In contrast to deterministic methods, the use of a probabilistic hazard level provides a clear and direct link between permissible risk and facility design criteria. The probabilistic approach also facilitates the assessment of hazard levels appropriate for different time periods, such as the pre- and post-closure periods identified in 10 CFR Part 60.

Traditional deterministic approaches also are limited in their ability to treat input variability. Typically, randomness and diversity in data interpretation (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. Probabilistic methods explicitly incorporate variability in input. This variability translates directly into uncertainty in the assessed hazard results and is expressed as distribution fractiles or confidence levels. Thus the probabilistic method supplies a more complete description of the hazard.

By integrating the hazard from all seismic sources, the probabilistic method also allows the significance of 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 as required by NUREG-1451 (Section 3.1.3 (1) (b) in McConnell et al., 1992).

Finally, although probabilistic methodologies have been applied primarily to the assessment of hazard from vibratory ground motion, their advantages apply equally to fault displacement hazard. Fault displacement is a time dependent process that has associated uncertainty. Its hazard must therefore be assessed probabilistically to support a risk-based design. The DOE methodology provides a consistent approach to the seismic hazards of vibratory ground motion and fault displacement that supports performance assessment and seismic design applications, and that provides a comprehensive information base for regulatory decision making.

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[6] "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.

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 1.2 provides the regulatory framework and requirements for seismic hazard assessment. Then, following this introduction, 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, the design process based on seismic safety performance goals is further described. This provides the design context for seismic hazard assessment. In Appendix E, 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 F.

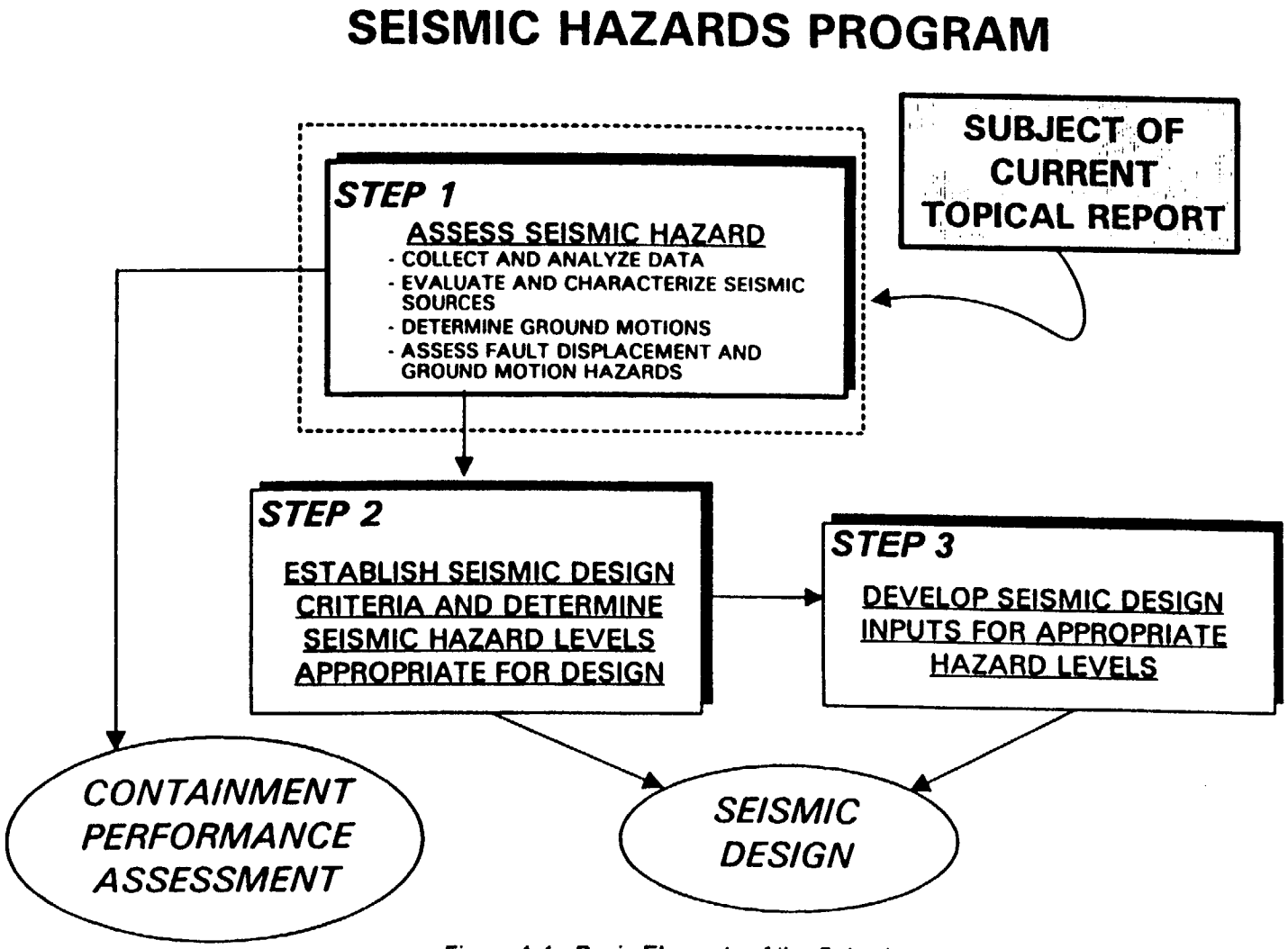


Figure 1-1. Basic Elements of the Seismic Hazards Program

Figure 1. Basic Elements of the Seismic Hazards Program

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 presented in 10 CFR Part 60. While a more complete description of these requirements is found in Section 1.2, they may be briefly summarized as follows:

- Structures, systems and components in the Geologic Repository Operations Area (GROA) 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 pre-closure period must be maintained.
- Features that might affect GROA 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 pre-closure and post-closure periods
- For both fault displacement and vibratory ground motion
- That can be used for risk-based design of both surface and subsurface facilities
- That can be used for long-term waste isolation performance assessment.

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

In developing the methodology, a goal was established to incorporate into it 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. Detailed descriptions of the methodology components are provided in Appendices A, B, and C. Section 2.4 provides a discussion of some related methodology issues. Finally, in Section 2.5, the major points of the Topical Report are summarized.

2.1 DESIRED ATTRIBUTES OF THE 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 a series of attributes that are described below:

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 decade 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 variability, these methods provide a more complete evaluation of hazard for risk-based design,

long-term performance assessment, and regulatory review than do deterministic methods. They provide additional information, beyond that which was available to negotiate a "maximum credible earthquake" in the traditional deterministic approach, that can be used to determine design basis earthquakes within a risk-based framework. Recent applications of probabilistic methodologies, associated lessons learned, and ongoing evaluations and integration of seismic hazard methodologies (e.g., the Senior Seismic Hazard Analysis Committee (SSHAC) study, jointly sponsored by the DOE, the NRC, and the EPRI) provide the basis for the methodology described in this report. In Appendix E 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. The methodology is capable of incorporating all relevant data collected as part of the site characterization program, including information on earthquake recurrence. A broad program of site characterization activities is being carried out to gather data necessary to assess seismic hazards at the proposed Yucca Mountain site. Data required for the characterization and evaluation of seismic sources, fault displacements, and ground motions are described in Appendices A and B. The methodology also allows seismic hazard assessments to be easily updated as new data are developed during site characterization.

3) **Issue-Focused**. The methodology addresses specific technical issues associated with disposal of high level radioactive wastes in a geologic repository at Yucca Mountain. For example, the probabilistic hazard results provide a rational basis for examining and comparing the hazard for different time periods. Thus, a single methodology supports development of seismic design inputs for the pre-closure period (100 years) and also for long-term performance assessment during the post-closure period (10,000 years or longer). The methodology also accommodates, through its incorporation of input variability, such issues as temporal and spatial clustering of earthquake occurrence and simultaneous rupture on multiple faults.

4) **Proper Uncertainty Treatment**. The methodology provides an unbiased assessment of seismic hazards by incorporating and properly treating various types of input variability. These types of variability include uncertainty in data interpretations and randomness in the earthquake process. In comparison with typical deterministic methods, treating uncertainty in a probabilistic framework results in a more complete characterization of seismic hazards. The uncertainty is directly incorporated into the calculation of hazard, rather than qualitatively contributing to selection of a deterministic value. This facilitates regulatory decision-making, risk-based design, and long-term waste isolation performance assessment. The methodology accommodates alternative relationships describing physical processes (e.g., earthquake occurrence), alternative values of parameters associated with those relationships (e.g., direction and amount of fault dip, slip rates, and maximum magnitudes), and alternative interpretations based on site characterization data.

5) **Flexible**. The methodology accommodates a 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 results from the probabilistic framework in which alternative input interpretations are explicitly incorporated together. In deterministic methods, a single interpretation is typically selected, and information related to alternative interpretations is therefore not included in the final hazard assessment.

6) **Facilitate Sensitivity Analysis**. The methodology is structured such that sensitivity analyses are facilitated. 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 and reductions in uncertainty have the greatest impact.

7) **Documentation**. The methodology incorporates documentation of the data sets, interpretations, and uncertainties. The documentation is sufficiently detailed to allow a third party to review the technical basis for interpretations made, 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 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 as the basis for developing seismic design inputs and to provide the likelihood of various initiating events in the assessment of long-term containment 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) will be covered in two future topical reports (see Section 1.1). By defining the scope of the current Topical Report in this manner, it is possible to focus on the issue of seismic hazards assessment independent of issues related to the appropriate conservatism for design. A methodology to assess vibratory ground motion and fault displacement hazards should be able to support development of seismic design inputs regardless of the level of conservatism in design.

The first step in the seismic hazards program is the collection and analysis of relevant data. Consistent with the approach described in NUREG-1451, these data will be used to identify, evaluate, and characterize seismic sources that significantly affect the design or performance assessment of the Geologic Repository Operations Area (GROA). Data are also being collected to assess the amount and characteristics of fault displacement and ground motion that will be associated with future earthquakes in the vicinity of 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 ground motion are analyzed (Figure 2, block 3). The results of these two efforts are then integrated in a probabilistic seismic hazard analysis. This results in a distribution of seismic hazard curves showing the

annual probability that different hazard levels will be exceeded. The methodology produces seismic hazard curves for both vibratory ground motion and fault displacement (Figure 2, block 4).

The hazard curves resulting from the methodology provide direct input to long-term waste isolation performance assessments of a GROA and provide a basis for development of seismic design inputs. For some applications, the probabilistic hazard results will be disaggregated to identify dominant sources contributing to a particular hazard level. These sources can then be treated deterministically in developing 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 final DOE methodology to determine appropriate hazard levels for design and to develop seismic design inputs (Figure 2, blocks 5 and 6) will be presented in future topical reports.

In developing the overall seismic hazards program, it is thus assumed that decisions concerning seismic design and long-term waste isolation performance assessment should be based on risk. Since risk is proportional to both the probability of an event's occurrence and the consequences of its occurrence, a probabilistic framework that inherently incorporates frequency of occurrence is appropriate for assessing seismic hazards. Within this framework, it is possible to make a determination of reasonable assurance and thus address regulatory requirements in a rational manner.

2.3 DESCRIPTION OF THE METHODOLOGY

This section provides a description of the procedures that will be used in the methodology to assess vibratory ground motion and fault displacement hazards. Details of the procedures are given 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, moment) distribution of future seismicity. In addition, 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 of input evaluation.

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 particular percentiles of the distribution.

Each of these steps is discussed below and 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 with a potential to affect GROA design or long-term waste isolation performance assessment (Type I faults in the nomenclature of NUREG-1451[McConnell et al., 1992]). Seismic sources also depict volumetric zones in which future earthquakes may occur, but for which specific faults are not identified. Seismic source zones are further used to characterize future underground nuclear explosions (UNEs). Data collected during site characterization activities form the basis for seismic source evaluation.

In identifying and characterizing seismic sources, the scale of feature to be considered and the level of investigation will 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 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 made iteratively; as preliminary hazard assessments are carried out, 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 is evaluated to provide its:

- three-dimensional spatial description (including variability in that description)
- probability of activity
- dependency with other seismic sources.

Alternate interpretations of the spatial extent of a seismic source permitted by the available data are documented and weighted according to their ability 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 and is based on the evidence of its activity during the Quaternary period. Such 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 among 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. Evaluation of seismic sources is described in more detail in Appendix A.

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 variability 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. Since 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 relations.

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 activities. Variability 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. For volumetric source zones, upper-bound magnitude will be based on an evaluation of the largest earthquakes that do not rupture the surface, and analogies to other seismic sources.

2.3.1.3 Evaluation of Ground Motion/Attenuation Functions

Depending on the effects that must be described, the ground motion assessment procedure can include both empirical and numerical components. Empirical descriptions of ground motion will be sufficient for most seismic sources; numerical descriptions will be used primarily to evaluate near-field effects. Use of either or both components will hinge on whether the seismic source is near the site, and on whether the effect to be described will significantly affect design or long-term waste isolation performance assessment of the GROA. 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 and UNE strong motion recordings collected in the western United States. This data set comes from sites having geological and seismic velocity characteristics similar to those at the Yucca Mountain site. Empirical ground motion relations describe the dependence of peak acceleration, peak velocity, and response spectral amplitude on earthquake or explosion magnitude and closest distance to the source. If required, separate empirical relationships can be given for shallow and deep sources, vertical and horizontal motions, and different styles of faulting. Evaluations include assessment of the variability in empirical ground motion/attenuation relations.

Numerical evaluations of ground motion use established physical descriptions of the earthquake or explosion source and the wave propagation path. Using the numerical approach, near-field effects such as the difference between foot-wall and hanging-wall motions and near-fault directivity can be included using the specific geometry of faults in relation to the site. Variability is assessed from the range of input parameters and interpretations supported by the data.

2.3.1.4 Probabilistic Hazard Calculations for Vibratory Ground Motion

As developed by Cornell (1968), the probabilistic hazard methodology aims to calculate the annual probabilities that various levels of ground motion (e.g., peak horizontal ground acceleration) will be exceeded at a site. Procedures to accomplish this assessment are described by Cornell and form the basis for recent state-of-the-practice methodologies that have been applied to nuclear power plants and to DOE facilities (see Appendix E for examples). The procedures incorporate all relevant site characterization data and yield results required for long-term waste isolation performance assessment and for safety performance goal-based design.

As described in more detail in Appendix C, 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 process and their distribution in magnitude can be represented by an exponential distribution. Thus, 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 the expression:

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

in which $\nu(z)$ is the average frequency during time period T at which the level of ground motion parameter Z exceeds z at the site resulting from earthquakes on all sources in the region. The inequality at the right of Equation 1 is valid regardless of the appropriate 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 the variability (randomness and uncertainty) in the time, size and location of future earthquakes and variability 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; $f_n(r \mid m)$ is the probability density function for distance to earthquake rupture on source n, which may be conditional on the earthquake size; and $P(Z>z \mid m,r)$ 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 $f_n(r \mid m)$ 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 (step 4, Figure 3) that represents the *randomness* inherent in the natural phenomena of earthquake generation and seismic wave propagation. There is also *uncertainty* in the characterizations of seismic sources and ground motion/attenuation. This uncertainty arises from incomplete knowledge of earthquake processes, limited data, and permissible alternative interpretations of the available data. The methodology explicitly incorporates these uncertainties into the analyses to quantify the uncertainty in the final hazard results.

As described in Appendix C, two approaches can be employed to incorporate uncertainties into the seismic hazard assessment. They are referred to informally 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 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 percentiles (step 5, Figure 3).

The Monte Carlo approach to 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 (step 5, Figure 3). 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 involved in 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 GROA, 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 evaluation.

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 found 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 is 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.

Consistent with NUREG-1451 (McConnell et al., 1992), seismic sources will be based on Type I faults—those with a potential to affect GROA design or performance assessment. In contrast with the assessment of vibratory ground motion hazard, for fault displacement only seismic sources that have a potential to cause primary or secondary faulting within the GROA are of interest. These seismic sources will be a subset of those evaluated to assess vibratory ground motion. Seismic source characterization for the assessment of fault displacement hazard will also include an evaluation of the possibility that "new" (displacement in previously intact rock) and unmapped faults can produce significant fault displacement within the GROA. The probability of activity for each seismic source and dependencies among sources will be determined in the same fashion as for vibratory ground motion hazard.

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 (see Section 2.3.1.2). For seismic sources based on faults, recurrence and maximum magnitude are determined on the basis of fault-specific data. Variability in the evaluations is also assessed and documented. If volumetric sources are required to assess fault displacement hazard, their earthquake recurrence relations and maximum magnitudes will be based on available data including seismic, geologic and tectonic information.

2.3.2.3 Evaluation of Fault Displacement Within the GROA

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 will be used to determine the amount of slip, including its variability, on a causative fault during a particular earthquake. An evaluation is also 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 is 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 among 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 if appropriate substitute definitions are incorporated:

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

- In Equation 2, $P(Z>z \mid m,r)$ 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 they were 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 methodology 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 hazard levels of interest will indicate those seismic sources that dominate the hazard. Extensive documentation of inputs and their variability, the seismic hazard results themselves, and the sensitivity analyses will together provide a wealth of information to 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 isolation.

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 safety performance goal-based 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. Evaluation of inputs to the methodology is based on field investigations, the seismic monitoring effort, and analyses of site characterization data. As detailed in Appendices A, B, and C, seismic sources will be identified on the basis of fault mapping and characterization; recurrence parameters will be determined on the basis of geologically determined slip rates, recurrence intervals identified from fault trenching investigations, and seismicity data; maximum magnitudes will be assessed from fault dimension information and segmentation evaluations; and ground motion will be evaluated from ground motion recordings. Variability of inputs, including both randomness and uncertainty, is characterized from the data and directly incorporated into the assessment, thus allowing the uncertainty of the results to be evaluated explicitly.

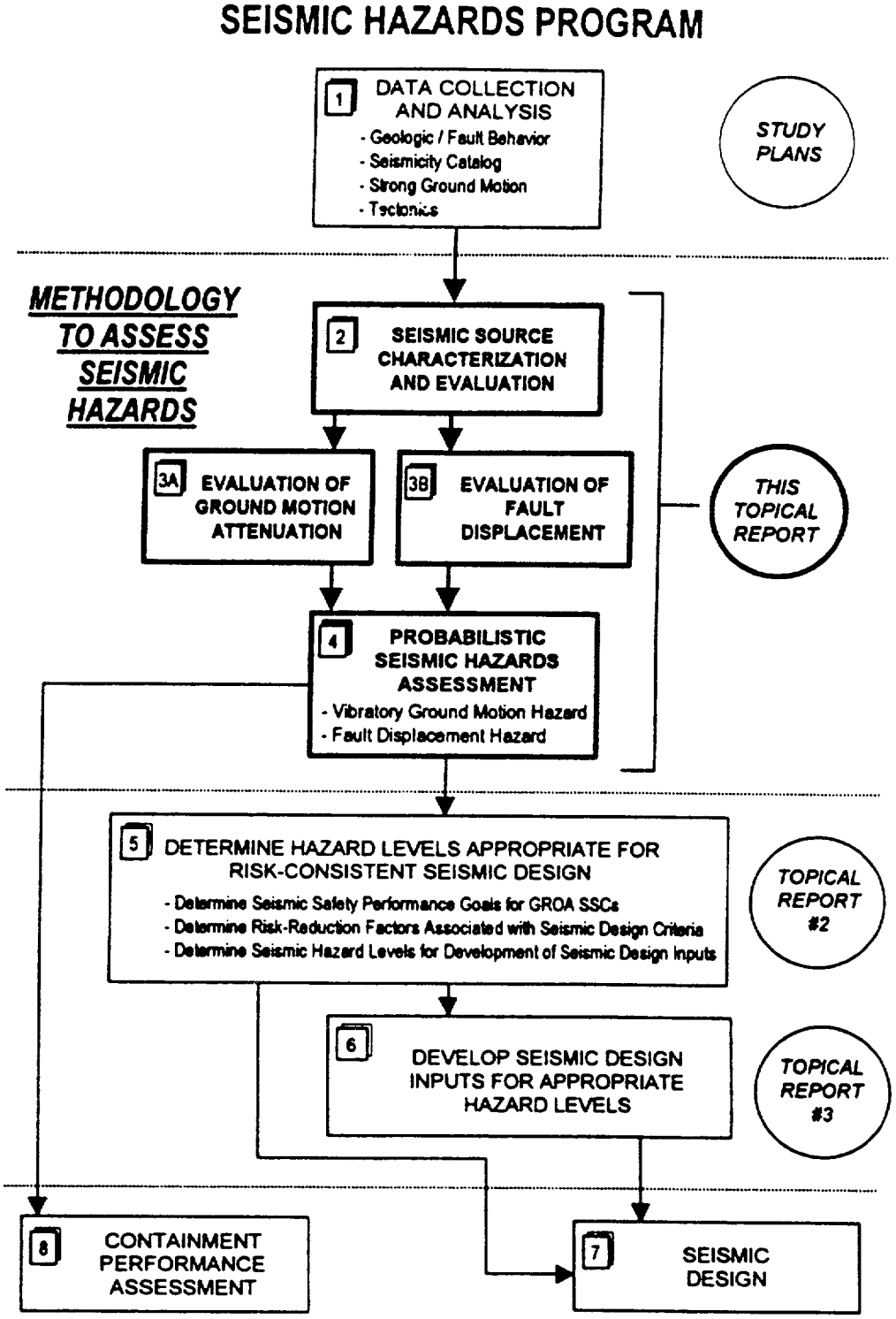
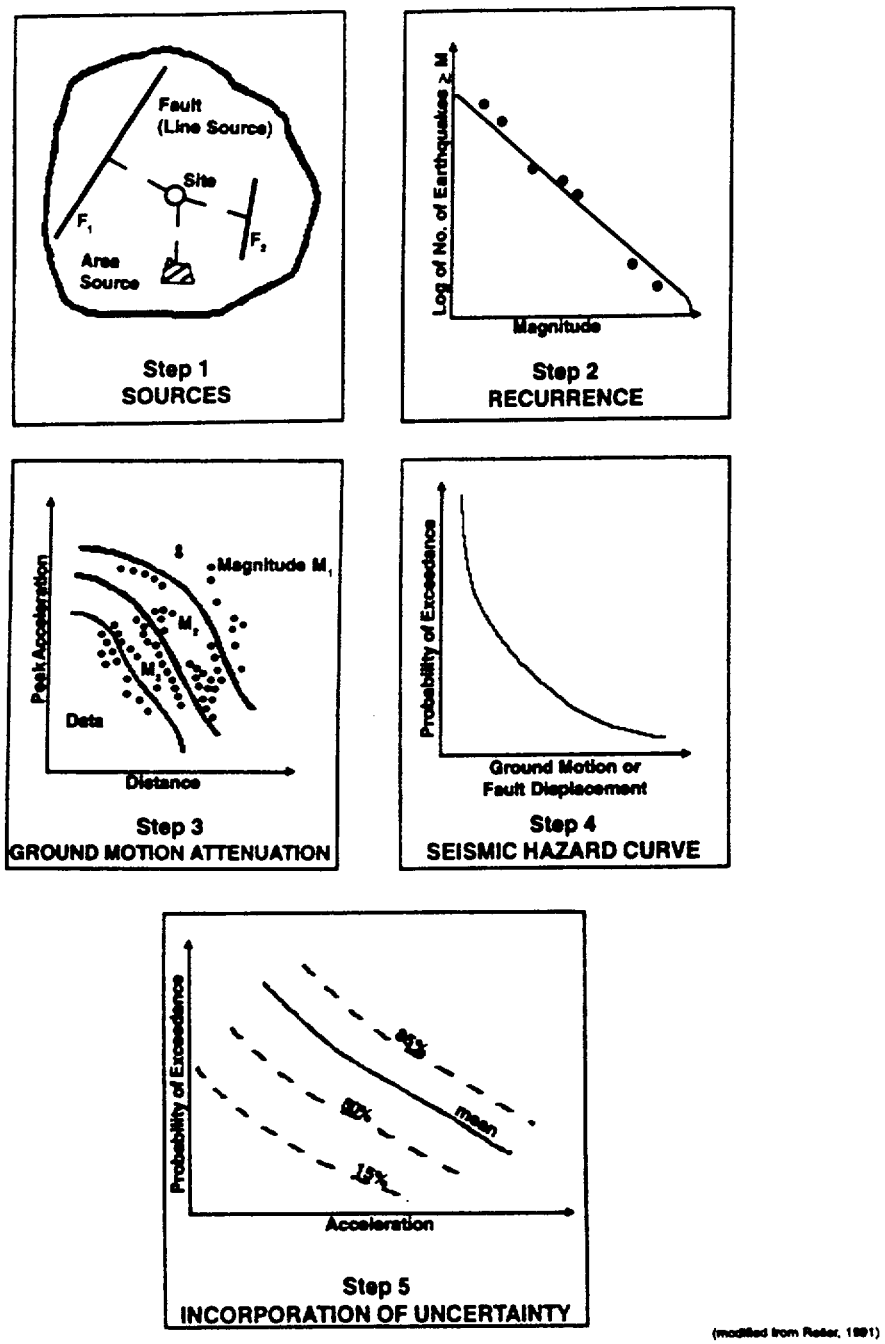


FIGURE 2-1. Components of the Methodology to Assess Seismic Hazards Within the Framework of the Overall Seismic Hazards Program

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



(modified from Reiter, 1991)

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

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 represents a region of the earth's crust in which the generation of seismic waves (vibrations transmitted through the earth) or the capability of surface deformation or both are known or suspected to be different from those of the adjacent crust. Typically, these differences are described by specific probability distributions for the source's size, spatial location, and occurrence in time. The traditional measurement of the size of an earthquake is Richter magnitude, although seismic moment and moment magnitude have gained favor over the past 10 years. Spatially, seismic sources can be described by points, lines, areas, or volumes. Temporally, the occurrence rate of a source can range from multiple events per year to less than one in several tens of thousands of years. Two general types of sources are considered at Yucca Mountain: earthquakes and underground nuclear explosions.

This Appendix identifies the parameters and discusses the procedures used to evaluate and characterize seismic sources for seismic hazard analyses at the potential geological repository, Yucca Mountain, Nevada. Seismic source evaluation and characterization include: identifying all seismic sources that could affect the site, defining the maximum and range of magnitudes associated with each source, defining the location and three-dimensional geometry of each source, defining the recurrence rates of various magnitudes for each source, and the uncertainties associated with all of these parameters for each source. The emphasis is on 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. Given the proximity of Yucca Mountain to the Nevada Test Site, the size and distribution of future underground nuclear explosions (UNEs) must be evaluated. Techniques for evaluating and characterizing UNEs and volcanic earthquakes are included also.

The steps involved in seismic source evaluation and characterization are: 1) recognition and spatial depiction of recently active faults or regions that are 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. Appendix A is organized following these three steps.

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

Candidate seismic sources for Yucca Mountain include exposed, buried, or hidden Quaternary faults, zones of historical seismicity, areal sources related to detachment faulting and volcanic activity, and testing sites of underground nuclear explosions. Spatially, seismic sources may range from discrete, three-dimensional faults to broad source zones, depending on the level of knowledge and physical nature of the earthquake environment. In much of western North America, including at Yucca Mountain, 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., Allen, 1968; 1986). Accordingly, the geological, seismological, and related geophysical investigations that will be used to characterize seismic sources at Yucca Mountain emphasize the collection of fault-specific information for determining the source location, temporal activity, source size, subsurface geometry (orientation, length and down-dip extent), and sense of slip.

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, areal 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

Seismic sources that could contribute to significant fault displacement or tectonic deformation in the Yucca Mountain site vicinity, and to any important characteristic of vibratory ground motion, must be identified, investigated, and characterized (e.g., McConnell et al., 1992). To accomplish this goal, the scale of feature and level of detail for study will generally vary as a function of distance from the site. Relative to nearby faults, more distant faults must generate larger and/or more frequent earthquakes to produce the same contribution to seismic hazard at the site of interest. Nearby faults generally require more detailed and comprehensive field investigations to evaluate potential tectonic deformation, fault displacement, and levels of ground motion in the site vicinity.

An iterative approach will be used for identification of features to be investigated. Initial investigations will be based on comprehensive literature reviews, field investigations, and considerations of alternative tectonic models. Sensitivity analyses of preliminary seismic hazards assessments will be used to identify types of faults that contribute more strongly to the hazard at the site. Such faults may require more detailed investigations to reduce uncertainties in the assessment of site seismic hazards.

A2.1.1 Fault Activity

Fault activity is defined as the assessment of whether a fault is seismogenic. One method of assessing the activity of a fault is by evaluating its association with historical and recent 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 pose a significant hazard to the site requires assessment (e.g., McConnell et al., 1992). Faults and geologic structures that have experienced recurrent motion during the Quaternary period (2 million years) are inferred to have potential for future earthquakes, and require investigation and characterization. Alternatively, 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 regime.

Additional criteria for assessing fault activity include association with observed seismicity, association with a known Quaternary structure, and favorable orientation relative to the contemporary stress regime (e.g., McConnell et al., 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.

Where Quaternary deposits, paleosols, or geomorphic surfaces are not present in an area containing known active faults, structural models provide a useful means of assessing a fault's potential activity. A

fault of unknown activity may be determined to be active based on structural models where movement on a known active fault can reasonably be associated with movement on the fault in question. The faults need not be physically connected for a kinematic link to exist. This approach requires an understanding of the three-dimensional geometry of the faults and the seismotectonic setting.

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 likely 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. Such evaluations will consider all available data, including alternative tectonic models, geomorphic data, seismicity, and the state of stress.

A2.1.2 Fault Geometry

Key elements in characterizing fault geometry are the mapped location, the direction and angle that the fault dips, and the down-dip extent. An evaluation of the fault's dip within the seismogenic crust is important to evaluate the potential down-dip width of a fault rupture and, for nearby faults, the distance from the fault plane to a site of interest. Most commonly, fault dip measurements at the surface or in the near-surface are extrapolated to seismogenic depths. Seismological indicators of subsurface geometry include earthquake focal mechanisms and the distribution of earthquake hypocenters. Subsurface imaging techniques such as seismic reflection profiles or balanced geologic cross-sections will provide useful constraints. Seismic reflection techniques image shallow-dipping geologic structures best; 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.

The down-dip extent (or width) of a fault can be evaluated only by indirect methods. Assessments of the down-dip extent typically rely on physical considerations such as the thickness of the seismogenic crust. The best indication of seismogenic crustal thickness in particular regions is thought to 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 between 10 and 15 km. The down-dip extent of faults is calculated from assessments of fault dip, which is possibly imaged at depth with seismic reflection techniques or extrapolated from measurements at the surface.

The tectonic models proposed for Yucca Mountain and vicinity have important implications for assessments of fault geometry. End-members of the various tectonic 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 are sometimes broken by younger steep faults. As discussed below, assessments of down-dip fault geometry and extent are important in computing earthquake magnitudes and recurrence rates.

A2.1.3 Sense of Fault Slip

One of the most fundamental characteristics of a fault is its sense of slip or style of faulting. The horizontal and vertical components of displacement and an assessment of fault dip are required to properly classify the sense of slip and net displacement on a fault. Alternatively, if the sense of slip and the amount of displacement for only one of these components is known, then it is possible to calculate the amount of net slip. 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 reverse or thrust faulting are slightly higher than ground motions associated with normal and strike slip faulting (e.g., McGarr, 1984; Campbell, 1991). These effects are expected to be less important for Yucca Mountain because it is located in a region characterized by predominantly normal and strike-slip faulting. The sense of slip for each fault source will be evaluated using available data, including paleoseismic investigations, geomorphic studies, geologic mapping of kinematic indicators such as slickensides and striae in fault exposures, earthquake focal mechanisms, and tectonic models.

A2.2 SEISMIC SOURCE ZONES

Seismic source zones are volumes of the Earth's crust that have uniform earthquake magnitude potential (uniform distribution of maximum magnitude throughout the volume). The seismic hazard methodology allows seismicity to vary within a seismic source as an additional aid to expressing uncertainty on seismic sources and rates of seismic activity. Commonly, source zones are defined to associate historical seismicity with specific geologic structures or in areas where causative faults have not been identified. Source zones are outlined on the basis of the spatial and temporal distribution of observed seismicity, complemented by information about the regional geologic structures and tectonic setting. In the western United States, source zones are used frequently to characterize random background seismicity (typically small- to moderate-magnitude earthquakes that do not rupture the ground surface).

The source zone approach will be useful at Yucca Mountain for characterizing: 1) seismogenic structures assessed as buried or hidden sources, such as detachment faults; background levels of small- to moderate-magnitude seismicity; 2) explosion sources limited to sites of underground nuclear weapons testing; and 3) volcanic earthquakes that could occur in regions of young magmatism.

A2.3 BURIED AND HIDDEN SOURCES

Buried seismic sources are seismogenic structures that have been mapped or imaged in the subsurface, but are not exposed; i.e., terminate below the surface. 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 for areas that generally lack faults or recognizable structures at the surface, but contain observed 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, these subsurface interpretative techniques can, in particular circumstances, be used to assess the degree of fault activity and the rate of fault slip.

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 buried structure are important to the assessment of the maximum magnitude that the structure may be capable of generating (discussed further in the maximum magnitude section), and fault slip rates are important to the assessment of recurrence rates.

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 located 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. Seismic source zones are commonly 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.

A2.4 SUMMARY OF APPROACH TO SEISMIC SOURCE ASSESSMENT AND RELEVANT DATA

Using the methods described above, seismic sources that contribute to vibratory ground motions and fault displacement at the Yucca Mountain site will be identified and characterized. The specific faults that require detailed characterization 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. Source identification and characterization will be carried out iteratively based on results of the probabilistic seismic hazard assessment showing what individual sources or classes of sources are significant to performance assessment and design.

Each seismic source will be assessed to determine its probability of activity. Active sources will be assessed 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. Such sources include buried or hidden sources 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 planar surfaces will be used to represent mapped Quaternary faults, while volumetric zones will be used to characterize buried and hidden faults, background seismicity, underground nuclear explosions, and volcanic sources. A preferred geometry will be assessed for each source, and the basis for that assessment documented. Alternative interpretations 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 and striae in fault exposures, earthquake focal mechanisms, and tectonic models.

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 Yucca Mountain, a region where the historic 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.

Faults near Yucca Mountain that are visible at the surface are being mapped, excavated, and investigated at different levels of detail with a variety of techniques. Therefore, maximum magnitudes at Yucca Mountain will be derived from interpretations of maximum fault rupture dimensions, including rupture lengths, and amounts of net displacement for individual earthquakes; parameters that are based on geologic and paleoseismic data that describe what has occurred during past ruptures. Consideration will also be given to constraints from the historical seismicity record. Maximum earthquakes will be obtained from a variety of pertinent paleoseismic data and possible rupture dimensions to evaluate the stability of the magnitude assessments and to quantify the ranges of uncertainty. For buried and hidden sources, approaches to determine maximum magnitudes will include assessments of fault dimensions, rupture displacements, fault mechanics, and the seismic moment relationships described below.

A3.1 METHODS BASED ON FAULT RUPTURE DIMENSIONS

Seismologic theory as well as measurements of historic fault ruptures indicate that the magnitude (or seismic moment) of an earthquake is related to dimensions of the rupture (length and down-dip width, or area) and the amount of fault displacement (e.g., Aki and Richards, 1980). Empirical data from surface-rupturing earthquakes show strong statistical correlations between the rupture dimensions and earthquake magnitude (e.g., Bonilla et al., 1984). Likewise, seismogram analysis has been used to derive rupture dimensions, slip models, and their scaling with respect to seismic moment (e.g., Somerville and Abrahamson, 1991). The empirical relationships have been refined and updated (Wells and Coppersmith, 1992), along with the relationship between seismic moment and moment magnitude (e.g., Hanks and Kanamori, 1979; Kanamori, 1983), and 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 empirical regressions are by Wells and Coppersmith (1992), which will be the relationships used for magnitude assessments at Yucca Mountain. The 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). Moment magnitude is the only scale related to physical properties of 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:

$$M_0 = \mu AD \tag{A-1}$$

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 independently from geologic and geodetic studies because surface rupture displacements and rupture lengths are quantities that can be determined 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.

Seismic moment can be empirically related to magnitude, which is the most common measure of earthquake size, although many distinct magnitude scales exist, and each measures a different frequency of the source spectrum (e.g., Kanamori, 1983). Seismic moment is related to moment magnitude M_w (or M) through the equation:

$$\log M_0 = 1.5M_W + 16.1 \tag{A-2}$$

which has been shown to be consistent with other magnitude scales over a wide range of magnitudes (Hanks and Kanamori, 1979; Kanamori, 1983). Moment magnitude is the preferred parameter for characterizing earthquake magnitudes. Typically, geologic and paleoseismic investigations are employed to assess the rupture dimensions and single-event displacements that characterize the sizes of past surface-rupturing earthquakes on a fault of interest.

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 Evaluations

The maximum earthquake magnitude is related to the fault geometry and fault behavior through an assessment of the maximum dimensions of a single rupture. Although occasionally an earthquake rupture traverses multiple fault segments, 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 are critical for defining segments and for modeling 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, which is described below in the section on real-time recurrence assessments. Application of elapsed time in the hazard analysis at Yucca Mountain will be most useful in assessing activity and understanding fault segmentation.

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, in order to recognize the boundaries between segments that could be considered barriers to rupture propagation. Fault rupture lengths and their uncertainties will be assessed by inferring the simultaneous rupture of one or multiple fault segments.

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., Bonilla et al., 1984; Wesnousky, 1986; Slemmons et al., 1989; Reiter, 1991; Wells and Coppersmith, 1992). The preferred method is to identify segments of the fault that appear to have ruptured as units in single earthquakes and use their lengths with the magnitude-rupture length regression to determine moment magnitudes. This approach relies heavily on detailed paleoseismic data that describes the timing of paleo-earthquakes, which will be available for most of the faults pertinent to Yucca Mountain. As discussed in Section A.3.1.2 on fault segmentation, individual or multiple segment rupture scenarios will be used for magnitude evaluations. The lengths from these scenarios will be correlated with moment magnitude using empirical relationships.

A3.1.4 Fault Rupture Area Relationships

Fault rupture area, which incorporates both the length and down-dip extent of the rupture, is more closely related to earthquake magnitude than rupture length alone. For a given rupture length, different down-dip widths of faults may rupture, depending largely upon fault type and tectonic environment. As the surface area of a rupture increases, the magnitude increases. 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, as well as surface faults.

Empirical relationships (e.g., Wyss, 1979; Bonilla et al., 1984; Somerville and Abrahamson, 1991; Wells and Coppersmith, 1992) have been established to describe the relationship between rupture area and magnitude for historical events. 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

Earthquake magnitude (seismic moment) is 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, 1992) and between average surface displacement and magnitude (Wells and Coppersmith, 1992). The magnitude-displacement relationships are useful because several geologic studies (e.g., Schwartz 1988b; Machette et al., 1992) have shown that prehistoric earthquake displacements can be measured from field studies, and these values can be used to determine magnitudes.

Commonly, paleoseismic trenching studies and variations in the geomorphic expression along a fault zone are used to determine the maximum and average displacements. 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, whereas maximum displacement is the largest of these values. Larger uncertainties exist in assessments of maximum displacement than average displacement because the displacement measurement is usually limited to only one location on the fault.

Displacements for Quaternary faults near Yucca Mountain will be evaluated from paleoseismic and geomorphic 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 the empirical relationships (Wells and Coppersmith, 1992) to determine earthquake magnitudes. Displacement measurements are important, especially for the fault displacement hazard assessment.

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, both earthquakes 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 is extremely rare relative to the period of historical observation. This is especially true for Yucca Mountain, a region with a brief seismic record relative to other areas in North America and 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 considered.

A3.3 SUMMARY OF APPROACH TO EVALUATE MAXIMUM EARTHQUAKE MAGNITUDE AND RELEVANT DATA

The moment magnitude of maximum earthquakes will be calculated for each relevant source using the empirical magnitude-rupture parameter regressions and the rupture lengths, rupture areas, and the maximum and average displacements determined from geologic and paleoseismic data. Multiple assessments of rupture dimensions will be used to lend stability to the magnitude evaluations. Uncertainties in the fault rupture parameters will be documented, in terms of the geologic basis for preferred and alternative values, and will be properly accounted for and incorporated into the seismic hazard analyses (e.g., National Research Council, 1988). Fault segmentation assessments will be based on all paleoseismic and fault behavioral data. Maximum magnitudes will be based on a consideration of multiple approaches and the relative resolving power of the approaches and their respective data sets. A maximum earthquake will be assessed for each source expressed as a probabilistic distribution that incorporates uncertainties in the geologic and paleoseismic data.

Important data for the maximum earthquake evaluation will be: 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 or frequency of occurrence of earthquakes of various magnitudes. Each seismic source, such as a fault or source zone, requires its own recurrence relationship. The recurrence curve (also called magnitude-frequency curve) has the form described by Gutenberg and Richter (1954) as the equation:

$$\log N = a - bM \tag{A-3}$$

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 general form, in which the magnitudes are exponentially distributed, was developed from earthquake catalogs for large regions, including global catalogs. As discussed below, variations from this typical magnitude-frequency distribution are more appropriate for individual fault sources such as those that will be identified and studied near Yucca Mountain.

A4.1 HISTORICAL SEISMICITY DATA

A traditional approach to evaluate earthquake recurrence rates is based on study of the historical seismicity record. 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 and location. 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).

As early as the 1960s, however, it was recognized from geologic data (e.g., Allen, 1968; 1975) that the seismicity on an individual fault does not exhibit a typical linear b-value distribution. Extrapolating seismicity on large faults does not produce events as large as experienced historically or documented in the geologic record. Integration of geologic and seismological studies of faults in the western United States and around the world have 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). A frequency versus magnitude plot for a single fault shows that extrapolation of small events to the maximum event underestimates the recurrence of large earthquakes on the fault (Youngs and Coppersmith, 1985). An approach that uses the paleoseismic record of late Quaternary faulting to determine the rate of infrequent large 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 maximum events.

A4.2 PALEOSEISMIC RECURRENCE DATA

The time period between geologically recognizable earthquakes 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 that has occurred during a measurable 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 with increased recurrence intervals. Fault slip rates offer an advantage over historical seismicity data by spanning several seismic cycles of large earthquakes on a fault. In addition, slip rates will be used with the seismic moment relationship to determine average earthquake recurrence rates.

The basic assumption in the use of slip rate is that it reflects the rate at which strain energy (seismic moment) accumulates along the fault and is available for release (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 plane 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 as described above.

Once seismic moment rate has been calculated for a fault, it must be partitioned into earthquakes of various magnitudes according to an interpretation of earthquake recurrence (magnitude distribution). The two most common interpretations represent earthquake recurrence as exponential or characteristic. Traditional methods for translating fault slip rate into recurrence relationships were based on exponential recurrence (e.g., Anderson, 1979). Because recurrence curves based on fault slip rate are obviously fault-specific rather than regional in nature, the characteristic earthquake formulation is more appropriate than the exponential for individual faults. Youngs and Coppersmith (1985) developed a generalized

recurrence density function to allow for slip rate to be used in the characteristic earthquake model. For the same slip rate, use of the characteristic earthquake formulation rather than an exponential one results in a significant reduction in the recurrence rate of moderate to small magnitude earthquakes and a modest increase in the rate of the larger events. In some cases, slip on a fault may be produced almost entirely by the large events, and the small and moderate events occur on splays or barriers that do not contribute to measurable slip on the main trace of the fault. This difference can affect the assessment of 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 interpretations will be evaluated for use at Yucca Mountain in an attempt to lend stability to the assessment and to encompass the inherent uncertainties.

An important consideration in assessing earthquake recurrence from fault slip rate is the sensitivity to the maximum magnitude used in the analysis. Increasing the maximum magnitude, given the same slip rate (same moment rate), will result in a significant decrease in the recurrence rate for 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.

A4.4 OTHER RECURRENCE ISSUES

Clustering: Most of the current models for earthquake recurrence are based on the assumption that the recurrence intervals between large-magnitude earthquakes are relatively constant or periodic. However, recent studies of faults in a variety of tectonic settings appear to show a spectrum of recurrence behavior ranging from very periodic to temporally-clustered behavior. It appears that active plate boundary-related faults display a 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. Increasing evidence from the historical and geologic records, including the Basin and Range, indicates that earthquakes may be clustered in both time and space.

Temporally, the fault or source appears to enter into a cluster, generating several large-magnitude earthquakes, and then enters into a period of quiescence that is considerably longer than the recurrence intervals during the cluster period. 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). An example of spatial clustering is where different, adjacent fault segments fail within a relatively brief time period of each other. 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). Temporal and spatial clustering is recognized behavior for some faults in the Basin and Range province (e.g., Wallace, 1987) where 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. Coppersmith (1988) has documented evidence for temporal and space clustering in the central and eastern United States.

Temporal clustering may have a significant effect on the accuracy of recurrence rates that are based on fault slip rates. For example, 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 much higher than the average. Conversely, if the fault is in a quiescent period, the average recurrence rate is assessed to be higher than would be expected in the near future. If the actual 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 included in the hazard analysis.

Real-Time Assessment: The basic probability relationship used in most hazard analyses is Poisson-exponential in which earthquakes occur as a Poisson process in time. While the Poisson process has been shown to match the observed data on a regional basis, it does not conform to the physical process believed to result in earthquakes--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 in nature. These observations have led to the use of "real-time" recurrence evaluations that forecast the probability of events in the next time period, rather than any time period. Typical use of a simple renewal evaluation 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 event on the fault of interest.

At present, real-time evaluations are not being used routinely in seismic hazard analyses for engineering purposes. Cornell and Winterstein (1988) have compared hazard results for the renewal approach and Poisson approach and find that in most cases the Poisson approach provides a reasonably conservative representation of the hazard. Although the renewal approach will be considered for application at Yucca Mountain, the Poisson formulation will likely be used because it is relatively simple to apply and is more appropriate for cases in which the hazard may be controlled by several faults (Reiter, 1991).

A4.5 SUMMARY OF APPROACH TO EARTHQUAKE RECURRENCE EVALUATION AND RELEVANT DATA

Earthquake recurrence relationships will be developed for each seismic source relevant to the Yucca Mountain site using the approaches described above. Recurrence rates for Quaternary fault sources will be based on all available geologic and paleoseismic data related to earthquake recurrence intervals and slip rates. Magnitude-frequency relationships and regional recurrence rates will be assessed for background seismicity levels and zones of concentrated seismicity from updated regional seismicity catalogs. Uncertainties in the recurrence rates and alternative magnitude-recurrence distributions will be evaluated, quantified for inclusion in the analysis, and incorporated into the hazard assessment.

Important data sets in the recurrence assessment will be regional and local Quaternary geologic maps, fault-specific earthquake recurrence and slip rate assessments from fault trenching and paleoseismic studies, interpretations of fault geometries, and regional earthquake catalogs.

A5.0 UNDERGROUND NUCLEAR EXPLOSIONS

Although no underground nuclear explosions (UNEs) have occurred at the Nevada Test Site since October 1992, and there are no current plans to resume testing, if the United States were to resume testing the tests would likely take place at the NTS. Thus, UNEs need to be considered in a complete 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 displacement.

A5.1 PRIMARY SEISMIC SOURCE

Evaluation of underground nuclear explosion (UNE) sources requires the same information as for earthquake sources: their future distribution in space, time, and size. Currently, a moratorium on nuclear testing at the Nevada Test Site (NTS) has been imposed. If the moratorium continues, the probability of activity for UNE sources is zero and further evaluation is unnecessary. Characterization of UNE sources, therefore, will begin with an assessment of the likelihood that they will resume. If the assessment concludes that future UNE activity is possible and that resulting ground motion at Yucca Mountain would contribute significantly to the hazard, then UNE sources will be characterized.

In characterizing UNE sources for a seismic hazard analysis, all existing or potential test areas will be considered. The spatial distribution of events within each test area, the range of yields (converted to magnitudes using appropriate relationships between nuclear explosion yield and seismic energy release), and the frequency of events as a function of yield will be determined from available information. The source characteristics are relatively well known for the historic period, and will serve as a guide for assessing future activity. Assessment of these parameters will require some appraisal based on current and future expectations concerning the testing program.

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 SEISMIC 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). Surface displacement related to underground nuclear weapons testing has occurred at the NTS. Although observed up to 5 km from an explosion (Bucknam 1969), it is generally limited to the local area of the explosion (e.g., Covington, 1987).

A6.0 VOLCANIC EARTHQUAKES

Another earthquake category relevant to seismic hazard analysis at Yucca Mountain is volcanic earthquakes. Included here are earthquakes that can be associated with processes such as 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 small in magnitude relative to tectonic earthquakes, they have recurrence rates potentially equal to the rate of volcanic eruptions, hence, they will be included in the seismic hazard assessment at Yucca Mountain.

The spatial and temporal distribution of volcanic events are the focus of considerable study at Yucca Mountain (e.g., Crowe et al., 1992; Perry and Crowe, 1992; Valentine et al., 1992). Observations show that volcanism has evolved from more silicic ash-flow tuffs erupted from the northern Yucca Mountain region in the middle to late Tertiary to relatively 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 surround these centers of Quaternary volcanism, and others that may be recognized in ongoing studies, in an attempt to characterize the locations and source parameters of volcanic earthquakes.

The largest magnitudes of volcanic events are usually much smaller than those of tectonic earthquakes, possibly because the rocks 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 to occur 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 represented by the earthquake swarm. Typically there is no main event in swarms. In general, all shocks are rather small and similar in magnitude. Swarms start with a few events, their number gradually increases until reaching a maximum, and then they drop 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.

Recurrence rates for volcanic events are complicated because no earthquakes in the record of historical seismicity near Yucca Mountain or in the southern Great Basin region have been identified as volcanic events, except for those along the eastern Sierra Nevada near Mammoth and Inyo Craters. Inferring recurrence rates from volcanically-analogous regions such as these may be difficult to accomplish without large uncertainties. In the context of Yucca Mountain, recurrence rates of volcanic earthquakes are probably more directly related to the 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.

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.

APPENDIX B

EVALUATION AND CHARACTERIZATION OF VIBRATORY GROUND MOTIONS AT YUCCA MOUNTAIN

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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 in engineering relationships for strong ground motion as important contributors to ground motions on rock and stiff alluvium. In the following description of the methodology, source and path effects are discussed first, then site effects on ground motions are considered. The methodology makes use of region- and site-specific ground motion recordings and information on seismic velocity structure.

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

In evaluating ground motions at Yucca Mountain both empirical and numerical methods will be used, as appropriate. If observational data are available that are representative of the source, propagation path, and site conditions for Yucca Mountain, empirical relationships will provide the primary approach. Available relationships will be considered and tested for their applicability to the Yucca Mountain region and modified if required. If a sufficient observational data base is not available, empirical methods will be supplemented by numerical methods. For some faults in the immediate vicinity of Yucca Mountain, it may be necessary to incorporate near-field effects on ground motion. If evaluations indicate that such effects are significant, numerical approaches will be used to assess them.

In this section, first the data that will be employed in assessing ground motions are addressed. Next the overall approach is described. This is followed by a discussion of the variability in ground motion and its incorporation into the methodology. Some specific ground motion effects are examined in more detail in the next section. Finally, the ground motion methodology is summarized.

B2.1 DATA NEEDS AND AVAILABLE DATA

A large number of strong motion recordings is 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 Nevada Test Site (NTS) underground nuclear explosions (UNEs), both at the surface and at depth in boreholes. Surface recordings exist at both rock and alluvial sites and for topographic conditions ranging from flat to steep. Also, as a result of the investigations that have been undertaken and are planned at the Yucca Mountain site, our knowledge of the physical properties of the site and the wave propagation characteristics of the site will be sufficient to allow a detailed characterization of ground motion response.

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 at

NTS stations, including stations at Yucca Mountain. The Yucca Mountain stations that have monitored explosions include 11 stations inside or within a few km of the perimeter of the proposed repository, four of which also have downhole recordings. These earthquake and explosion recordings could 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.

As part of site characterization activities, appropriate seismic velocity and density data will also be collected for the shallow crust beneath the site. These data will support assessments of wave propagation and site response.

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 relations 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).

B2.2 GROUND MOTION RELATIONSHIPS FOR SEISMIC HAZARD ASSESSMENT

The ground motion evaluations will include both empirical and numerical components. The empirical component will be derived from analyses of a large set of earthquake and explosion strong motion recordings from the western United States. Existing relationships will be considered for their appropriateness to the Yucca Mountain region. If necessary, such relationships will be modified using available data to describe ground motions in the Yucca Mountain vicinity more accurately. 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 selected to match the magnitude, closest distance, site conditions, and other site-specific aspects (such as faulting mechanism) of earthquakes or explosions that are important for development of design ground motions. The primary data base of strong motion recordings will include sites having geological and seismic wave velocity characteristics comparable to those for the Yucca Mountain site. Data bases including a broader range of site 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.

Important developments have occurred in the past several years in the methodology used to derive empirical ground motion attenuation relations using regression. A summary of modern regression methods is given by Joyner and Boore (1993). In particular, the procedure to separate inter-event and intra-event randomness using the random effects formulation developed by Abrahamson and Youngs (1992) is an important advance. This approach is adopted for the DOE methodology.

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 km), and for UNEs and very shallow earthquakes; for dip-slip faulting, the difference between ground motions on the foot-wall and hanging-wall may be included; and 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. A comparison will be made between the predictions of these

relationships and ground motions from Basin and Range earthquakes and explosions, and earthquakes from other regions that are representative of earthquake source and wave propagation conditions at the Yucca Mountain site region. Modifications to the empirical relationships will be made based on this comparison if warranted by the data.

Numerical methods will be used to supplement the evaluations of ground motion from empirical relations. Both theoretical and stochastic numerical methods will be employed. Theoretical numerical evaluations will provide site-specific determinations of source geometry and wave propagation effects, and will augment the empirical data in quantifying style-of-faulting and near-fault effects on ground motions. While empirical relationships will be based on a large set of recorded data applicable to the site in a general way, they do not reflect the actual geometrical orientation of the faults near the site nor the local seismic wave velocity structure beneath the site. Despite the large number of strong motion recordings obtained during the past decade, the empirical data sample contains only a limited range of geometrical orientations of the earthquake sources in relation to near-fault recording stations. Theoretical numerical methods provide a basis for examining these effects.

A stochastic numerical method (the band-limited white noise method) will also be used to supplement the empirical method. This approach treats seismic energy as randomly distributed over a source and incorporates seismic source, propagation path and site components of ground motion. It has been shown to describe observed ground motion observations under a wide range of conditions and complements the results from empirical and theoretical numerical methods.

In the numerical component of the ground motion evaluation, recorded data will first be used to check the assumptions on which the numerical 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 effect, 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 range of numerical approaches exists that can augment the information provided by empirical ground motion attenuation relationships (EPRI, 1990). The selection of the approach 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
- the adequacy of the evaluations in describing these ground motion characteristics over the frequency range of importance at the site.

If necessary, different methods will be used for long period ground motions, which are characterized by relatively deterministic behavior, and high frequency ground motions, which are characterized by relatively stochastic behavior.

The numerical component of the ground motion evaluation uses physical descriptions of the earthquake or explosion source and the wave propagation path to generate ground motion time histories. The characteristics of the site (i.e., the shallow part of the path beneath a site of interest) are also included in the description. Seismic source evaluations and characterizations using the methodology described in

Appendix A provide the inputs into the numerical ground motion assessment. Inputs include the fault geometry, sense of slip, and rupture dimensions and average slip as a function of seismic moment.

For the theoretical approach, an earthquake source will be described by a discrete set of fault elements covering the rupture surface. The seismic radiation from the fault elements, or from an explosion source, 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. These can also be determined either empirically or theoretically. The selection of empirical or theoretical approaches to describing the source and wave propagation effects in each of the situations just described will be based on considerations of 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.

Using numerical evaluations, the effects of faulting style, difference between foot-wall and hanging-wall motions, and near-fault directivity will be estimated using the specific geometry of the faults in relation to the site. The uncertainty in ground motion determinations derived from the numerical evaluations is discussed in Section B2.3.

B2.3 ASSESSING VARIABILITY IN GROUND MOTION VALUES

As described in Section 2.3 and Appendix C, the variability in ground motion values includes the effects of randomness in the underlying process of earthquake rupture and seismic wave propagation, and uncertainty in the ground motion relationships. These two sources of variability are present in both empirical and numerical ground motion relationships. The effect of uncertainty in ground motion can be incorporated by using multiple ground motion relationships. In the following, we describe methods of assessing the variability and randomness first in empirical approaches and then in numerical approaches.

Empirical ground motion relationships are mathematical formulations selected to fit specific sets of recorded data. In using empirical ground motion relationships, it is therefore necessary to include the uncertainty associated with selecting this mathematical description as part of the overall variability in estimated ground motions. This will be accomplished by using more than one empirical ground motion relationship. The use of multiple attenuation relations also incorporates differences in ground motion relationships that result from different selections or categorizations of data.

With respect to the randomness in empirical ground motion relationships, the use of the random effects formulation has provided estimates of inter-event and intra-event contributions to variance, and clearly demonstrated the reduction in total variance with increasing earthquake magnitude (Youngs et al., 1993). For peak acceleration, this reduction 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 variability in numerical evaluation approaches, a rigorous procedure for assessing the uncertainty in ground motion values derived from numerical relationships has been developed by Abrahamson et al. (1990). There are two contributions to this uncertainty. The first contribution, which consists of modeling and random 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 evaluated from the variability in ground motion amplitudes that results from variations in these parameters based on assessed probability distributions.

B2.4 SPECIFIC ASPECTS OF GROUND MOTION EVALUATION

In some cases, uncertainties in ground motion relationships can be reduced by explicitly taking into account additional variables that affect ground motion. Some of these effects are described below.

B2.4.1 Effect of Local Geology

Site conditions at Yucca Mountain include alluvium and rock; current information indicates soft soil site conditions do not exist. Empirical attenuation relations for various site categories will be selected from the literature or developed from data bases of strong motion recordings for each site category. Recent analyses have found a difference in attenuation between "soft rock" and "hard rock" conditions (e.g., Campbell, 1991). The relevance of different rock categories to the Yucca Mountain site will be considered in the evaluation of attenuation relations. In both empirical and numerical ground motion relationships, information on material properties of the rock and alluvium at the site (compressional and shear velocities, bulk densities, soil properties and classification, and shear modulus) are required to categorize the site and assess its response. This site-specific information will be used directly in developing attenuation relations using numerical methods. Further aspects relating to site response are discussed below in Section B3.0.

B2.4.2 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. While theoretical calculations predict that ground motions from normal faulting events should be equivalent to those from reverse faults (i.e., a few tens of percent higher than those for strike-slip faulting), empirical observations suggest that ground motions for normal faulting are comparable to those for strike-slip faulting in the western United States. This will be evaluated by examining the residuals with respect to strike-slip attenuation relations of data recorded from normal faulting earthquakes. Other source parameters which influence ground motion levels, such stress drop, will also be examined to understand the relation between ground motion from earthquakes in the Basin and Range (predominantly dip-slip) and from those in California (predominantly strike-slip) (Doser and Smith, 1989; Kanamori and Allen, 1986).

There are westward dipping faults on both sides of the site. The hanging wall is that part of the ground surface that overlies a dipping fault; the site is on the hanging wall for faults that outcrop to the east and on the foot wall for faults that outcrop to the west. A difference in ground motion level is observed between ground motions recorded on the foot wall and hanging wall of dip-slip faults (Abrahamson and Somerville, 1993). For distances between ten and twenty kilometers, the peak accelerations on the hanging wall tend to be larger than average and those on the foot wall lower than average. The difference between hanging wall motions and foot wall motions becomes less at closer distances, and is zero by definition at zero distance. This pattern 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 foot wall 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.

B2.4.3 Effect of Rupture Directivity on Near-Fault Ground Motions

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 at high frequencies, there are no unusual effects observed in the near-fault region. The principal effect in the near-fault region is that the amplitudes of the vertical motions become comparable to those of the horizontal motions, whereas they are less than the horizontal at greater distances, as described further below. Rupture directivity effects are generally difficult to discern in 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.

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 relatively brief duration compared with that at other locations. Differences between fault-normal and fault-parallel motions become significant at periods longer than about one second for strike-slip faulting (Somerville and Graves, 1993), with fault-normal motions as much as 50 percent larger on average than the average of the two horizontal components. The incidence of directivity effects (and the resulting difference between fault-normal and fault-parallel motions) in dip-slip faulting is expected to be less than for strike-slip faulting. If it is concluded that the predominant style of faulting at the site is normal faulting, then it may not be necessary to consider these differences, but it will be important to consider them if there is a significant strike-slip component of faulting on near-site faults.

The effects of rupture directivity on long period ground motions will be incorporated in empirical attenuation relations, as has been done in part by Sadigh et al. (1993). 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).

B2.4.4 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 attenuation relationships for vertical ground motions.

B2.5 SUMMARY OF APPROACH TO GROUND MOTION EVALUATION

Evaluation of ground motions at Yucca Mountain will employ both empirical and numerical approaches. Empirical relationships describing ground motion attenuation will be based on appropriate observational data. To the degree allowed by the data and as they significantly affect ground motion evaluations, the relationships will include the effects of site conditions, component of ground motion (horizontal or vertical), type of faulting, systematic differences in hanging-wall versus foot-wall motions, and directivity. The empirical approach will be supplemented by numerical methods to characterize evaluated ground motion more completely and to assess ground motion uncertainties. Depending on available data, theoretical numerical approaches will incorporate either empirical or theoretical source functions and Green's functions. A stochastic numerical approach will also be employed. For numerical approaches, uncertainties will be evaluated in terms of sensitivity to inputs, the appropriateness of the physical descriptions of the earthquake process, and the knowledge of future earthquake and propagation path parameters (e.g., moment, attenuation, and stress drop).

B3.0 EVALUATION OF SITE EFFECTS ON GROUND MOTION

Site effects can result from the modifying influence on ground motion of local shallow geologic structure and topography. Site characterization activities will investigate the occurrence of such effects at Yucca Mountain and, if required, procedures will be used to account for site effects in assessments of ground motion. In this section the possible sources of site effects are discussed, and potential methods for incorporating such effects, and their variability, in evaluations of ground motion are presented.

B3.1 DATA NEEDS AND AVAILABLE DATA

A large number of strong motion recordings is available from the Yucca Mountain site to provide a basis for developing a characterization of site effects on ground motion. The data include seismograms of both earthquakes and UNEs, recorded both at the surface and at depth in boreholes. The downhole recordings show the effects of amplification of ground motions as they approach the surface, providing information for the development of models of the variation of ground motion with depth below the surface that are needed for the design of the repository. Surface recordings exist at both rock and alluvial sites, and for topographic conditions ranging from flat to steep. Also, as a result of the subsurface investigations that have been undertaken and are planned at the Yucca Mountain site, our knowledge of the physical properties of the site and the wave propagation characteristics of the site will be sufficient to allow a characterization of ground motion response.

B3.2 SUMMARY OF SITE RESPONSE RESULTS REQUIRED FOR SEISMIC HAZARD ASSESSMENT

Site response refers to the modification of incident ground motions by the shallow geologic structure and material properties that underlie Yucca Mountain, including the effect of topography and depth of burial on ground motions at the site. If required, the site response will be incorporated into ground motion estimates in two ways. For use with ground motion attenuation relations, it will be applied as a modification to ground motion peak values and spectral ordinates derived from these ground motion attenuation relations. This modification, which may influence the overall level of the ground motions and their spectral shape, will be derived empirically from analysis of ground motions recorded at the site or assessed from numerical evaluations of site response. In addition, site response will be included directly in ground motion evaluations based on numerical methods.

Site response will be assessed from the data both empirically and numerically. In the empirical approach to site response analysis, a procedure will be developed for establishing a relevant reference level against which the site ground motions are compared to assess the site response. The site response will then be applied as a modification to ground motion values at the reference level. Within the overall empirical approach, the reference level may be determined empirically or numerically. An example of an empirical method is a ground motion attenuation relation for which site conditions are explicitly considered as a variable. An example of a numerical approach is the Brune source spectrum modified by a geometrical spreading factor and a spectral decay parameter that consists of a distance dependent (path) term and a distance independent (site) term (e.g., Humphrey and Anderson, 1992). In this approach the average spectral decay parameters represent the average site response. The site response at a given station is defined as the difference between the ground motions recorded at the station and the ground motions assessed at the station by the numerical evaluation. The adequacy of either approach will be assessed during its implementation considering the appropriateness of assumptions and data sets used in analyses.

Site effects can also be incorporated directly in numerical evaluations of ground motion. For example, if recordings at the site of small earthquakes such as those from the Little Skull Mountain earthquake are adequate for use as empirical Green's functions or empirical source functions, these recordings

include the site response and so the site response is incorporated empirically by this procedure. Alternatively, site response can be computed using a model of the shallow seismic velocity structure at a site of interest and numerically propagating incident seismic waves through the structure. Such determinations will be tested and constrained by comparing them to available recordings of earthquakes and UNEs both at the surface and at depth in boreholes. This procedure for calculating site response may be interfaced with the numerical ground motion evaluations described in Section B2.

B3.3 ASSESSING VARIABILITY IN SITE RESPONSE

Contributions to variability in ground motion estimates are described above in Section 2.3 of the main report and in Appendix C. The variance in ground motions described by empirical ground motion attenuation relationships is derived from the variability in recorded data for a given site category. 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 relevant at a specific site if we have no knowledge of its site response. If we are to incorporate a site response, we need to replace the estimate of variance in the empirical attenuation relation with that derived from site data. Generally, we would expect an individual site to have a lower variance than that of empirical attenuation relations for a given site category. However, if the variance of the site response is derived from small earthquakes, it may not be applicable to larger earthquakes because of the observed tendency of the variance to decrease with increasing magnitude. All these factors will be assessed and incorporated into the site response assessment.

It is found that for larger magnitudes, the intra-event contribution to the variance is larger than the inter-event contribution. The relatively small inter-event contribution indicates that differences in ground motions between different events of the same magnitude are relatively small, especially at large magnitudes. Most of the variability in ground motions is attributable to individual path and site effects. This indicates that if the path and site response characteristics at a given site are known, then the variance in the ground motion may be significantly lower.

For site response determined using numerical methods, and interfaced with a numerical ground motion evaluation that addresses source and path effects, the methodology described in Section B2.4 for estimating uncertainty (Abrahamson et al., 1990) will be used to describe the variance in site response. The uncertainty with respect to numerical assessment approaches will be evaluated from differences between recorded surface motions and surface motions calculated using downhole motions together with a numerical wave propagation procedure and a description of the velocity structure between the downhole and surface recorders. The parametric uncertainty will be derived from 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.

B3.4 SPECIFIC ASPECTS OF THE SITE RESPONSE EVALUATION

B3.4.1 Effects of Shallow Velocity Gradient

In numerical ground motion evaluations, information on material properties of the rock and alluvium at the site (compressional and shear velocities, bulk densities, soil properties and classification, and shear modulus and damping ratio and their variation with strain level) can be used to estimate the site response using standard 1-D models. More complex 2-D and 3-D models can be employed if warranted by the site's structural complexity or lateral heterogeneity of the site materials. To make full use of the recorded data, seismic velocity and density measurements will be made in the site region. In particular, downhole measurements of seismic velocities in wells, especially those that contain or have contained seismic instrumentation, will be used for the development of wave propagation and site response assessments using recorded data.

B3.4.2 Amplitude Variation Due to Depth of Burial

Assessments of amplitude variation due to depth below the surface will be derived both from downhole data recorded at the Yucca Mountain site and from numerical methods validated using these data. Strong motion data from explosions have been recorded at the surface and downhole at several Yucca Mountain sites. These recordings provide an opportunity to evaluate the variation of ground motions with depth beneath Yucca Mountain. The presence of steep topography at some sites (discussed below) will require that the effects of topography and depth of burial be separated. Currently available data suggests the velocity seismograms of explosions recorded at Yucca Mountain are dominated by surface waves. However, compressional and shear waves are also present and the influence of depth of burial on all relevant wave types will be evaluated.

A more complete assessment of the variation of amplitude with depth can be obtained by numerically evaluating the depth variation of the recorded data, and using more general source models (including earthquakes) to determine the reduction of ground motion with depth. This activity includes the determination of the effects of shallow velocity gradient described above. To test these assessments, downhole seismic velocity and density measurements will be used. Once these site effects characterizations have been tested against recorded data, they will be used to assess site-specific effects of depth of burial, such as the nature of these effects in the near-fault environment.

The reduction factors derived from explosion data recorded on Yucca Mountain and from numerical modeling will be compared with those that have been observed downhole from earthquake data in rock. For example, 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 from the 9/7/92 aftershock of the Little Skull Mountain earthquake at an epicentral distance of 3.5 km; the corresponding reduction of the vertical motions was 0.5. Other relevant data for rock sites include those from the Garner Valley array (Archuleta et al., 1992) and from several sources in Japan.

B3.4.3 Effect of Nonlinear Soil Behavior

For alluvial materials, the effect of nonlinear behavior on ground motion response can be assessed using measurements of shear modulus and damping and their dependencies on strain level and confining pressure. These methods give the ground motion time history at the surface of the soil by selecting a ground motion at the base of the soil profile and propagating it through the profile. The simplest method is based on Seed and Idriss (1967), who described the non-linear hysteretic stress-strain properties of soils by using an equivalent linear elastic method of analysis. This method, together with more advanced methods based on non-linear descriptions, have been summarized by Finn (1988). Strong ground motion recordings of nuclear explosions from downhole arrays at alluvial sites at Yucca Mountain and other NTS sites provide data with which to validate methods for determining the effect of nonlinear soil behavior. If evaluations of ground motion indicate that nonlinear effects of soil behavior need to be taken into account, the adequacy of the shear waves in these explosion recordings for evaluating nonlinear soil behavior will be assessed.

B3.4.4 Effects of Topography

The Yucca Mountain site is characterized by relatively steep topography, especially on its western flank, where there is a drop of 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.

Strong motion data from explosions have been recorded at the surface and downhole at Yucca Mountain sites. These recordings provide an opportunity to evaluate the influence of topographic effects on ground motions at Yucca Mountain. In particular, the availability of downhole as well as surface recordings should allow the evolution of the topographic effects to be traced. While seismograms of explosions recorded at Yucca Mountain are dominated by surface waves, shear waves are also present. The influence of topographic effects on both shear waves and surface waves will be evaluated. Topographic effects can be conveniently analyzed using finite difference models (Frankel and Leith, 1992).

B3.5 SUMMARY OF APPROACH FOR EVALUATING SITE RESPONSE

Site response at Yucca Mountain will be evaluated using both empirical and numerical approaches. Comparison among ground motions recorded at the surface, and between surface motions and those at depth in boreholes, will provide empirical factors that can be used to modify reference evaluations of ground motion. This empirical approach will be complemented by numerical methods to assess observed site response. Numerical approaches to ground motion evaluation that incorporate empirical Green's functions will implicitly include site response. Numerical procedures to describe wave propagation through the shallow structure beneath a site will also be used to provide evaluations of site response that can be compared with observations. Uncertainties in evaluating site response will be assessed for both empirical and numerical approaches and incorporated in final evaluations of ground motion.

APPENDIX C

SEISMIC HAZARD ASSESSMENT PROCEDURES

APPENDIX C

SEISMIC HAZARD ASSESSMENT PROCEDURES

C1.0 INTRODUCTION

Section 2 of this Topical 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 Department of Energy (DOE), and the Nuclear Regulatory Commission (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 algorithm for seismic hazard assessment is based on the model developed by Cornell (1968). This model consists of the first four steps as shown in Figure C-1 and described as follows. (The fifth step is discussed separately 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 in the form of a probability density function describing the distribution of earthquakes in distance for each seismic source, which depends on source location and geometry, and by a probability of activity. Dependencies among sources also form part of the seismic source input. The interpretations of seismic sources are developed as discussed in Appendix A. For fault-specific seismic sources close enough to the Yucca Mountain site so that three-dimensional aspects of the source are important, these aspects will be included in the source characterization and represented in the density function. For seismic source zones that do not contain recognized active faults, the source zone geometry and area will be based on seismicity and more general geologic structure and tectonic data, and a two-dimensional representation of the source will be used together with a distribution of earthquakes in depth.

Table C-1 summarizes the types of data that are used to develop an interpretation of seismic sources. The interpretation will seek to explain the data sets fully, and a baseline interpretation will be made that most completely explains the data. Alternative interpretations will be developed when needed to explain aspects of the data. This process of providing multiple alternative interpretations provides an assessment of uncertainty in the seismic sources that captures both data and knowledge uncertainty. 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.

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. The Poisson-exponential recurrence relationship is normally appropriate for seismic source zones except when the seismicity rate is very high. For fault-specific seismic sources the applicability of the characteristic earthquake recurrence relationship must be considered. A specific evaluation will be made to determine the applicability of the Poisson-exponential relationship at Yucca Mountain and, if warranted, time dependent or characteristic recurrence relationships will be used. The approaches to be used in evaluating recurrence and maximum magnitude are described in Appendix A.

The parameters of the recurrence relationship will be developed from historical seismicity or geologic slip rate data or a combination of these two data sets. 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.

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 numerical components.

The inherent stochastic nature of the earthquake rupture and propagation phenomenon leads to variability in the assessed ground motion. The ground motion measure at a site, therefore, is a stochastic parameter. In Equation C-2, 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 closest distance from the earthquake source to the site).

As applied in the seismic hazard methodology, therefore, 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 log normal distribution of the uncertainty in Z, given m and r. 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 median of Z, then the uncertainty in Z is described by a log normal distribution such that:

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

In Equation C-1, 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 part in Equation C-4, $P(Z>z|m,r)$, is equal to the value of the complement standard Normal Probability function:

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

Since the attenuation functions are generally developed for a given region and site conditions, they will be customized for the Yucca Mountain site. This will be done as explained in Appendix B by including in the formulation of the relationships the specificity of the geology and earth structure at the site.

The data used in assessing the ground motions include available recordings of ground motions as well as the 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 interpretations and analyses described in Appendix B of this Topical Report.

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, such as displayed in Step 4 of Figure C-1, shows the 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., year), and M is the magnitude of an earthquake, given that one occurs. Each source is characterized by an X and M. The computation incorporates the following assumptions:

- As stochastic variables within a seismic source:
  - X and M are independent
  - temporally, X has a Poisson distribution
  - spatially, X has locally a uniform distribution
  - there is a minimum magnitude m^0 of engineering concern; magnitudes less than m^0 are not considered in the calculation
- Between seismic sources:
  - Xs are independent
  - Ms are independent
  - Xs and Ms are 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:

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

in which $\nu(z)$ is the average frequency during T, resulting from earthquakes on all sources in the region, that the level of ground motion parameter Z exceeds z at the site. The inequality at the right of Equation C-3 is valid regardless of the appropriate probability model for earthquake occurrence, and $\nu(z) \bullet T$ provides an accurate and slightly conservative estimate of the hazard for probabilities of 0.1.

The frequency of exceedance, $\nu(z)$, is a function of uncertainty in the size and location of future earthquakes, and in 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 $\alpha_n(m^0)$ 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; $f_n(r \mid m)$ is the probability density function for distance to earthquake rupture on source n, which is usually conditional on the earthquake size; and $P(Z>z \mid m,r)$ is the probability that, given a magnitude m earthquake at a distance r from the site, the ground motion exceeds level z. In practice, the double integral in Equation C-4 is replaced by a double summation with discretized density function $f_n(m)$ and $f_n(r \mid m)$.

The seismic hazard result is typically expressed as a hazard curve normalized for a one year period (i.e., $T = 1$), expressing the annual probability of exceedance of the ground motion parameter, as shown in Figure C-1, Step 4.

For most seismic environments, the Poisson exponential recurrence relationship is appropriate (Cornell and Winterstein, 1988). However, the seismic environment of the Yucca Mountain site may require that a non-stationary model of earthquake occurrence be used (i.e., non-stationary Poisson, or other forms of renewal models). Such models, which require extensive data to estimate their parameters with confidence, will be evaluated. If time dependency is used, 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 due to differential fault displacement. The methodology is focused on co-seismic fault displacements related to earthquakes, but it can also be used to assess triggered slip due to UNEs. Because of the significant uncertainties associated with the assessment, the approach is probabilistic and incorporates explicitly 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.

Methodologies for the probabilistic assessment of fault displacement hazard have been developed for Yucca Mountain (e.g., Coppersmith and Youngs, 1992; Coppersmith et al., 1993), and much of the analysis follows the traditional 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 are identified and described by their location, three-dimensional geometry, and sense of slip; their probabilities of activity are assessed; and their dependencies are documented (see Appendix A). The seismic source evaluation for assessment of fault displacement hazard is a subset of that developed for vibratory ground motion hazard. For assessment of vibratory ground motion hazard, the seismic sources include both fault sources and areal or volumetric source zones. Fault sources are readily incorporated into fault displacement studies, but areal source zones typically represent earthquakes that do not rupture the surface. Areal sources will be used in the assessment of fault

displacement hazard if they are required to account for the possibility of new faults or the existence of significant unmapped faults. New faults are defined as the rupture of previously intact rock. Previously unmapped faults are faults that are inferred to exist but are not mapped. Fault-specific seismic sources are expected to be controlling for assessing the fault displacement hazard at the Yucca Mountain site.

C3.2 STEP 2: EARTHQUAKE RECURRENCE

For each seismic source, the maximum magnitude and the frequency of occurrence as a function of magnitude are evaluated. Again, the characterization of seismic sources is identical to that for assessment of vibratory ground motion hazard. As discussed in Appendix A, each of the significant faults will be characterized by its earthquake recurrence relationship and maximum magnitude. The methodology also provides for the possibility that fault displacement occurs in areas off the known mapped faults.

C3.3 STEP 3: FAULT DISPLACEMENT RELATIONSHIPS

Relationships are developed to describe the location and amount of primary and secondary displacement given a surface-rupturing earthquake. The fault rupture evaluation provides a description of the pattern, amount, and probability of differential fault displacement for the primary faults and secondary faulting around the primary faults. A primary fault is defined as a fault that is large enough in dimension 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 as having surface displacement related to secondary strain release, rather than directly related to co-seismic slip. 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. The expected pattern of primary and secondary faulting associated with earthquakes in the Yucca Mountain region will be assessed based on the empirical observations of Basin and Range ruptures. Any relationships between the width of the zone of secondary deformation and hanging-wall/foot-wall, 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 will provide constraints on the expected horizontal and vertical components of 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 also consider the possible differences in the locations or amounts of displacement at the surface versus at the depth of the repository.

The principal basis for assessing primary displacement will be the slip rate on mapped faults. The slip rate will either provide the fundamental constraint on the average seismic moment release rate (if earthquakes are being considered), or the average rate of surface faulting. If paleoseismic data on recurrence intervals and/or the amount of displacement per event are available for particular faults, these data will also be incorporated into the evaluation of the likelihood of fault displacement. The probability of secondary faulting will be assessed conditionally on the occurrence of primary faulting of particular amounts or earthquakes of various sizes. The data used to assess the fault displacement hazard are summarized in Table C-5. The choice of the type of data and quantity is governed by both the need for physical characterizations (deterministic interpretations) and the need for assessment of the uncertainty (identify alternative interpretations and quantify uncertainties in parameters).

C3.4 STEP 4: FAULT DISPLACEMENT HAZARD CURVE

For a particular combination of seismic source and fault displacement inputs, the final product of the fault displacement analysis will be a hazard curve of the probability of exceeding various amounts of displacement at various locations in the vicinity of the surface facilities and the underground repository. For use in performance assessments of the repository, an integrated probability distribution of the amount of displacement anywhere within the repository will also be provided. This distribution incorporates the estimated length of faulting within the repository horizon. Depending on the geometries of spent waste storage facilities being considered, the probability of fault intersections can be provided (e.g., Coppersmith and Youngs, 1992).

C4.0 VARIABILITY AND 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. There are, however, two components of variability in these parameters: 1) randomness or stochastic variability, and 2) uncertainty or the variability due to lack of knowledge. Randomness is a characteristic of a natural physical process, and increasing the amount of data will not reduce the amount of variability but only help in characterizing it more accurately. Uncertainty, also called epistemologic variability, is dependent on our knowledge of physical phenomena. Uncertainty is due to different physical interpretations, mathematical formulations, and parameters for a given phenomenon. With additional data it may be possible to reduce uncertainty. In Step 5 of Figure C-1, the full variability (that due to both randomness and uncertainty) in the representations and parameters is expressed by a distribution of hazard curves, including mean and percentile curves.

C4.1 REPRESENTATION OF THE UNCERTAIN PARAMETERS

It is the state-of-the-practice to express the variability in each step of the calculation by describing each of the variable parameters with a probability distribution function. For practical reasons, and depending on the method chosen to propagate the uncertainty, those probability distributions can be either discrete or continuous.

C4.1.1 Variability in Seismic Source Inputs

Generally, variability in the seismic sources is represented by alternative interpretations permitted by the data, including different tectonic hypotheses. Alternative interpretations may be given in the form of: 1) weighted alternative boundaries for the seismic sources, each with its probability of activity; or 2) by weighted alternative seismic source maps. It is important to note that even with the most detailed site characterization achievable some uncertainty in the seismic source interpretations will remain. The methodology described herein provides a framework so that this uncertainty is incorporated explicitly into the assessment of the seismic hazard. Fault sources will be characterized by weighted alternative source geometries including length, location, depth, and dip (see Appendix A). Weights will be based on how well the alternative geometries explain the available data. The discrete probability distribution of seismic source maps is constructed by enumeration of all the possible combinations of sources.

C4.1.2 Variability in Earthquake Recurrence and Maximum Magnitude

The variability 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 Appendix A, Section A4.0) or by a joint distribution of the actual rate of occurrence for each magnitude. An independent distribution

of the maximum magnitude is also needed. These probability distributions can be either discrete or continuous.

C4.1.3 Variability in Ground Motion Attenuation or Fault Displacement

The full spectrum of uncertainty is represented by a set of weighted ground motion attenuation and fault displacement relationships. For vibratory ground motion, these relationships represent alternative approaches for assessing ground motion (e.g., empirical, theoretical and stochastic), as well as alternative methods within a general approach (see Appendix B). For fault displacement, the relationships represent different methods of evaluating the distribution and amount of rupture displacement on primary and secondary faults (see Section C3.3). One important issue is the selection of a numerical value for the parameter which expresses the random uncertainty. The value of this parameter (σ in Equation C-2), also uncertain, is characterized by a probability distribution. Ground motion recordings at Yucca Mountain will be used to evaluate this parameter and its distribution.

C4.2 PROPAGATION OF UNCERTAINTIES

The propagation of uncertainties is accomplished by one of two different techniques that produce equivalent results. The logic tree approach is based on enumerating all the sets of combinations of parameters identified by the provider of input. In the Monte Carlo simulation a number of simulations are performed to draw from the probability distributions of all the parameters identified as uncertain.

C4.2.1 The Logic Tree Approach

Figure C-2 shows schematically the mechanics of the method in the form of a logic tree. Each node on the tree represents a point of multiple possible alternatives that reflect the uncertainty in the particular parameter or representation symbolized by the node. Each alternative is represented by a distinct 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 branch with an associated probability. These probabilities are 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.

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 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. Thus, 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 value 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.

In addition, the following disaggregated results will be provided:

- The contribution to the total hazard by bins of distance and magnitude, by bins of distance and ground motion variance, and by bins of magnitude and ground motion variance
- The mean and median magnitude and distance values that represent the total hazard
- The hazard by seismic source
- The mean and median magnitude and distance represented by each seismic source hazard contribution.

The sensitivity and disaggregated 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 beneficial. The disaggregated results together with the sensitivity results 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.

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 and fault striae
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

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
Geodetic leveling, trilateration, and global-positioning satellite (GPS) surveys
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

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

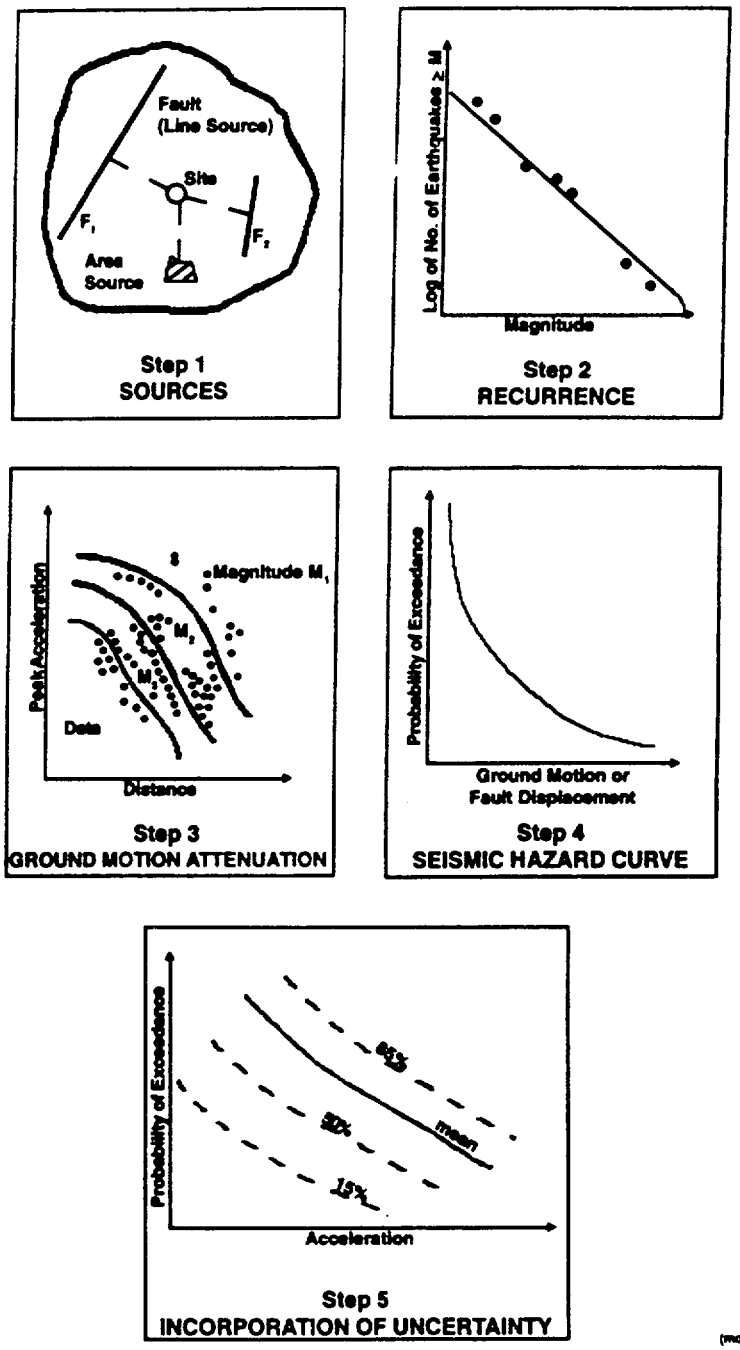
Estimates of overall fault length and fault segment length of Quaternary faults
Estimates of down-dip fault width from tectonic models
Focal depth estimates of earthquakes
Estimates of total displacement and displacement per event on Quaternary faults
Fault rupture models of primary and secondary fault ruptures
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

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

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 US 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

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



(modified from Reiter, 1991)

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

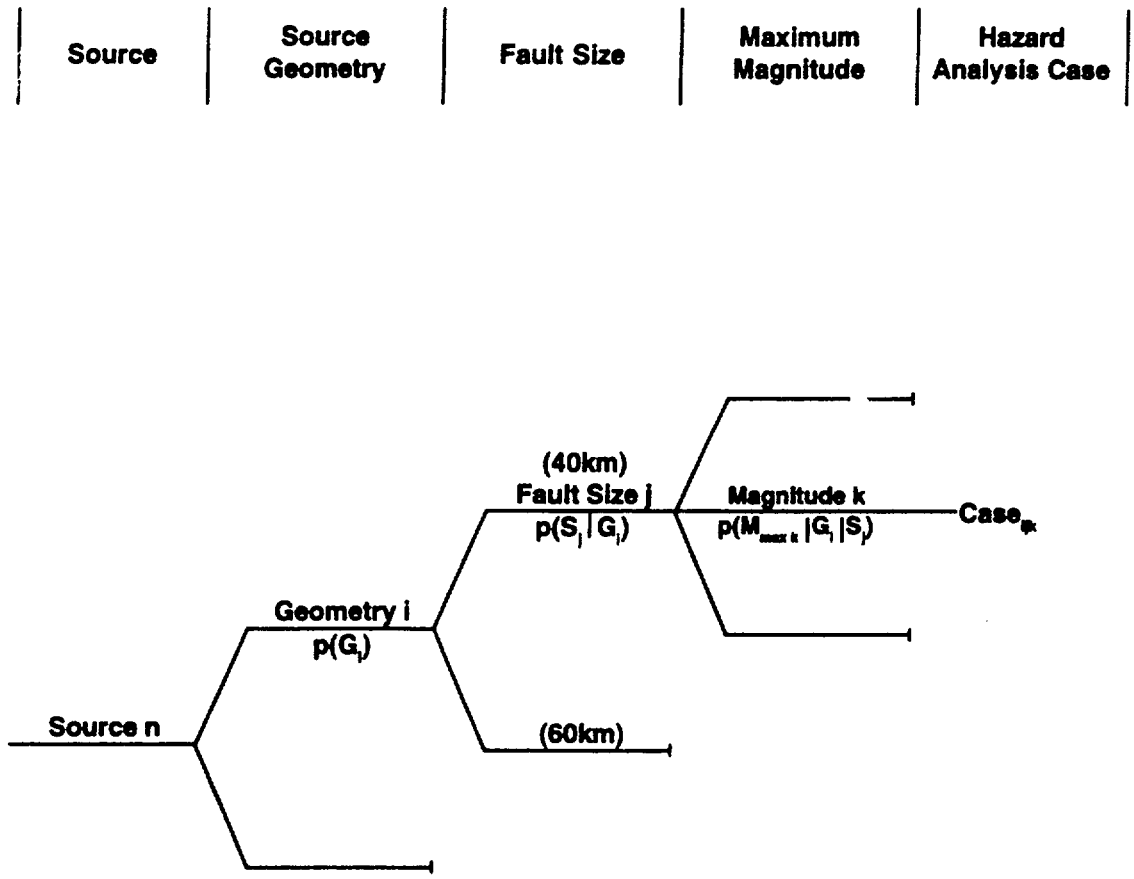


Figure C-2. Example Logic Tree Showing Uncertainties in Source Geometry, Fault Size, and Maximum Magnitude for a Given Fault Source n

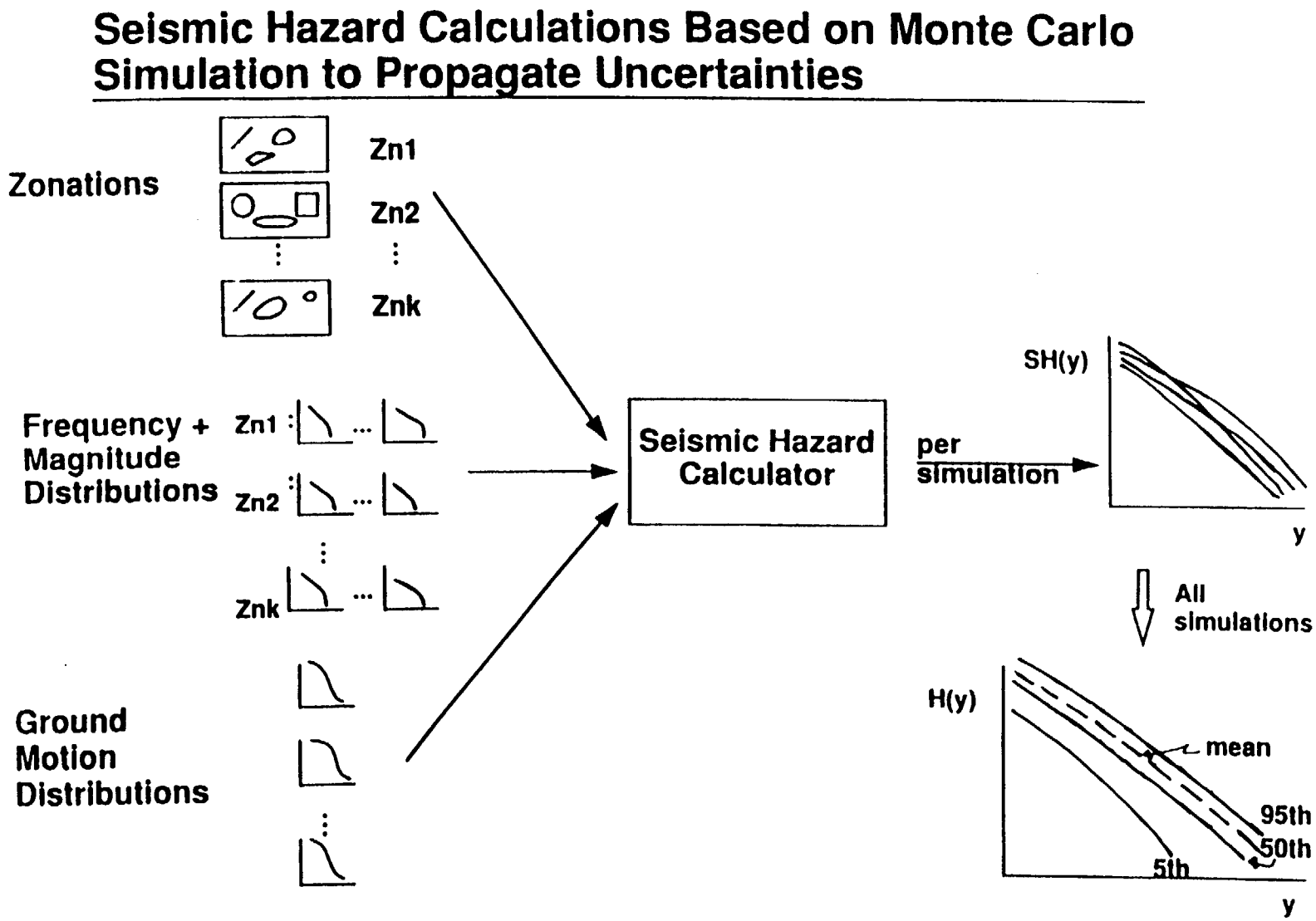


Figure C-3. Schematic Representation of the Monte Carlo Method of Propagating Uncertainties

APPENDIX D

DESIGN CONTEXT AND THE USE OF SEISMIC HAZARD ASSESSMENT RESULTS

APPENDIX D

DESIGN CONTEXT AND THE USE OF SEISMIC HAZARD ASSESSMENT RESULTS

D1.0 INTRODUCTION

This Appendix describes the design context of the proposed seismic hazard assessment (SHA) methodology and discusses the intended use of the results of SHA in the facility design process. Specifically, the objective of this Appendix is to demonstrate that the proposed SHA methodology can be used as an integral part of the DOE's existing engineering performance goal-based seismic design* and evaluation methodology that is suitable for a facility with general design and performance requirements similar to those of the potential GROA at Yucca Mountain. Sections D2 and D3 of this Appendix provide a background, evolution and an outline of this design method that has been in use in the DOE's nuclear and non-nuclear facilities for more than a decade. This method requires as input a probabilistic description of seismic hazard which the proposed SHA will provide. The suitability of this method in designing the potential repository facilities is discussed in Section D4.0.

D2.0 BACKGROUND AND EVOLUTION OF PERFORMANCE GOAL-BASED SEISMIC DESIGN METHOD

An ideal seismic design method should utilize design acceptance criteria and codes compatible with the facility mission, functional requirements, and specific safety goals. The design method should also incorporate the uncertainties associated with the characterization of seismic events that determine the magnitude of seismic design loads as well as the uncertainties in characterizing structure, system, and component (SSC) fragilities or capacities.

In conventional design of facilities, the facility mission and the functional requirements of the SSCs in the facility primarily determine the basic facility and SSC configuration. Typically, these and the desired safety requirements are met in the design by conforming to the provisions of applicable industry-accepted design codes and regulatory provisions. Examples of such codes are Uniform Building Code (UBC) for building structures and components, American Concrete Institute (ACI) code for concrete structures, and the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code for reactor vessels, steel containments, and piping components. These industry-accepted codes (except the UBC, which is not applicable for seismic designs of nuclear-type hazardous facilities) do not typically provide any guidance for the determination of seismic hazard levels that would be compatible with the permissible risks associated with the failure or unacceptable performance of the facilities and SSCs. Seismic hazard levels for a majority of the existing nuclear power plants were determined using the Operating Basis Earthquake (OBE) and Safe Shutdown Earthquake (SSE) concepts of 10 CFR 100, Appendix A. These concepts define a design basis earthquake for safety-related SSCs, but do not define it explicitly in terms of recurrence interval or probability of exceedance. Facilities and SSCs are then seismically designed using NRC-acceptable load combinations, analysis techniques, and acceptance criteria and industry-accepted codes and standards. The term "deterministic" is commonly used to describe such conventional design methods. Sometimes it implies erroneously that the seismic hazard level determined this way will never be exceeded and that if the acceptance criteria are satisfied, for all practical purposes, the SSCs designed for this seismic level will never fail because "adequate" safety factors have been provided in the design codes.

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* "Performance goal" is used in this Appendix in the sense of "seismic safety performance goal" as in the main body of the report (see footnote 5).

The above described deterministic design method has been in use for many decades. The safety factors built into the design codes have evolved through industry's experience (safety is determined by comparing loads or demands to capacities). These factors were introduced primarily to account for the uncertainties in the prediction of SSC strengths or capacities; whereas, the uncertainties in the loading itself are not explicitly accounted for. Thus, for SSCs or facilities for which the expected load is well established, or can be determined with relatively very little uncertainty, the long established deterministic design methods are well suited, except that these methods do not lend to easy determination of risks associated with a facility, and consensus is often difficult to achieve when loading from rare events, such as earthquakes, must be considered. Also, these deterministic methods result in non-uniform risk both geographically and for different natural phenomena hazards (NPH).

Since the late 1970s, new developments in seismic design methods have been directed towards overcoming these two inadequacies of conventional deterministic design methods, i.e., the inability to account for very low probability loads realistically and the inability to link safety goals and design codes directly. Initial efforts resulted in the use of load factors and variable acceptance criteria that indirectly account for the variation in the probability of occurrence of the loading events. The use of seismic probabilistic risk assessment (PRA) was also introduced. Load factors and variable acceptance criteria were used in the design of SSCs and also to evaluate their adequacies, but seismic PRA was used only to assess the risks associated with the facilities already built or designed. The use of load factors and variable acceptance criteria is simple and convenient, but cannot explicitly account for the variation in the probability of occurrence of loading events. On the other hand, the use of PRA in an iterative design process is not practical, because it requires: 1) the development of component fragility curves; 2) probabilistic assessment of facility failure resulting from a large number of component failure scenarios; and 3) PRA-based design and evaluation experience beyond that of average design engineers. So the search for a more explicit method continued into the 1980s.

Work during the past 10 years resulted in the development of a performance goal-based design and evaluation methodology that has been outlined in two Department of Energy (DOE) documents, UCRL-15910 (Kennedy et al., 1990) and draft DOE-STD-1020-92 (DOE, 1993), and in two recent technical papers (Kennedy, 1992; Nelson et al., 1992). The DOE plans to use the general design/evaluation methodology presented in these documents, and outlined in Sections D3 below, as the basis for the seismic design and evaluation of SSCs in the potential GROA facilities. However, the numerical and functional performance goals set in the aforementioned DOE documents may be modified to satisfy the unique design and performance requirements of potential GROA facilities at Yucca Mountain; these will be addressed in the second topical report on the seismic design process.

D3.0 AN OUTLINE OF THE DOE'S PERFORMANCE GOAL-BASED DESIGN METHOD

The DOE design/evaluation criteria for natural phenomena hazards (NPH) are founded on an approach whereby the mission and the failure consequences of the structures, systems, and components (SSCs) determine the stringency of their design. The requirements for earthquake mitigation are established so that the appropriate level of seismic protection is achieved for:

- occupant and public health and safety
- the environment
- production and research objectives
- preventing property losses.

SSC design performance goals are established on the basis of the relative risk to the public, worker, collocated worker, or the environment induced by the failure of the SSC. Acceptable risks are based on the general guidance for DOE nuclear facilities provided in the Secretary of Energy Notice (SEN), SEN-35-91, NUCLEAR SAFETY POLICY. This states, "DOE has adopted two quantitative safety goals to

limit the risks of fatalities associated with its nuclear operations. These goals are essentially the same as those established for nuclear power plants by the Nuclear Regulatory Commission (NRC) and, like the NRC goals, should be viewed as aiming points for performance." The goals, in essence, are that the risk of fatality to an average individual in the vicinity of a DOE nuclear facility, from accidents or cancer should not exceed 0.1 percent of the risk to which the public are generally exposed.

For NPH design of SSCs, the DOE's performance goal approach of design is implemented by defining four NPH performance categories, each with a qualitative performance goal for behavior and a quantitative target probabilistic performance goal. The performance goal is expressed as an annual probability of exceedance of acceptable behavior limits beyond which damage or failure is unacceptable. The performance goals for each performance category of SSCs in typical DOE facilities are presented in Table D-1. (Performance goal values for potential GROA facilities at Yucca Mountain, especially for the underground facilities, may be different from Table D-1 values because of unique configurations and functional requirements). These performance goals range from those provided implicitly by model building codes (such as the UBC), at Performance Category 1, to approximately those provided by nuclear power plant criteria, at Performance Category 4. To implement such performance-goal based seismic design criteria, the DOE's method defines seismic hazards in probabilistic terms, i.e., in terms of frequency or return period.

To illustrate the basic principle of the DOE's performance goal-based design method, let us consider the annual probability of exceedance of SSC damage due to earthquakes, designated as P_F in Table D-1 (P_F is Seismic Performance Goal or, simply, the probability of failure). The annual probability of exceedance of the earthquake hazard is correspondingly designated P_H (the Seismic Hazard Exceedance Probability or, simply, the probability of hazard). P_F is not only a function of P_H but also depends on factors of safety introduced by the seismic design/evaluation procedure and the acceptance criteria. The ratio of P_H to P_F is called the risk reduction ratio, R_R, which establishes the level of conservatism to be achieved through means such as facility layout, design detailing, and seismic design criteria. For example, if P_H is the same as P_F, then $R_R = 1$, and the seismic design approach will introduce no conservatism. However, if conservative design approaches are used, P_H can be larger than P_F, implying $R_R > 1$. For appropriate safety, the Design Basis Earthquake (DBE) and accompanying seismic design for a specific SSC are established in three steps:

Step 1: Establish an acceptable target seismic performance goal, P_F, for the components being designed or evaluated.

Step 2: Establish a set of conservative seismic acceptance criteria which introduce a significant risk reduction ratio, R_R, that reduces the risk of unacceptable seismic performance below the annual frequency of exceedance of the DBE.

Step 3: Establish the DB at an annual frequency of exceedance, P_H, equal to R_R (from Step 2) times P_F (from Step 1), i.e.:

$$P_H = R_R \, (P_F) \tag{D-1}$$

Table D-2 provides a set of seismic hazard exceedance probabilities, P_H, and risk reduction ratios, R_R, for Performance Categories 1 through 4 required to achieve the seismic performance goals specified in Table D-2 for SSCs in typical DOE facilities. For potential GROA facilities at Yucca Mountain these values may be different as will be addressed in a second topical report.

The seismic hazard exceedance probabilities, P_H, shown in Table D-2 produce ground motion levels which are: 1) consistent with UBC levels for Performance Category 1; 2) consistent with NRC regulated

fuel facility evaluation levels for Performance Category 3; and 3) consistent with nuclear power plant safe shutdown earthquake (SSE) levels for Performance Category 4. A description of how the performance goals were selected for typical DOE facilities and how the results of seismic PRA studies of nuclear power plants were utilized for this purpose is presented in a paper by Short et al. (1990)

SSC performance is a function of: 1) the likelihood of hazard occurrence, and 2) the strength of the structure or equipment item. Therefore, the DOE's design and evaluation criteria have been developed to attain performance goals by: 1) specification of hazard probability for definition of earthquake loadings, and 2) specification of response evaluation methods, acceptance criteria, and design detailing requirements with controlled levels of conservatism. Acceptable performance is reached by consistent specification of all design or evaluation criteria elements.

Once the seismic hazard exceedance probability (P_H) and the corresponding seismic hazard level are determined, the DOE's seismic design and evaluation methodology for the appropriate performance category achieves the necessary level of conservatism using deterministic design approaches which are familiar to engineers. Thus, this method explicitly accounts for the seismic loading uncertainties and at the same time, essentially permits the use of industry design codes and standards.

D4.0 SUITABILITY OF THE PERFORMANCE GOAL-BASED METHOD FOR THE REPOSITORY DESIGN

The potential repository at Yucca Mountain will consist of surface facilities with a conventional design life of 50 to 100 years and subsurface facilities or components for which seismic design performance goals will be established based on long-term waste containment and isolation performance requirements. The performance goal-based seismic design methodology outlined in Section D3.0 will be especially suitable for use in designing such facilities for the reasons discussed below:

1) This method permits the determination of seismic hazard level, analysis and evaluation requirements, and design acceptance criteria that are consistent with the overall safety goal. In such design methods, the linkage with the safety goal is distinct, traceable, and rationally established. Since the method is intended to meet certain safety and performance goals, it can render the design and construction cost of a facility consistent with the societal risk resulting from its postulated failure. (A purely deterministic and conventional seismic design method, by comparison, is either unable to account rationally for relative mission and safety significance of facilities and unconventional performance requirements, or at best accounts for these in an indirect and often inscrutable way).

2) The subsurface facilities or SSCs in the potential geologic repository that constitute the engineered barrier system (EBS), in combination with the geologic environment, together have a 10,000 year or longer performance requirement to contain and isolate waste. The design of such facilities may require consideration of very low probability seismic events. For example, the engineered waste emplacement and engineered barrier system should perform in a seismic event such that it does not result in early failure of waste canisters. The use of a performance goal-based design method provides a rational basis for meeting this performance objective.

3) The Yucca Mountain site has a number of faults, some of which may have a very low, but finite, probability of being active during the 100 year pre-closure period (repository operational period) of surface facility life or the 10,000 year or longer post-closure performance period of the subsurface facility. A purely deterministic design method cannot properly weigh the relative significance of such low probability occurrences. On the other hand, the performance goal-based method of design provides the means to account for events associated with such low-activity faults.

4) The use of performance goal-based seismic design will permit quantitative assessment of repository seismic performance (quantity and frequency of release) with relative ease, and will facilitate the overall facility performance assessment.

Table D-1. Structure, System, and Component (SSC) Seismic Performance Goals for Various Performance Categories in Typical DOE Facilities*

Performance Category	Seismic Performance Goal Description	Numerical Seismic Performance Goal (Annual Probability of Unacceptable Performance), P_F
1	Maintain Occupant Safety	= 10^{-3} of the onset of SSC damage to the extent that occupants are endangered
2	Occupant Safety, Continued Operation with Minimum Interruption	= 5×10^{-4} of the onset of SSC damage to the extent that the component cannot perform its function
3	Occupant Safety, Continued Operation, Hazard Confinement (SSC failure may result in limited off-site release of radioactive or hazardous materials)	=10^{-4} of the onset of SSC damage to the extent that the component cannot perform its confinement function
4	Occupant Safety, Continued Operation, Hazard Confinement (SSC failure shall not result in significant off-site release of radioactive or hazardous materials)	= 10^{-5} of the onset of SSC damage to the extent that the component cannot perform its confinement and containment function

* For potential GROA facilities at Yucca Mountain the performance goals will be based on facility-unique requirements and may be different from those provided in this table.

Table D-2. Seismic Performance Goals and Recommended Seismic Hazard Probabilities for SSCs in Typical DOE Facilities*

Performance Category	Seismic Performance Goal, P_F	Seismic Hazard Exceedance Probability, P_H	Ratio of Hazard to Performance Probability, R_R
1	1×10^{-3}	2×10^{-3}	2
2	5×10^{-4}	1×10^{-3}	2
3	1×10^{-4}	1×10^{-3}	10
4	1×10^{-5}	2×10^{-4}	20

*The values for potential GROA facilities at Yucca Mountain will be based on specific site characteristics and may be different from those shown in this table.

APPENDIX E

HISTORICAL CONTEXT OF THE PROPOSED SEISMIC HAZARD ASSESSMENT METHODOLOGY

APPENDIX E

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 (SHA). A number of the studies on which the methodology is based have been developed, reviewed, and/or endorsed by the U.S. Nuclear Regulatory Commission (NRC) for the nuclear industry. Although there are many key differences between a repository facility and a nuclear power plant facility, an important historical context is established by review and comparison with previous studies. This Appendix outlines the SHA methodologies that either have been presented in previous studies, or are currently being developed and have anticipated completion dates in late 1994 and in 1995. 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 SHA methodology presented in this topical report and in other recent and ongoing studies are summarized in Table E-1. Methodologies that incorporate probabilistic seismic hazard assessments (PSHA) were developed by the Lawrence Livermore National Laboratory (LLNL) and the Electric Power Research Institute (EPRI) in the 1980s; reviewed and/or endorsed by the NRC, both methodologies have been used extensively for evaluating nuclear power plant sites in the central and eastern United States. The LLNL and EPRI methodologies are currently being reviewed by the Senior Seismic Hazard Analysis Committee (SSHAC). Funded by the U.S. Department of Energy (DOE), EPRI and NRC, the SSHAC will recommend improvements that are intended to lead to a standard PSHA methodology for the next decade. As a result of the significant developments in SHA methodology during the past decade, the NRC is developing a draft rule, 10 CFR 100 Appendix B, that when adopted will replace the current Appendix A geologic siting criteria for new nuclear power plants. The draft rule incorporates a probabilistic procedure along with a deterministic procedure.

Two studies have direct application to the SHA 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 is currently developing guidelines for high-level nuclear waste repositories. EPRI recently sponsored development of a methodology for evaluating fault displacement through the proposed Yucca Mountain repository in their Earthquakes and Tectonics Project.

In a licensing context, two examples of programs approved or developed by the NRC and relevant to this topical report are provided in this Appendix. These are the reevaluation of the seismic design bases for the Diablo Canyon Nuclear Power Plant in California, and guidance developed by the NRC to include consideration of seismic events in the Individual Plant Examination of External Events (IPEEE) for severe accident vulnerabilities required for licensed nuclear power plants.

E1.0 SEISMIC HAZARD METHODOLOGIES OF OTHER STUDIES

E1.1 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 resulting study was reviewed by NRC, a committee of the National Research Council, and numerous private consultants. The study results were compared to those of a parallel study conducted by EPRI

(EPRI, 1988). The comparison showed generally good agreements in the median values of the seismic hazard; however, there were significant differences in the assessments of the uncertainties at some sites.

In 1989 LLNL was asked by DOE to develop site-specific assessments of the seismic hazard at the Savannah River Site (SRS) in South Carolina as part of the New Production Reactor (NPR) project. A complete review of the PSHA methodology previously developed and of the data acquisition process was subsequently performed for the NPR project. Work performed for the NPR project 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.

The basic steps in conducting a probabilistic SHA which were followed in the LLNL study are:

- Collect pertinent information on the seismic environment of the site.
- Interpret the data and assess input parameters.
- Express uncertainties as alternative interpretations or ranges on parameters permitted by the data.
- Compute probabilistic hazard curves using the resulting input assessments.

The seismic hazard is defined in terms of the annual probability of exceeding a maximum ground motion parameter, say, peak ground acceleration (PGA). Seismic hazard curves are computed for combinations of input assessments representing the range of uncertainty in scientific knowledge and data.

For the 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.

E1.2 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, p. 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.

There are multiple alternative explanations for the causes of earthquakes and there is variability in earthquake parameters. Therefore, there is considerable uncertainty about seismic hazard. Inputs to a seismic hazard analysis that contain uncertainty include: 1) seismic sources, 2) seismicity parameters, 3) maximum magnitude, and 4) ground motion relationships. In the EPRI study, uncertainty was captured by using as inputs the tectonic interpretations developed by six Earth Science teams. In addition, each team was encouraged to provide alternative tectonic interpretations, recurrence relationships and interpretations, and maximum magnitudes, in order 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).

E1.3 THE SENIOR SEISMIC HAZARD ANALYSIS COMMITTEE (SSHAC) STUDY

Given the significant developments in PSHA methodology in the parallel LLNL and EPRI efforts during the 1980s (see Sections E1.1 and E1.2), DOE, NRC, and EPRI are jointly funding a project to review the EPRI and LLNL methodologies as well as other studies, and recommend a standard methodology for the next 10 years or more. For this project, a committee of experts, the Senior Seismic Hazard Analysis Committee (SSHAC), was formed to direct the review and formulate the recommendations.

The SSHAC has identified strengths and weakness in both methodologies, but noted that the algorithms used yield equivalent results when similar input is used. The differences in the results principally came from the handling of the uncertainties. Rather than comparing and judging the EPRI and LLNL studies, the SSHAC has focused on formulating guidelines and recommendations for a PSHA methodology. Recommendations on the acceptable methods as well as those which are not recommended will be included. The conclusions and recommendations of the SSHAC are expected late in 1994. They will be reviewed by a committee of the National Research Council. While the DOE anticipates that its methodology will be largely consistent with the recommendations of the SSHAC, when those recommendations are issued the DOE will review its methodology and make changes if warranted.

E1.4 PROPOSED 10 CFR PART 100, APPENDIX B METHODOLOGY

The draft rule, 10 CFR Part 100 Appendix B, when adopted will replace the current Appendix A criteria for the seismic and geologic siting of future nuclear power plants. NRC has several goals in developing Appendix B, including incorporating the use of probabilistic analysis, and simplifying the 10 CFR Part 100 regulation by moving most of the details to Regulatory Guides and the Standard Review Plan.

Public comments on the draft Appendix B have been received and the draft is currently being revised by the NRC. It is expected that the actual rule will be significantly different from the proposed rule, but similar to the methodology proposed in this topical report.

In developing Appendix B, considerable thought was given to the best use of the probabilistic analyses to improve upon the current process of setting the design basis for nuclear power plants. One of the

major difficulties of the current rule is to determine the appropriate magnitude and distance for the safe shutdown earthquake (SSE) to properly reflect the uncertainty in a site's seismic environment (seismic sources, earthquake recurrence rates, maximum events and seismic wave attenuation relationships). The approach adopted in the proposed rule is to disaggregate the probabilistic analyses results to determine the magnitude (M) and location (D) of the controlling earthquakes. The details of the process are given in Draft Regulatory Guide 1015. It 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 probability of exceedance (PE) level defined by seismic design safety goals to determine a ground motion level. This PE level is expected to be based on the median probability of exceeding the SSE for the existing nuclear power plants. The M and D determined are then used in the ground motion attenuation relationships found to be most appropriate for the site to compute site-specific response spectra and time histories for seismic design evaluation.

E1.5 ANS COMMENTS ON PROPOSED 10 CFR PART 100, APPENDIX B METHODOLOGY

The Nuclear Power Plant Standards Committee of the American Nuclear Society (ANS) (ANS, 1993), while commenting on the proposed rule-making 10 CFR Parts 50, 52, and 100, "*Reactor Site Criteria*," made recommendations pertinent to the SHA methodology proposed in this topical report. The draft for 10 CFR 100, Appendix B, that was issued for public comment, contained the following provision: *"The ground motion at the site shall be estimated from all earthquakes up to and including the expected maximum earthquake associated with each source which could potentially affect the site using both probabilistic and deterministic approaches."*

Commenting on this provision, ANS stated:

> *"The requirement of the deterministic evaluation should be deleted. Due to inherent uncertainties in the seismic source interpretations, it is most logical to rely on probabilistic evaluations. Within the last ten years, probabilistic seismic hazard assessment methodologies have reached a level that they can be used with confidence to assess the adequacy of Safe Shutdown Earthquake ground motion."*

The ANS further noted that the following instruction, contained in the June 15, 1990 staff requirements memorandum of the Commission, was not considered in developing the seismic design basis:

> *"The staff should establish a formal mechanism, including documentation for ensuring that future regulatory initiatives are evaluated for conformity with the Safety Goal."*

ANS commented:

> *"The safety goal policy statement has been considered and used in the non-seismic portions of the proposed rulemaking and there are no reasons to exclude it from consideration and use in the seismic portions of the proposed rulemaking."*

Addressing the issue of which statistical measure (e.g., mean, median, 85th percentile, etc.) should be used to determine the controlling earthquakes, ANS commented:

> *"Mean values are recommended because they are used in the safety goal policy statement and are preferred in PRA work. To use the seismic hazard curves to develop site specific peak ground acceleration (PGA), they must be entered at a (generic) "reference probability," which can be derived from the safety goal policy statement.*
>
> *"The generic reference probability should be derived from the safety goal policy statement rather than the methodology in the proposed rule, which ignores the safety goals and uses median proba-*

bilities developed from the un-weighted SSEs of all existing plants regardless of design, location or vintage. The proper selection of the reference probability is of critical importance because it is the one number which all sites must use to determine their site specific PGAs from their site specific seismic hazard curves. A direct link between the reference probability and the safety goals is both possible and desirable in order to provide legitimacy for the reference probability."

The methodology proposed in this topical report addresses the above comments and recommendations.

E1.6 ASCE GUIDELINES AND RECOMMENDATIONS FOR EVALUATION AND SEISMIC DESIGN OF HIGH LEVEL NUCLEAR WASTE REPOSITORIES

The American Society of Civil Engineers (ASCE) Subcommittee on Dynamic Analysis and Design of High Level Nuclear Waste Repositories has recently prepared a document entitled "Seismic and Dynamic Analysis and Design Considerations for High Level Nuclear Waste Repositories" (ASCE, 1993*). The document was developed to establish guidelines that can be used to develop 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. Towards this objective, the ASCE document recommends the use of a performance goal-based design and evaluation philosophy that would permit the use of state-of-the-practice seismic hazard assessment methods and deterministic design codes and industry standards. Even though the guidelines and recommendations provided in the document are generic to geologic repositories, some examples and literature cited are drawn from studies related to the Yucca Mountain site. The seismic hazard methodology proposed in this topical report has basic elements that are identical or similar to those recommended in the ASCE document.

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 and provides guidelines to be used in performing seismic hazard assessment, analysis, and design. It also provides some general guidelines on the overall philosophy of the seismic design and evaluation process that it recommends for design. In the seismic hazard assessment area, generic guidelines are provided for determining design vibratory ground motion and design displacements associated with fault ruptures.

E1.6.1 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 a containment performance goal. The design of such facilities will require consideration of very low probability seismic events. Primarily because of these reasons (i.e., unconventional functional or performance requirements and the unusually long life of some facilities), the ASCE document contains recommendations that a performance goal-based seismic design and evaluation process capable of utilizing state-of-the-practice probabilistic-deterministic (composite) seismic hazard assessment methodologies be used. The document states that the DOE should develop a seismic design methodology and criteria document for the Geologic Repository Operations Area (GROA) based on the general design procedures presented in two DOE documents, UCRL-15910 (Kennedy et al., 1990) and DOE-STD-1020-92 (DOE, 1993), and in recent technical papers by Kennedy (1992) and Nelson et al. (1992). The application of these procedures in the GROA design will necessitate the development of certain GROA-specific criteria and methodology documents addressing the following issues:

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* As of writing this topical report, the ASCE Guideline has been submitted for review and approval by the ASCE Committee. The summary presented here is based on the review draft of the ASCE document.

- Compatibility between seismic performance goals and design criteria of Structures, Systems, or Components (SSCs) in a GROA
- Performance categorization of safety-related SSCs in a GROA
- Acceptance criteria and methodology for designing SSCs for seismic fault ruptures.

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

E1.6.2 General Guidance on Seismic Hazard Assessment

The ASCE document contains a recommendation that elements of both deterministic and probabilistic approaches be combined for the seismic design of a GROA, using the framework provided by the Panel on Seismic Hazard Analysis of the National Research Council (National Research Council, 1988). This combined approach consists of performing a probabilistic analysis that integrates overall seismic sources and earthquakes that significantly contribute to the site hazard, and then deriving a consistent single earthquake that represents that ground motion for analysis and design. Using a probabilistic method, seismic sources, maximum earthquakes and 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. From this, the design seismic level is established (that achieves the applicable performance goal for the facility based on an acceptable probability of exceedance) accounting for the uncertainty in the hazard curves.

Once the seismic design level is established along with its mean annual probability of exceedance, the probabilistic analysis disaggregates the hazard into different types of causative events (e.g., into magnitude and distance ranges, magnitude and ground motion variability) to determine the elements of the seismic environment that dominate the hazard, or to identify specific dominant seismic sources. From these dominant events, deterministic analyses are then performed to examine in detail the seismic characteristics (e.g., stress drops, rupture properties, wave propagation, site effects, etc.) of those earthquakes and their associated ground motions at the site.

A single earthquake can be used to accurately represent the ground motion spectrum approximately corresponding to a given annual probability of exceedance for the range of structural frequencies generally of interest. This single earthquake can then be used as a guide for the construction of time histories and for detailed time-domain response calculations.

E1.6.3 Guidance on Vibratory Ground Motion Determination

The major guidelines for the development and use of the hybrid 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 distribution of magnitudes associated with an earthquake prediction should be used if the probability of occurrence is based on a prediction. 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 has been observed to be non-controversial and, as such, it has been recommended that 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 sources of variability (i.e., randomness versus uncertainty) should be recognized. The uncertainty in input should be represented by uncertainty in the hazard curve and should not be included in the multiple integrals in the hazard calculations (as is done to account for randomness).

7) It is desirable to use multiple experts to obtain a justifiable range of seismic hazard results to 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.

E1.6.4 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 GROA:

1) The failure modes of a GROA 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 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.

With the above rationale for considering the design of GROA facilities for fault rupture hazards, the ASCE draft guideline provides some general guidelines that are summarized below:

1) Hazards due to surface fault rupture can be mitigated by: i) avoiding fault traces (i.e., establishing appropriate setback distances from the fault); ii) demonstrating that the nature and amount of deformation can safely be accommodated in the design of the facility; and/or iii) 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.

E1.7 EPRI YUCCA MOUNTAIN EARTHQUAKES AND TECTONICS PROJECT

As part of their High Level Waste (HLW) 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 HLW 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 HLW project are to develop an integrated methodology for early site containment performance assessment 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 the 10,000-year containment period of the proposed Yucca Mountain repository. The Phase 1 study created a structure that can effectively deal with the uncertainties of each input element; however, the implementation has been limited to demonstration of the methodology.

During Phase 2 of the EPRI HLW 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 two-fold: 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 due to 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 induced by rupture 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.

E2.0 SEISMIC HAZARD ASSESSMENT APPLICATIONS IN A REGULATORY FRAMEWORK

E2.1 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 (LTSP) 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 LTSP.

The reevaluation of the seismic design bases was specified in the Unit 1 Full-Power Operating License, issued by the U.S. Nuclear Regulatory Commission (NRC) on November 2, 1984. The Diablo Canyon LTSP 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, 1989). 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.

E2.1.1 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.

E2.1.2 Evaluation of Ground Motions

The objectives of the ground motion studies of the LTSP were to re-evaluate 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 (effects); 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 LTSP.

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 separate 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 mismatch 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, 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.

E2.2 THE INDIVIDUAL PLANT EXAMINATION OF EXTERNAL EVENTS (IPEEE) GUIDANCE FROM THE NRC

Seismic events must be considered in the Individual Plant Examination of External Events (IPEEE) for severe accident vulnerabilities required by the NRC for licensed nuclear power plants. NUREG-1407 (1991) defines the acceptable methods to identify potential seismic vulnerabilities for the purpose of performing an IPEEE. These methods are a seismic probabilistic risk assessment (PRA) or a seismic margins methodology (SMM). To perform a seismic PRA for the United States east of the Rocky Mountains (CEUS), NUREG -1407 (1991) recommends the use of methodologies developed by LLNL and EPRI (see Sections 1.1, 1.2, and 1.3 in this Appendix); for plants in the Western United States, a licensee is instructed to conduct its own study. Performance of an SMM is a deterministic analysis, and must be performed in accordance with standard practices.

For the Palo Verde Nuclear Generating Station (PVNGS), located near Wintersburg, Arizona, an investigation of seismic hazard at the site has been conducted (Risk Engineering, Inc., 1993). The results of this investigation will be used to guide decisions regarding levels of seismic evaluation for the IPEEE program. Although the LLNL and EPRI seismic PRA studies for the CEUS could not be applied directly to this Western US site, the methodologies of these studies were followed so that comparisons could be made between the hazard at the PVNGS and at other nuclear power plants 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.

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

Studies	Elements of the SHA Methodology					
	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[1]	x?	x?	x?		x?	x?
Proposed 10 CFR 100 Appendix B[1]	x?	x?	x?		x?	x?
ASCE Guidelines	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	

[1] Study in progress; elements that are likely to be included are queried

APPENDIX F

REFERENCES

APPENDIX F

REFERENCES

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STANDARDS AND REGULATIONS

10 CFR Part 60, Code of Federal Regulations, Title 10 - Energy, Part 60, "Disposal of High Level Radioactive Wastes in Geologic Repositories."

Energy Policy Act of 1992, Public Law 102-1018, Title VIII - High-Level Radioactive Waste, Section 801, Nuclear Waste Disposal.