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PROBABILISTIC SEISMIC HAZARD ANALYSES FOR FAULT DISPLACEMENT AND VIBRATORY GROUND MOTION AT YUCCA MOUNTAIN, NEVADA

FINAL REPORT
VOLUME 1 TEXT

Prepared for the

U.S. Geological Survey

by the

Civilian Radioactive Waste Management System
Management & Operating Contractor

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Report Coordinators

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PROBABILISTIC SEISMIC HAZARD ANALYSIS (PSHA)
FINAL REPORT

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LIST OF ACRONYMS

AAR	Arabasz, Anderson, Ramelli team
ASM	Ake, Slemmons, McCalpin team
CNWRA	Center for Nuclear Waste Regulatory Analysis
CRWMS	Civilian Radioactive Waste Management System
DOE	U.S. Department of Energy
DSR	Doser, Fridrich, Swan team
EPRI	Electric Power Research Institute
ESF	Exploratory Studies Facility
GM	Ground Motion
IAEA	International Atomic Energy Agency
M_{max}	maximum magnitude
M_w	moment magnitude
M&O	Management and Operating (Contractor)
NRC	U.S. Nuclear Regulatory Commission
NTS	Nevada Test Site
PGA	peak ground acceleration
PSHA	Probabilistic Seismic Hazard Analyses
QA	quality assurance
QARD	Quality Assurance Requirements and Description
RVT	Random Vibration Theory
RYA	Rogers, Yount, Anderson team
SBK	Smith, Bruhn, Knuepfer team
SDO	Smith, de Polo, O'Leary team
SSCs	structures, systems, and components
SSFD	Seismic Source and Fault Displacement
SSHAC	Senior Seismic Hazard Analysis Committee
UHS	uniform hazard spectrum
UNE	underground nuclear explosion
USBR	U.S. Bureau of Reclamation
USGS	U.S. Geological Survey
WCFS	Woodward-Clyde Federal Services

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EXECUTIVE SUMMARY

As part of the U.S. Department of Energy's (DOE) evaluation of Yucca Mountain as the site of a potential geologic repository for spent nuclear fuel and high-level radioactive waste, vibratory ground motion and fault displacement hazards were assessed probabilistically. The assessment methodology incorporated expert characterization of seismic sources, surface fault displacement, and ground motion. The experts also quantified estimates of uncertainties in their interpretations. Based on these inputs, hazard was calculated and expressed as the annual frequency at which levels of ground motion or fault displacement will be exceeded. These results form the basis for developing seismic design inputs and provide information on the frequency of occurrence of potentially disruptive events for assessments of long-term performance of a potential repository.

The assessment of seismic hazards relied upon the findings of scientific investigations carried out over the past 20 years or more to study the Yucca Mountain vicinity. Building upon earlier investigations of the Nevada Test Site region, characterization of the Yucca Mountain site has included:

- Evaluation of faults within about 100 km for evidence of Quaternary activity
- Detailed fault-trenching studies of active faults near Yucca Mountain to determine the history and characteristics of past earthquakes
- Monitoring of current seismicity
- Compilation of a catalog of historical and instrumentally recorded earthquakes in the Yucca Mountain region
- Development of a ground motion attenuation relation for extensional tectonic regimes which include the Yucca Mountain region
- Investigation of local site attenuation characteristics
- Numerical modeling of ground motion from scenario earthquakes
- Assessments of the tectonic stress field from hydrofracture measurements and earthquake focal mechanisms
- Collection and analysis of geophysical data to assess tectonic models and identify subsurface faults

- Collection and analysis of data to measure ongoing crustal deformation.

Results of these studies are described in the report "Seismotectonic Framework and Characterization of Faulting at Yucca Mountain, Nevada, (USGS, written communication, 1996). In addition, scientists from the State of Nevada, the Center for Nuclear Waste Regulatory Analyses, and various universities have contributed to the current understanding of the seismotectonic framework for Yucca Mountain. This extensive data base of information formed the basis for the Yucca Mountain seismic hazards analysis.

The probabilistic seismic hazard analysis (PSHA) methodology, which is described in the Topical Report *Methodology to Assess Fault Displacement and Vibratory Ground Motion Hazards at Yucca Mountain, Revision 1* (DOE, written communication, 1997a), allows for the uncertainties inherent in characterizing future ground motions and fault displacements to be explicitly incorporated into the assessment of hazards. By providing information on the annual frequency with which different levels of ground motion or fault displacement will be exceeded, the results support a graded approach to seismic design and provide information needed for performance assessment.

Title 10 of the Code of Federal Regulations, Part 60 defines two events that must be considered in seismic design: Frequency Category 1 and Frequency Category 2 events. In the Topical Report *Preclosure Seismic Design Methodology for a Geologic Repository at Yucca Mountain, Revision 2* (DOE, written communication, 1997b), DOE requires that design for Frequency Category 1 events will use ground motion with an annual frequency of exceedance of 10^{-3} and fault displacements with an annual frequency of exceedance of 10^{-4}. Corresponding values for Frequency Category 2 events are 10^{-4} and 10^{-5} for ground motion and fault displacement, respectively. Although criteria are defined for fault displacement design, the primary approach is to avoid faults capable of significant movement in laying out a repository.

Results of the seismic hazards analysis also support assessment of the long-term performance of a repository at Yucca Mountain. The annual frequencies of exceedance for ground motion and fault displacement provide information on how often the potentially disruptive effects of earthquakes will affect a repository.

Approach to Implementing Probabilistic Seismic Hazards Analyses. Topical Report *Methodology to Assess Fault Displacement and Vibratory Ground Motion Hazards at Yucca Mountain* (DOE, written communication, 1997a) describes DOE's approach to seismic hazard assessment. The approach is generally consistent with state-of-the-practice guidance provided by the Senior Seismic Hazard Analysis Committee (SSHAC, 1997) and the *NRC's Branch Technical Position on the Use of Expert Elicitation in the High-level Radioactive Waste Program* (NRC, 1996).

The PSHA for Yucca Mountain was performed in three strongly integrated parallel activities leading to the determination of fault displacement and vibratory ground motion hazards. The activities were (1) evaluation and characterization of relevant seismic sources including potential for fault displacement; (2) evaluation and characterization of vibratory ground motion attenuation, including effects of earthquake source, wave propagation path, and a rock site; and (3) probabilistic calculation of both fault displacement and vibratory ground motion hazards.

The hazard analyses are based on evaluations of seismic source characteristics, fault displacement, and earthquake ground motions that reflect interpretations of different scientific hypotheses and models using available data. These interpretations include uncertainties due to the inability of data to resolve different hypotheses and models. To evaluate scientific uncertainty, experts were used. Uncertainties were quantified using a logic tree approach in which different interpretations form different branches of a logic tree. Branches are given a weight depending on the expert's evaluation, using the available data, that each branch is the correct interpretation. Using this approach and the Cornell-McGuire formulation of the hazard calculation, uncertainties are propagated through the analysis. The hazard results are presented as mean, median, and fractile hazard curves representing the total uncertainty in input interpretations.

Seismic Source Evaluation and Characterization. Seismic source and fault displacement evaluations were performed by six expert teams (Table ES-1). The evaluations were conducted following a structured elicitation process that included information assimilation and interpretation workshops and individual team elicitations. The process was facilitated by the Seismic Source and Fault Displacement (SSFD) Facilitation Team, which was responsible for

TABLE ES-1
SSFD AND GM EXPERTS

SSFD TEAMS	AFFILIATION
Walter J. Arabasz	University of Utah
R. Ernie Anderson	U.S. Geological Survey
Alan R. Ramelli	Nevada Bureau of Mines & Geology
Jon P. Ake	U.S. Bureau of Reclamation
D. Burton Slemmons	Consultant
James McCalpin	GEO-HAZ Consulting, Inc.
Diane I. Doser	University of Texas, El Paso
Christopher J. Fridrich	U.S. Geological Survey
Frank H. (Bert) Swan	Geomatrix Consultants, Inc.
Albert M. Rogers	GeoRisk Associates, Inc.
James C. Yount	U.S. Geological Survey
Larry W. Anderson	U.S. Bureau of Reclamation
Kenneth D. Smith	University of Nevada, Reno
Ronald Bruhn	University of Utah
Peter L. K. Knuepfer	Binghamton University
Robert B. Smith	University of Utah
Craig dePolo	Nevada Bureau of Mines & Geology
Dennis W. O'Leary	U.S. Geological Survey

GM EXPERTS	AFFILIATION
John G. Anderson	University of Nevada, Reno
David M. Boore	U.S. Geological Survey
Kenneth W. Campbell	EQE International Inc.
Arthur F. McGarr	U.S. Geological Survey
Walter J. Silva	Pacific Engineering & Analysis
Paul G. Somerville	Woodward-Clyde Federal Services
Marianne C. Walck	Sandia National Laboratories

carrying out the technical elicitation and aiding the experts in structuring and quantifying their subjective evaluations. The elicitation process included a total of six workshops and a one-day elicitation meeting with each team. Each SSFD expert team evaluated seismic sources for ground motion and fault displacement hazard computation. The evaluations included alternative interpretations expressing the teams' uncertainties.

Two basic types of seismic sources were considered by the SSFD experts: fault-specific sources and areal source zones. For fault-specific sources, both local and regional faults were considered. Areal source zones are defined to represent zones of distributed seismicity that are not apparently associated with known specific faults. Local faults within a distance of about 20 km were characterized in terms of probability of activity, their geographic locations, rupture lengths, sense of slip, fault dips, and maximum seismogenic depths. The geometric characterization depended on the tectonic model(s) considered by the experts. Approaches used to evaluate the maximum earthquake for faults (maximum magnitude [M_{max}]) were based on empirical relationships between magnitude and the maximum rupture dimensions (e.g., surface rupture length, rupture area, and maximum and average displacement). Earthquake recurrence rates for the faults were described using either recurrence intervals and/or slip rates. Four recurrence models were used depending on the teams' evaluations: characteristic, truncated exponential, modified truncated exponential, and maximum moment.

In the characterization of local faults, alternative faulting behavior and structural models were evaluated by the SSFD expert teams to capture the range of complex rupture patterns and fault interactions. A planar-fault block model was preferred by most teams; linkages along strike or coalescence downdip were considered by all teams. Simultaneous rupture of multiple faults was also included in all of the teams' interpretations. Some teams considered detachment models to constrain the extent and geometry of the local faults while others included the detachment as being itself seismogenic.

Regional faults were evaluated and characterized by all SSFD expert teams using similar approaches. Regional faults are those faults within about 100 km that were evaluated to be capable of generating earthquakes of moment magnitude (M_w) 5 or greater. The number of regional faults included as seismic sources by teams ranged from 11 to 36. This reflects the teams' evaluations regarding the activity of various faults. All teams modeled the regional faults as planar faults to maximum seismogenic depths with dips depending on the style of faulting (90° for strike-slip faults, 60° or 65° for normal-slip faults). Alternative fault lengths were included to express uncertainty in their mapped lengths.

Seismicity related to volcanic processes, particularly basaltic volcanoes and dike-injection, was explicitly modeled in volcanic source zones by only two teams. Volcanic-related earthquakes were not modeled as a separate source by the other teams, but owing to the low magnitude and frequency of volcanic-related seismicity, were accounted for by the areal source zones.

For areal seismic source zones, the experts defined their boundaries and assessed M_{max} and recurrence. Several teams defined a site areal source zone representing the area where more detailed investigations have been conducted, and thus where the mapping of fault sources is more complete. M_{max} distributions for the areal zones represent uncertainty in the largest random earthquake in the region (associated with the minimum threshold for surface faulting) and/or estimated for a geologic structure that was not explicitly included as a fault-specific seismic source. Earthquake recurrence for the areal zones was derived from the historical seismicity record. Four alternative historical catalogues, which were provided to the SSFD expert teams, were evaluated for completeness, dependent events (e.g., foreshocks and aftershocks) removed, and underground nuclear explosions and other forms of blasting identified. All teams used the truncated exponential recurrence model to estimate earthquake recurrence rates within the areal source zones. Varying treatments of the background seismicity included (1) uniform smoothing of seismicity and (2) nonuniform smoothing using Gaussian kernels having different smoothing distances.

Fault Displacement Characterization. In addition to characterizing seismic sources, the SSFD expert teams also evaluated the potential for surface fault displacement at Yucca Mountain. Fault displacement characterization was carried out for nine locations within the Conceptual Controlled Area boundary. The test locations were defined to span the range of conditions for which fault displacement characterization is needed. They ranged from sites on block-bounding faults to a site in unfaulted rock and included sites on secondary faults and on fractures, both with a series of hypothetical displacement histories. Table ES-3 lists the test locations and their resulting hazard.

The SSFD expert teams developed original approaches to characterize fault displacement potential. These approaches were based primarily on empirical observations of faulting characteristics at Yucca Mountain and in the Basin and Range Province during past earthquakes. Empirical data were fit by statistical models to allow use by the experts.

The potential for fault displacement was categorized as either principal or distributed faulting. Principal faulting is faulting along a main plane (or planes) of crustal weakness that is the locus for release of seismic energy during an earthquake. Where the principal fault rupture extends to the surface, it may be represented by displacement along a single narrow trace or over a zone that is a few to many meters wide. Distributed faulting is rupture that occurs on faults in the vicinity of the principal rupture in response to the principal displacement. Distributed faulting is spatially discontinuous and may occur over a distance of several tens of meters to many kilometers from the principal rupture. A fault that can produce principal rupture may also undergo distributed faulting in response to principal rupture on other faults.

The approaches developed by the SSFD expert teams address characterizing the frequency of displacement events, λ_{DE} and the conditional probability $[P(D>d)]$ that, given an event, the observed displacement, D, will be greater than some value of interest, d. Approaches to characterize λ_{DE} divide into two categories: the *displacement approach* and the *earthquake approach*. The displacement approach provides an estimate of the frequency of displacement events directly from observed feature-specific or point-specific observed data. The earthquake approach relates the frequency of slip events to the frequency of earthquakes on the seismic source evaluated for seismic source characterization input to the ground motion hazard assessment.

For distributed faulting, the conditional probability of exceedance, $P(D>d)$, contains two-parts: the variability of slip from event to event, and the variability of slip along strike during a single event. The teams developed several approaches for characterizing the distribution of slip at a location given a principal faulting event.

Principal faulting hazard was assessed for sites located on faults that the SSFD expert teams identified as being seismogenic. The preferred approach for estimating the frequency of displacement events used slip rate divided by the average displacement per event. The expert teams used a number of approaches to evaluate the $P(D>d)$ based on empirical distributions derived from Yucca Mountain trenching data.

To characterize λ_{DE}, the teams used the frequency of earthquakes developed for the ground motion hazard assessment multiplied by the conditional probability that an event produces surface rupture at the site of interest. The along-strike intersection probability was computed using the rupture length estimated from the magnitude of the event randomly located along the fault length. Most teams used an empirical model based on historical ruptures to compute the probability of surface rupture. The preferred approach to assess the conditional probability of exceedance was to define a distribution for the maximum displacement based either on the magnitude or the rupture length of the earthquake. This distribution was convolved with a distribution for the ratio of the displacement to the maximum displacement to compute $P(D>d)$.

The preferred approach to characterize the frequency of displacement events on features subject to only distributed faulting was to use slip rate divided by the average displacement per event. The slip rates were based on the cumulative displacement and slip history. The teams used similar approaches for evaluating the conditional probability of exceedance to those used in the displacement approach for characterizing principal faulting hazard. The empirical distributions used are correlated with a scaling relationship used to estimate the average displacement per event.

The SSFD expert teams displayed the most variability in characterizing distributed faulting potential using the earthquake approach. The basic evaluation of the frequency of earthquakes was derived from the seismic source characterization for ground motion hazard assessment defined by each team. The probability that an earthquake causes slip at the point of interest was assessed in a variety of ways. The preferred approach utilized a logistic regression model based on analyses of the pattern of historical ruptures. The widest variations in approaches were those for assessing the distribution for displacement per event on the distributed ruptures.

Ground Motion Attenuation. Ground motion evaluations were developed using a similar process to that for seismic source and fault displacement characterization. Seven ground motion (GM) experts (Table ES-1) performed the evaluations. The evaluations were conducted following a structured elicitation process, which included information assimilation and interpretation workshops, working meetings, and individual expert elicitations. The process was facilitated by the GM Facilitation Team, which consisted of persons experienced in technical elicitation and in structuring and quantifying experts' subjective evaluations. The elicitation process included three workshops, two working meetings, and a one-day elicitation meeting with each ground motion expert.

The GM experts estimated median ground motion, aleatory uncertainty, and associated epistemic uncertainties for a matrix of earthquake magnitudes, source-to-site distances, and faulting styles and for a suite of spectral frequencies. These estimates were based on empirical and numerical simulation-based models and combinations of conversion factors. The matrix of point estimates consisted of 51 combinations of parameters considered to adequately define attenuation for the seismic sources considered by the SSFD expert teams. The matrix covered the range from M_W 5.0 to 8.0, distances from 1 to 160 km, and strike-slip and normal faulting (both hanging wall and footwall). The range of frequencies for which ground motion was evaluated spans the range of interest for the proposed Yucca Mountain facility: 0.3, 0.5, 1, 2, 5, 10, and 20 Hz in addition to peak ground acceleration (PGA) and peak ground velocity (PGV).

The GM experts' evaluations of point estimates were used as the bases to compute attenuation relations. The regression analysis to develop the attenuation relations was performed by the GM Facilitation Team. Each GM expert defined the distance measure used in the regression analyses for his/her point estimates. Each expert evaluated whether the footwall and hanging wall point estimates were regressed together, as a single normal faulting attenuation equation, or separately, yielding separate models for sites on the hanging wall and footwall. In addition, the experts evaluated the degree of magnitude saturation at close distances. The GM experts also evaluated two special cases, multiple parallel fault rupture and a shallow detachment fault, and developed scaling rules to apply to their models to represent these seismic sources.

Vibratory Ground Motion Hazard Results. Vibratory ground motion hazard was computed at a defined reference rock outcrop having the properties of rock at a depth of 300 m below the ground surface at Yucca Mountain - the waste emplacement depth. Ground motion was computed at this reference location as a control motion for later determination of seismic design bases motions for surface and potential waste-emplacement level (underground) locations.

The reference rock outcrop was defined to have a shear-wave velocity of 1900 m/sec and a median value of kappa (near-surface attenuation parameter) of 0.0186 sec. Based on limited data, this was the best estimate of kappa for the Conceptual Controlled Area available at the time of the study. If ongoing studies of kappa reveal that the median value for the shallow crust beneath the reference rock outcrop is different from 0.0186 sec, the median attenuation models provided by the GM experts can be adjusted using scale factors. Only the median ground motions would be effected. It is also expected that kappa will vary over the Conceptual Controlled Area due to variations in rock properties. This variability has been accounted for by the GM experts in their estimates of uncertainty in their ground motion attenuation relationships.

Based on equally weighted evaluations of the six SSFD expert teams and the seven GM experts, the probabilistic hazard for vibratory ground motion was calculated at the reference rock outcrop for PGA, PGV, and spectral accelerations at frequencies of 0.3, 0.5, 1, 2, 5, 10, and 20 Hz and are expressed in terms of hazard curves. The hazard is also expressed in terms of uniform hazard spectra. PGA, 0.3 and 1.0 Hz spectral acceleration values and PGV are summarized below for the annual exceedance probabilities of 10^{-3} and 10^{-4}.

Table ES-2

MEAN GROUND MOTION HAZARD AT 10^{-3} AND 10^{-4} ANNUAL EXCEEDANCE PROBABILITIES

Frequency (Hz)	**Horizontal**		**Vertical**	
	10^{-3}	**10^{-4}**	**10^{-3}**	**10^{-4}**
PGA	0.169g	0.534g	0.112g	0.391g
0.3	0.051g	0.168g	0.029g	0.105g
1.0	0.162g	0.471g	0.073g	0.222g
PGV	15.3 cm/sec	47.6 cm/sec	7.4 cm/sec	23.4 cm/sec

Vibratory Ground Motion Sensitivity Results. Extensive evaluations of the sensitivity of hazard results to evaluated parameters were performed. The earthquake recurrence approach (either slip rates or recurrence intervals) and recurrence models (e.g., characteristic, exponential, or maximum moment) were found to contribute most to uncertainty in the ground motion hazard, at the design basis hazard of 10^{-3} and 10^{-4} per year (Frequency Categories -1 and -2, respectively). M_{max} has a small effect on uncertainty especially for 10 Hz motions, because a large fraction of the hazard at this frequency comes from more frequent moderate-magnitude events. Geometric fault parameters (e.g., rupture lengths, dips, maximum depths) are minor contributors to uncertainty. These parameters have a moderate effect on the locations of earthquakes and on evaluations of M_{max}, but do not affect earthquake recurrence.

Although the SSFD expert teams' results vary somewhat, deaggregation of the mean hazard for an annual exceedance probability of 10^{-4} shows that at high frequencies (e.g., 5 to 10 Hz), ground motions are dominated by earthquakes smaller than M_w 6.5 occurring at distances less than 15 km. The sources of these events are the Paintbrush Canyon - Stagecoach Road and Solitario Canyon faults (or coalesced fault systems including these two faults) and the host areal seismic source zone. Dominant events for low-frequency ground motions, (e.g., 1 to 2 Hz) display a bimodal distribution showing significant contributions to the total hazard from large nearby earthquakes from the same three sources mentioned above and M_w 7 and larger earthquakes beyond distances of 50 km. The latter contribution is due mainly to the relatively higher earthquake recurrence rates for the Death Valley and Furnace Creek faults. Multiple-rupture interpretations involving comparable seismic moment release on more than one fault (i.e., those requiring modification of the attenuation equations) make a small contribution to the total hazard. Buried strike-slip faults, volcanic seismicity, and seismogenic detachments contribute negligibly to the total hazard. Uncertainty due to team-to-team differences in SSFD expert teams' evaluations is less than a factor of three from lowest to highest team.

The major contributor to epistemic uncertainty in the ground motion hazard is the experts' epistemic uncertainty in ground motion amplitude (within-expert epistemic uncertainty). Expert-to-expert uncertainty is moderate. This is believed to be the result of using a common information base and having elicitation and feedback, which minimized knowledge differences.

Fault Displacement Hazard Results. Probabilistic fault displacement hazard was calculated at nine demonstration sites within the Conceptual Controlled Area. Two of the sites have four hypothetical conditions representative of features encountered within the ESF. The integrated hazard results provide a representation of fault displacement hazard and its uncertainty at the nine sites, based on the interpretations and parameters developed by the six SSFD expert teams. Separate results are obtained for each site in the form of summary hazard curves. Table ES-3 summarizes the mean displacement hazard results for the two design basis annual exceedance probabilities, 10^{-4} and 10^{-5} (Frequency Categories -1 and -2, respectively), at the nine sites.

TABLE ES-3

MEAN DISPLACEMENT HAZARD AT NINE DEMONSTRATION SITES

		Mean Displacement (cm)	
		Annual Exceedance Probability	
Site	Location	10^{-4}	10^{-5}
1	Bow Ridge fault	<0.1	7.8
2	Solitario Canyon fault	<0.1	32
3	Drill Hole Wash fault	<0.1	<0.1
4	Ghost Dance fault	<0.1	<0.1
5	Sundance fault	<0.1	<0.1
6	Unnamed fault west of Dune Wash	<0.1	<0.1
7	100 m east of Solitario Canyon fault		
7a	2-m small fault	<0.1	<0.1
7b	10-cm shear	<0.1	<0.1

Site	Location	Mean Displacement (cm)	
		Annual Exceedance Probability	
		10^{-4}	10^{-5}
7c	fracture	<0.1	<0.1
7d	intact rock	<0.1	<0.1
8	Between Solitario Canyon and Ghost Dance		
8a	2-m small fault	<0.1	<0.1
8b	10-cm shear	<0.1	<0.1
8c	fracture	<0.1	<0.1
8d	intact rock	<0.1	<0.1
9	Midway Valley	<0.1	0.1

With the exception of the block-bounding Bow Ridge and Solitario Canyon faults (sites 1 and 2, respectively), the mean displacements are all 0.1 cm or less at a 10^{-5} annual exceedance probability. For the Bow Ridge and Solitario Canyon faults at 10^{-5} probability, the mean displacements are 7.8 and 32 cm, respectively. Thus, sites not located on a block-bounding fault (i.e, sites on the intrablock faults, other small faults, shear fractures, and intact rock) are assessed to have displacements of 0.1 cm or less for return periods up to 100,000 years.

The fault displacement hazard results display large uncertainty although the hazard levels are quite low. This uncertainty is indicative of the state-of-the-practice in PSHA for fault displacement, which is less mature than PSHA for ground motions. Nonetheless, the results obtained here are considered robust by virtue of the extensive efforts at expert elicitation and feedback, as well as the methodological developments, that were undertaken as part of this study. Sites with the highest fault displacement hazard show uncertainties comparable to those obtained in ground motion PSHA. Sites with low hazard show much higher uncertainties.

There is also a not unexpected correlation between the amount of geologic data available at a site and the uncertainty in the calculated hazard at that site. For sites where there are significant geologic data, the team-to-team uncertainty is less than one order of magnitude. For sites where there are few or no data, the individual team curves span three orders of magnitude. The larger uncertainty at these sites is considered to be due to data uncertainty, i.e., less certain constraints on the team's fault displacement characterization models.

REFERENCES

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1.0
INTRODUCTION

The Nuclear Waste Policy Amendments Act of 1982, as amended, assigns to the U.S. Department of Energy (DOE) the responsibility of evaluating Yucca Mountain as a potential geologic repository to site the nation's first permanent disposal facility for spent nuclear fuel and high-level radioactive waste. As part of this effort, two projects related to the seismic performance of the repository have been carried out: (1) probabilistic seismic hazard analyses (PSHA) and (2) the development of seismic design basis parameters. Both projects are being performed jointly by the U.S. Geological Survey (USGS) and the Civilian Radioactive Waste Management System (CRWMS) Management and Operating (M&O) contractor. The USGS has been assigned the primary responsibility for the PSHA Project and Woodward-Clyde Federal Services (WCFS), a member of the M&O Team, has been assigned the task to manage the project. This report describes the PSHA Project. The determination of seismic design basis input is being conducted by a Seismic Design Basis Team under contract to the CRWMS M&O (Risk Engineering, written communication, 1998a).

The PSHA Project was performed in three strongly integrated parallel activities leading to evaluations of fault displacement and vibratory ground motion hazards and to a documentation of the technical bases for these evaluations. The resulting hazards form the basis for determination of seismic design basis inputs for the Yucca Mountain repository structures, systems, and components (SSCs). Seismic design basis covers surface and subsurface SSCs. Both the preclosure and postclosure performance periods of the repository (100 and up to 100,000 years, respectively) were addressed in this project. The activities performed were: (1) evaluation and characterization of seismic sources including the characterization of potential fault displacement; (2) evaluation and characterization of vibratory ground motion attenuation, including earthquake source, wave propagation path, and rock site effects; and (3) computation of hazard results for both fault displacement and vibratory ground motion. This report describes the process followed to carry out the PSHA Project and includes documentation of the interpretations and uncertainties used as input to the hazard calculations for both the seismic source and fault displacement characterization and ground motion characterization.

1.1 PROJECT OBJECTIVES AND SCOPE OF WORK

The overall approach that the DOE has undertaken to address potential seismic hazards at Yucca Mountain is documented in three topical reports: "Methodology to Assess Fault Displacement and Vibratory Ground Motion Hazards at Yucca Mountain" (Topical Report No. 1) (DOE, written communication, 1997a) and "Preclosure Seismic Design Methodology for a Geologic Repository at Yucca Mountain" (Topical Report No. 2) (DOE, written communication, 1997b). Topical Report No. 3 planned for completion later this fiscal year, will document the results of both the PSHA and Seismic Design Basis Projects. The methodology adopted and used in the PSHA Project is described in Topical Report No. 1. The methodology and acceptance criteria used by the DOE to determine the preclosure seismic design of repository SSCs is described in Topical Report No. 2.

The objectives of the PSHA Project are to: (1) evaluate the fault displacement and vibratory ground motion hazards and their uncertainty at the Yucca Mountain site and (2) provide documentation of the technical basis for determining these hazards. The PSHA also provides quantitative hazard results to support an assessment of the potential repository's long-term performance with respect to waste containment and isolation and forms the basis for developing seismic design inputs for the License Application of the potential repository. The hazards results are in the form of annual frequencies of various levels of fault displacement at nine locations within the repository Controlled Area and of vibratory ground motion at a "reference rock outcrop." The reference rock outcrop is defined as free-field ground surface at the elevation of the proposed repository (300 m below the repository ground surface at Point A; Figure 1-1).

The hazard analyses are based on evaluations of seismic source characteristics, earthquake ground motions, and fault displacement that reflect interpretations of different scientific hypotheses and models using available data. These interpretations have associated uncertainties related to the ability of data to resolve different hypotheses and models with certainty. The interpretations described in this study are based on seismological, geological, geophysical, and geotechnical data specific to the Yucca Mountain site and the surrounding region within at least a radius of 100 km. To evaluate scientific uncertainty, seismic source and fault displacement characterizations have been made by six teams of experts, who in composite are expert in the seismicity, tectonics, and geology of the Yucca Mountain site and region. Ground motion evaluations have been made by seven individuals expert in the generation and attenuation of earthquake ground motions.

Interpretations for hazard assessment have been coordinated and facilitated through a series of workshops. Each workshop was designed to accomplish a specific step in the overall evaluation and to ensure that the relevant data were being appropriately considered and integrated. This process, which for this project is called the elicitation process, was designed to insure that credible hypotheses and models were evaluated and input to the fault displacement and vibratory ground motion hazard assessment.

The seismic hazard computational procedures used for this project produced quantitative assessments of seismic hazard based on input interpretations provided by the experts. Uncertainty in individual interpretations was captured in a logic tree structure as weighted alternatives and propagated through the hazard calculations. Thus the quantification incorporates uncertainty in the hazard due to scientific uncertainty in the input interpretations as well as to random variability in input parameters. The hazard results are presented as mean, median, and fractile hazard curves representing the total uncertainty in input interpretations.

1.2 RELATIONSHIP OF PSHA PROJECT TO PRECLOSURE AND POSTCLOSURE SEISMIC DESIGN BASIS DETERMINATION AND POSTCLOSURE PERFORMANCE ASSESSMENT

The following describes how the PSHA Project results will be used in the development of both preclosure and postclosure seismic design bases and in the assessment of postclosure performance.

1.2.1 Preclosure Seismic Design Basis Determination

The PSHA Project provides the needed information base for determining fault displacement and vibratory ground motion levels appropriate for seismic design of the proposed repository SSCs. The criteria for determining seismic design inputs are described in Topical Report No. 2 (DOE, written communication, 1997b) and will be used together with the PSHA results by the Seismic Design Basis Team to establish the seismic design basis for fault displacement and ground motions for the proposed repository. The seismic design basis will be documented in a separate report, "Seismic Design Input for a High-Level Waste Repository at Yucca Mountain, Nevada," which is in preparation (Risk Engineering, written communication, 1998a).

In accordance with Topical Report No. 2, seismic design inputs will be developed for Frequency Categories-1 and -2. For vibratory ground motion, the reference annual frequencies of exceedance for these two categories are 10^{-3} and 10^{-4}, respectively, or return periods of 1,000 and 10,000 years. The corresponding annual frequencies (and return periods) for fault displacement are 10^{-4} (10,000 years) and 10^{-5} (100,000 years), respectively.

Vibratory ground motion hazard has been assessed at the reference rock outcrop (Point A; Figure 1-1). As part of the seismic design basis determination now in development, design basis motions in the form of peak values, response spectra, and time histories for acceleration and velocity and for both horizontal and vertical components are being computed at Points B and C (Risk Engineering, written communication, 1998a). Also, peak ground velocity and dynamic strains are being computed at Points B and C and with depth between the ground surface and the repository level. The methodology for determining seismic design basis motions at the proposed locations of the surface facilities, which will be on alluvium in Midway Valley, illustrated by Point D on Figure 1-1, is being described as part of the separate seismic design basis evaluation. Actual computations of the seismic design basis motions for the surface facilities will be completed when the facility design and layout is more mature and the geotechnical properties of the alluvium have been obtained.

The seismic design basis motions will be developed considering four controlling earthquakes: an earthquake controlling high frequencies (5 to 10 Hz) and an earthquake controlling low frequencies (1 to 2 Hz) for the two return periods of 1,000 and 10,000 years. These four controlling earthquakes are derived by de-aggregating the probabilistic hazard as determined in the PSHA Project in terms of mean magnitude $(\overline{M})$, mean distance $(\overline{d})$, and ground motion deviation (ε).

For fault displacement, the principal design criterion provided in Topical Report No. 2 (DOE, written communication, 1997b) is to avoid faults that have the potential for offsets of engineering significance where reasonably feasible. Only in cases, if any, where fault avoidance is not feasible and for which the potential fault displacement is significant, as quantified by the PSHA, will fault displacement design be implemented in the design of the Yucca Mountain SSCs.

1.2.2 Postclosure Design Evaluation

Vibratory ground motion and fault displacement hazard information developed by the PSHA Project will be used to evaluate the effects of disruptive processes during the postclosure period on repository performance. SSCs important to safety must be designed and constructed to meet postclosure as well as preclosure performance requirements (DOE, written communication, 1997b). The DOE is employing a systems approach, which establishes the life cycle functions of repository SSCs, to ensure that they are designed to meet their performance requirements. Postclosure performance requirements may be controlling for some SSCs for which repetitive ground motion or fault displacementis is important.

An example is the postclosure performance with respect to rockfalls in emplacement drifts. Presently the DOE does not intend to rely on rockfalls not occurring in emplacement drifts for any period of time to meet postclosure performance (DOE, written communication, 1997b). Rather, the DOE intends to evaluate the effects of rockfalls, including incremental effects of repetitive seismic loading, on postclosure performance and, if necessary, design to mitigate their consequences. The seismic hazard curves developed by the PSHA Project will be integrated with consequence curves for this assessment. Other postclosure performance evaluations will make similar use of the PSHA Project results.

Postclosure performance evaluations generally involve integration of hazard curves taking account of uncertainty. The vibratory ground motion and fault displacement hazard curves developed by the PSHA Project contain the necessary information for this evaluation.

1.2.3 Postclosure Performance Assessment

Postclosure Total System Performance Assessment - Viability Assessment (TSPA-VA) will evaluate the effects of spatially and temporally varying processes on waste isolation and containment after the repository system is sealed and closed (CRWMS M&O, written communication, 1997). To accomplish the TSPA-VA, the respository system is divided into a series of natural spatial component models: the waste package, the engineered barrier system, the host rock, etc. The total system assessment model is constructed by linking the component models of the total system such that the input boundary conditions of each successive component are provided by the output of the preceding one. The base case total system performance is obtained by synthesizing the performance of the various component models.

The TSPA-VA treats vibratory ground motion and fault displacement hazards (together with other disruptive processes) as disruptive events and evaluates the impact (in terms of offsite consequences) on the base case repository system performance of their occurrence. The analysis procedure is essentially similar to any probabilistic seismic risk assessment in which the seismic hazard quantifies initiating event frequencies. The hazard is input as a vector of ground motion values or fault displacement values, and recurrence frequencies. The component model performance analysis converts the initiating event frequencies to component consequence frequencies, which are propagated through succesive component models to the total system performance, to obtain the effect of the hazard on the repository performance. Gauthier et al. (1995) have demonstrated the analysis process and performed preliminary evaluations of the response of repository component models to ground motion hazards. The fault displacement and ground motion hazard results of the PSHA Project will be used directly together with the refined component model response analyses, in subsequent TSPA-VA.

1.3 PREVIOUS STUDIES FOR YUCCA MOUNTAIN

The following briefly summarizes previous studies which are relevant to the probabilistic seismic hazard at Yucca Mountain.

1.3.1 Seismotectonic Studies

Since the late 1970s, Yucca Mountain has been investigated by DOE as a potential geologic repository for the storage of high-level radioactive wastes. As part of a broad interdisciplinary program designed to comprehensively evaluate site suitability, a series of specific studies bearing on the structural geology, tectonic evolution, and seismicity of the Yucca Mountain area and region was undertaken in the mid-1980s to analyze vibratory ground motion and fault displacement hazards that may affect repository design and performance (W.R. Keefer, USGS, written communication, 1996).

The structural geology and deformational and volcanic histories of the southern Great Basin have long been subjects of study since the beginning of the century. A period of extensive geologic and related studies at and near Yucca Mountain began in 1956, when efforts were initiated to investigate the feasibility of underground testing of nuclear devices at the Nevada Test Site, which includes the eastern part of Yucca Mountain. An integrated program of geologic mapping, stratigraphic and hydrologic studies, geophysical surveys, drilling and tunneling, and laboratory analyses of physical and chemical properties of rocks and surficial materials resulted in a large accumulation of new scientific data that provided the basic framework for interpreting the complex geologic and hydrologic conditions of the approximately 3900 km^2 test site area as well as adjoining areas (Eckel, 1968). Geologic mapping of all the 7½-minute quadrangles covering the test site including Yucca Mountain, at a scale of 1:24,000, was largely completed during the 1960's. The accumulated data, discussed in Eckel (1968), were instrumental in the subsequent selection of Yucca Mountain as a potential site for the underground storage of high-level radioactive wastes.

The Site Characterization Plan in 1988 (DOE, written communication, 1988) presented an integrated program of multidisciplinary studies designed to collect, analyze, and interpret the many and varied kinds of data that are considered essential for meeting regulatory, performance, and design requirements for a geologic repository. Since its issuance, the Site Characterization Plan has guided virtually all later investigations at Yucca Mountain, including seismotectonic studies within the Preclosure Tectonics Program (DOE, written communication, 1988), which were designed to develop an understanding of, and to characterize, the tectonic events and processes that could impact the potential repository SSCs.

1.3.2 PSHA Studies

Since the inception of the Yucca Mountain Project, several PSHA studies have been performed. The first analysis by URS/John A. Blume & Associates, Engineers (URS/John A. Blume & Associates, written communication, 1986) evaluated the ground motion hazard at Yucca Mountain for repository conceptual design. In that study, only areal source zones were defined and they were based on the historical earthquake record and limited paleoseismic data. Based on that probabilistic analysis, peak horizontal accelerations of 0.25, 0.40, and 0.65 g were calculated for return periods of 500, 2,000, and 10,000 years.

In a subsequent study, URS/John A. Blume & Associates, (written communication, 1987) evaluated both ground motion and fault displacement hazards to assess the effects of model and parametric uncertainties on the computed hazards. In that analysis, active faults were specifically characterized and modeled based on the available paleoseismic data. A simplified fault model was used to calculate the fault displacement hazard based on a joint probability for surface rupture displacement, length, and rupture radius exceedances together with the fault recurrence models. The calculated probabilistic ground motion hazard was dominated by the Paintbrush Canyon and related faults and by background seismicity and was most sensitive to the relationships between slip rate and fault lengths used in the analysis. The surface fault displacement hazard was calculated for the Paintbrush Canyon fault, and related primary (block-bounding) faults in the site vicinity. The resulting hazard was most sensitive to the assumed slip rate-fault length relations.

In a 1994 study for seismic design of the Exploratory Studies Facility (ESF), the CRWMS M&O performed a PSHA for ground shaking (Quittmeyer *et al.*, WCFS, written communication, 1994; Wong *et al.*, 1996). In that study, 24 Quaternary faults and a background areal zone were included in the analysis. Characterization of seismic sources included consideration of additional paleoseismic data collected as part of the site characterization activities. Four western U.S. empirical ground-motion relationships for rock were used to characterize the ground motion attenuation. The resulting peak horizontal accelerations for return periods of 1,000 and 10,000 years were 0.27 g and 0.66 g, respectively.

In a recent PSHA for the preliminary design of the Waste Handling Building (Wong *et al.*, 1998), the ESF study was updated by incorporating new paleoseismic data, particularly on the local faults, and the extensional regime ground motion attenuation relationship by Spudich *et al.* (1996). The resulting peak horizontal accelerations were 0.16, 0.21, and 0.50 g, for return periods of 500, 1,000, and 10,000 years, respectively. These motions were significantly lower than the ESF values due to the high weight (0.50) assigned to the Spudich *et al.* (1996) relationship (which results in calculated ground motions about 20% lower than California-based attenuation relations) and lower slip rates for the local faults based on more recent paleoseismic data.

In a demonstration project in 1992, Electric Power Research Institute (EPRI) sponsored an expert elicitation PSHA for fault displacement at Yucca Mountain. The objectives were to (1) demonstrate methods for eliciting expert judgment and (2) quantify the uncertainties associated with earthquake and tectonic issues for use in the EPRI High-Level Waste performance assessment.

In addition to these site-specific studies, PSHAs have been performed for hazard mapping on a national and state basis. Since 1948, ground shaking hazard maps have been developed for the entire U.S. that form the basis for the zonation in the Uniform Building Code. In the most recent maps (Frankel *et al.*, 1996), the peak horizontal accelerations for return periods of approximately 500, 1,000, and 2,500 years are about 0.16, 0.19, and 0.29 g, respectively, for the Yucca Mountain site. In a study for the Nevada Department of Transportation, R. Siddharthan *et al.* (written communication, 1993) developed statewide probabilistic hazard maps, which show peak horizontal acceleration values for the Yucca Mountain site of 0.24 g and 0.30 g for return periods of 500 and 1,000 years, respectively. Other PSHAs for vibratory ground motions have been performed for the Nevada Test Site by Rogers *et al.* (1977) and Coats and Murray (1984).

1.4 PROJECT ORGANIZATION

The major components of the project organization included the Principal Investigator, the Project Management Team, Review Panel, technical teams including the facilitation, data management, and calculations teams, and the two expert panels. Team members and experts are shown on Figure 1-2 and in Tables 1-1 to 1-4.

Although not part of the project organization, an important part of the PSHA process was the inclusion of model and data specialists. Specialists participated in the project by providing the expert evaluators with descriptions of their data, models, and interpretations, during workshops and the field trip. These technical specialists and their affiliations are listed in the summaries of the workshops and the field trip (Appendices C and D). At certain workshops, members of both the facilitation teams and evaluation experts also acted as technical specialists advocating a particular model, data set, or interpretation.

Dr. John Whitney was the Principal Investigator for the Project. In this role, he provided overall technical guidance for the work. In addition, he was responsible for implementing the Quality Assurance procedures by which the work was controlled.

1.4.1 Project Management Team

Management of the PSHA Project was provided by the Project Management Team. This team provided overall management of the project, managed the Project Review Panel, advised on technical issues relating to the project, and oversaw the efforts of the four technical teams. They also ensured consistency with regulatory requirements, DOE policies and guidelines, and program needs. They provided logistical and organizational management of the workshops and the preparation of reports. Regarding the latter, the Project Management Team ensured that appropriate project reviews were implemented in a participatory mode (SSHAC, 1997) to achieve completeness and high technical quality, and that project schedules and milestones were met. The team consisted of Dr. Carl Stepp, Project Director, Deputy Project Directors, Mr. Ivan Wong and Dr. Jean Savy, and Dr. Richard Quittmeyer, Senior Scientist responsible for CRWMS M&O geoscience activities.

1.4.2 Review Panel

The Review Panel (Figure 1-2) consisted of four individuals who are experts in the range of disciplines and topics that constitute the assessment of seismic hazards. Each member of the panel was responsible for a specific technical scope of work of the project: Dr. C. Allin Cornell - PSHA methodology and process, Dr. Thomas Hanks - vibratory ground motion, Dr. James N. Brune - seismic source characterization and vibratory ground motion, and Dr. David P. Schwartz - seismic source characterization and fault displacement evaluations. The panel review was fully participatory (SSHAC, 1997). Panel members attended the workshops and meetings relevant to their assigned scope of review; they provided formal review comments and recommendations within their technical scope following each workshop, and reviewed draft reports and prepared comments and recommendations that were reviewed and implemented by the Project Management Team.

1.4.3 Technical Teams

To plan, organize, and lead the technical workshops, facilitate the experts in their interpretations, and perform the required hazard calculations, four technical teams were assembled: (1) Seismic Source and Fault Displacement (SSFD) Facilitation, (2) Ground Motion (GM) Facilitation, (3) Data Management, and (4) PSHA Calculations (Figure 1-2).

1.4.3.1 Seismic Source and Fault Displacement Facilitation Team. This team facilitated the experts' seismic source and fault displacement evaluations for the hazard analyses. They provided the technical leadership to facilitate interactions and elicit interpretations by the experts. The SSFD Facilitation Team organized, planned, and led all technical workshops related to characterization of seismic sources and evaluations of the potential for fault displacement. Their responsibilities included (1) planning the technical scope, preparing any necessary white-paper documentation of the state-of-the-art, obtaining input and participation in workshops of data, model, or interpretation proponents, and facilitating discussion in the workshops; (2) preparing workshop agendas, conducting the workshops, and writing workshop summary reports; (3) eliciting interpretations of the experts; (4) providing feedback to the experts regarding the hazard results of their interpretations; and (5) preparing an Activity Report to describe the process followed to develop the experts' interpretations and to present the interpretations themselves. The team was led by Dr. Kevin Coppersmith. Other members of this team and their principal responsibilities are listed in Table 1-1.

1.4.3.2 Ground Motion Facilitation Team. This team facilitated the characterization of ground motion attenuation by the GM experts for a suite of parameters that was used in the PSHA. The responsibilities of the GM Facilitation Team were the same as those of the SSFD Facilitation Team. Dr. Norm Abrahamson led this team; other members and their principal responsibilities are listed in Table 1-2.

1.4.3.3 Data Management Team. The Data Management Team provided common data sets to the experts. The team compiled relevant data and provided derivative data products and evaluations as identified by the experts during the data needs workshops. The goal was to eliminate differences in interpretations caused by different data and knowledge bases. The historical earthquake catalog was compiled by the Data Management Team. This team was led by Dr. John Whitney and Ivan Wong and support was provided by the USGS and WCFS personnel (Figure 1-2).

1.4.3.4 PSHA Calculations Team.

The PSHA Calculations Team performed both preliminary and final seismic hazard computations. The computed seismic hazard is in the form of seismic hazard curves for (1) a range of spectral periods for vibratory ground motions and (2) for locations representing the range of faulting conditions within the Controlled Area. The team also modified the existing seismic hazards computational code for ground shaking to incorporate the code for calculating the hazard from fault displacement. The team was led by Dr. Gabriel Toro and consisted of staff at Risk Engineering, Inc. (Figure 1-2).

1.4.4 Experts

Scientific interpretations and uncertainty were incorporated into the probabilistic hazard analyses by including multiple evaluations of scientific evaluators with complementary experience and knowledge. These experts evaluated hypotheses, models, and processes using available data, and developed and documented interpretations for input into the PSHA calculations. For the seismic source and fault displacement characterizations, six three-person expert teams performed the interpretations. The aggregate expertise of each group covered the seismic geology, geology, tectonics, seismology, and geophysics of Yucca Mountain and the Basin and Range Province. Each SSFD expert team was responsible for identifying and characterizing the seismic sources significant to Yucca Mountain vibratory ground motions or fault displacement hazards. In addition, each SSFD team provided a characterization of the fault displacement potential for calculation of the fault displacement hazard at locations within the Controlled Area. These teams performed as virtual experts, expressing interpretation uncertainty that represented the teams uncertainty.

For ground motion attenuation characterization, seven individual GM experts provided evaluations for input to the PSHA. Each expert provided ground motion point estimates for a specified range of parameters. The GM experts were selected to cover the two principal approaches to estimating ground motions, empirical and numerical modeling, and included one expert in nuclear explosion ground motions. Tables 1-3 and 1-4 list the SSFD and GM experts, respectively, and their affiliations. Biographies of the experts are provided in Appendix A.

1.5 PROJECT ACTIVITIES

Planning of the PSHA Project by the Project Management Team began in August 1994 with the development of Study Plan 8.3.1.17.3.6 "Probabilistic seismic hazard analysis" and the Project Plan: "Probabilistic analysis of fault displacement and vibratory ground motion and development of seismic design bases for Yucca Mountain." The latter included the seismic design basis activities to insure integration with the PSHA Project. Selection of team members and experts followed in the fall of 1994.

Major activities of the PSHA Project were the workshop elicitation interactions conducted by the facilitation teams. These workshops provided the experts with the expert elicitation methodology, facilitated interaction among the experts, defined the data needed to perform their evaluations, provided a forum for discussing the range of relevant technical issues requiring evaluation, and facilitated the presentation and evaluation of state-of-the-knowledge research as well as proponent models and interpretations. The first workshop was held in April 1995. Due to Yucca Mountain Project funding constraints, the project was suspended in FY96 and resumed in FY97 with the remaining workshops. A thorough discussion of the workshops and the PSHA process as a whole is presented in Chapters 2.0 to 4.0 and 7.0; workshop summaries are in Appendices C and D. A final project meeting to present the results of the PSHA was held in April 1998 (Appendix C). The following briefly describes the general aspects of the three primary activities in the PSHA Project: the seismic source and fault displacement and ground motion characterizations and the hazard calculations.

1.5.1 Seismic Source and Fault Displacement Characterization

The purpose of this activity is to characterize known seismic sources significant to ground shaking and fault displacement hazard at Yucca Mountain. The SSFD expert teams were asked to provide and document in an elicitation summary their interpretations of the location, geometry, probability of activity, maximum magnitude, and recurrence rates of all seismic sources they identified as being significant to Yucca Mountain both in terms of vibratory ground motions and fault displacement. In addition, they were asked to characterize the fault displacement potential of faults and features at nine locations within the Controlled Area, including both primary and distributed faulting.

The process of evaluating and characterizing seismic sources for vibratory ground motion hazard assessment and characterizing potential for fault displacement for fault displacement hazard assessment generally followed the guidance in NUREG/CR-6372, "Recommendations for Probabilistic Seismic Hazard Analyses: Guidance on Uncertainty and Use of Experts" (NRC, 1997a), and in NUREG-1563, "Branch Technical Position on the Use of Expert Elicitation in the High-Level Radioactive Waste Program" (NRC, 1996). The determination of seismic design basis ground motion generally follows the guidance in Regulatory Guide 1.165, "Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motion" (NRC, 1997b), and NUREG-1451, "Staff Technical Position on Investigations to Identify Fault Displacement Hazards and Seismic Hazards at a Geologic Repository" (NRC, 1992). The evaluation and characterization of the potential for fault displacement made use of the guidance in NUREG-1494, "Staff Technical Position on Consideration of Fault Displacement Hazards in Geologic Repository Design" (NRC, 1994).

A very important objective of the SSFD characterization was to identify and assess the uncertainties in seismic source and fault displacement characterization. This aspect of the evaluation was designed to capture uncertainty both in the *models* used to characterize seismic sources, and the *parameter values* used in the models. The experts, who were both from within and outside the Yucca Mountain Project, represented a range of experience and expertise relevant to performing the evaluations. A deliberate process was followed in facilitating interactions among the experts, in training them to express their uncertainties, and in eliciting their interpretations. The resulting evaluations, therefore, provide reasonable assurance that the knowledge and uncertainties about seismic source and fault displacement characterization relevant to PSHA at the Yucca Mountain site has been captured and expressed in the seismic hazard results. The seismic source and fault displacement characterization is described in detail in Chapters 3.0 and 4.0.

1.5.2 Ground Motion Characterization

The goal of this activity was to characterize vibratory ground motion at the proposed repository as a function of ground motion frequency, given an earthquake magnitude and distance. The evaluation of ground motion resulted in ground motion attenuation relations specific to the repository site. The relations include earthquake source, propagation path, and site effects specific to Yucca Mountain. The attenuation relations describe ground motions for the range of structural response periods required for design of the proposed facility SSCs. Both horizontal and vertical components of motion have been characterized. Like the seismic source and fault displacement characterization, the experts evaluated the uncertainties in ground motion as part of their characterizations.

Ground motion attenuation relationships were characterized for both fault-specific and areal sources. Ground motions resulting from the different styles of faulting (strike-slip, normal, or reverse) were incorporated into the characterization. Thus the seismogenic sources, to a degree, define the technical issues that the ground motion characterization had to address. The ground motion characterization activity thus required coordination with the SSFD Facilitation Team and the PSHA Hazard Calculations Team. A detailed description of the ground motion characterization is contained in Chapters 5.0 and 6.0.

1.5.3 Probabilistic Seismic Hazard Analyses

The PSHA methodology for vibratory ground motions was first developed by Cornell (1968, 1971) and has become standard practice in evaluating seismic hazards. Subsequent to Cornell's work, the basic computational analysis method has changed little, but PSHA methodology has undergone extensive development principally by the U. S. Nuclear Regulatory Commission (NRC) and utilities that operate nuclear power plants. The most extensive and important developments have been structured procedures for quantifying subjective scientific evaluations of seismic sources, source earthquake recurrence characteristics, and ground motion input to seismic hazard assessment. This work has resulted in development of procedures to quantify input interpretations including experts' uncertainty in their evaluations, and a process for conducting PSHA that provides reasonable assurance that scientific and data uncertainties are properly captured and represented in the hazard results. These procedures and their application have undergone extensive review by the NRC and have been accepted for application to determine seismic design bases for nuclear facilities (EPRI, 1988, 1989; NRC, 1988, 1991, 1997a; SSHAC, 1997).

A probabilistic hazard assessment results in calculated annual probabilities that a given level of vibratory ground motion (e.g., peak horizontal acceleration) will be exceeded at a site. The resulting seismic hazard curve is obtained by integrating over all earthquake sources and magnitudes of potential future earthquake occurrence and ground motion variability. The methodology for assessing fault displacement hazard probabilistically is nearly identical to that for vibratory ground motions--the most important difference being that expert evaluations of fault displacement potential are the inputs to the assessment.

The calculation of ground motion hazard and fault displacement employs similar processes. For ground motion hazard, three basic inputs are required: (1) the identification of relevant seismic sources and characterizations of their source geometries; (2) an evaluation of the rate of earthquake occurrence, recurrence model, and maximum magnitude distribution for each seismic source; and (3) attenuation relationships that provide for the estimation of a specified ground motion parameter as a function of magnitude, source-to-site distance, and when needed, fault type and geometry. Inputs (1) and (2) are developed by SSFD expert teams and (3) by GM experts. For assessing fault displacement hazard, the ground motion attenuation relationships are replaced by relationships that describe the distribution, sense, and amounts of displacement with earthquake occurrence. Potentials for both primary and secondary fault displacement are characterized. Uncertainties in these input evaluations are expressed as alternative interpretations using a logic tree structure. In this study, the probabilistic ground shaking hazard was calculated using a Quality Assurance-approved computer code FRISK 88 version 2.0 developed by Risk Engineering, Inc. (written communication, 1998) For the calculation of the fault displacement hazard, the evaluations provided by the SSFD experts were coded and incorporated into the basic hazard code. Extensive sensitivity analyses were performed and provided to the experts. A detailed description of the calculated results is contained in Chapters 7.0 and 8.0.

1.6 QUALITY ASSURANCE

The PSHA Project was performed under the USGS Quality Assurance Program for the Yucca Mountain Project. DOE's Quality Assurance Requirements and Description document (QARD) (DOE/RW-0333P) provides the QA requirements for the Yucca Mountain Project and the USGS Quality Assurance Program is written to meet applicable requirements of the QARD. The key elements of the program applicable to PSHA were personnel qualifications and training, scientific expert elicitation, software controls, records management, and data management.

Personnel qualifications files consisting of position descriptions, resumes, and verification statements have been collected for members of the Project Management Team, the Review Panel, and the technical teams. Training in expert elicitation and in the applicable procedures was provided via workshops and reading assignments. At the time that the PSHA was performed, the QARD was silent on requirements applicable to scientific expert elicitation; however, the USGS developed a new Quality Management Procedure to include appropriate requirements for scientific expert elicitation. Revision 8 of the QARD, to become effective in June 1998, now includes requirements for scientific expert elicitation based on NUREG-1563, "Branch Technical Position on the Use of Expert Elicitation in the High-Level Radioactive Waste Program" (NRC, 1996). During a QA audit (USGS-ARP-98-01) of the USGS in October 1997, DOE's Office of Quality Assurance compared the USGS procedure, the PSHA Project Plan, and implementation to the NUREG guidance and to the then-draft QARD requirements. The QARD and the NUREG require the experts to document the reasons for any modifications to their interpretations. Within the structured expert elicitation process implemented for this Project, this requirement of the NUREG is considered to be met by the workshop summaries. The summaries contain descriptions of preliminary evaluations by experts. Any additional specific requirement to justify evolving evaluations is considered to have the unacceptable consequence of anchoring and biasing the expert's evaluations. The audit team accepted this position and justification.

Software QA requirements were applicable only to the computer codes for ground shaking and fault displacement hazard developed and modified by Risk Engineering. The Risk Engineering code modifications were required to be verified and the released code placed in the USGS Yucca Mountain Project Branch software configuration management system. Any software used by the experts in developing their interpretations were exempted from the QARD software requirements.

The report and the information required to support the development of Risk Engineering computer codes will be submitted to the CRWMS M&O records processing center. The hazards curves and logic trees will be submitted to the CRWMS M&O technical data base.

1.7 DOCUMENTATION OF PSHA EXPERT EVALUATIONS

The integrity of a PSHA is considered to rest principally on how it is structured and implemented to derive seismic source and ground motion inputs for hazard computation. For performing the Yucca Mountain PSHA, a structured process was adopted to obtain inputs that insured independent evaluations by recognized experts, representing the scientific community's state of knowledge. Evaluations were elicited through a process involving workshops each structured and implemented to achieve a specifically defined step in the overall evaluation (Sections 3.2 and 5.3), and through individual meetings between the facilitation teams and the experts. All workshops and meetings between the facilitation teams and experts were documented by summaries that are part of the basic documentation of the PSHA Project (Appendices C and D).

Two defining principles guided the elicitation process: 1) the experts are evaluators and their combined evaluations represent the informed scientific community's state of knowledge, and 2) the experts themselves are the owners of their independent evaluations. Thus, the elicitation process continually emphasized the role of the experts as independent evaluators responsible for considering proposed hypotheses and models using available data. It also emphasized that the experts themselves were responsible for describing their final evaluations in a summary report that would become part of the PSHA Project documentation.

Preliminary evaluations were developed by the experts and presented, discussed, and documented in the workshops. In recognition of principle (1) and the unacceptable risk of anchoring the interpretations at an immature stage, the experts were not required to provide written descriptions of their preliminary evaluations beyond the presentation materials in the workshops. Based on the experience base developed over the past decade or more in carrying out seismic hazard assessments, requiring specific documentation of experts' preliminary evaluations and specific justification for any change was considered to present an unacceptable risk of anchoring, and thus biasing, the evaluations before completion of the elicitation process. The experts also were provided feedback of hazard results based on their preliminary input evaluations. This feedback activity took place after the experts had completed draft expert summaries that described their input evaluations. These draft summaries are part of the PSHA Project basic documentation. Following the feedback activity, the experts were free to make changes in their evaluations before completing and submitting their final summaries for the seismic hazard calculations. The experts' final summaries of their interpretations are the final products of their evaluations. These are included in this report as Appendices E and F.

1.8 PROJECT PRODUCTS AND REPORT ORGANIZATION

This PSHA Final Report is a DOE Level 3 milestone. It is comprised of three Activity Reports that describe and summarize the three major project activities. These Activity Reports, which are Level 4 documents, are the "Seismic Source and Fault Displacement Characterization Project" (Geomatrix Consultants, written communication, 1997), "Ground Motion Characterization at Yucca Mountain, Nevada" (N. A. Abrahamson and A. M. Becker, Consultants, written communication, 1997a), and "Probabilistic Seismic Hazard Calculations for Yucca Mountain, Nevada" (Risk Engineering, written communication, 1998c`). In addition, as part of the milestone requirements, for the Final Report, included in Volume 3 are Appendix K "Yucca Mountain Project Records and Data Tracking Information for Data Used and Cited Within the Report," and Appendix L "Milestone SP32IM3 Description/Completion Criteria Compliance Location."

Following this Introduction (Chapter 1.0), there are eight chapters and 11 appendices in the Final PSHA Report. Chapter 2.0 describes the process of selecting the experts and provides a general description of the expert elicitation. Chapters 3.0 and 5.0 describe the facilitation approaches taken in the seismic source and fault displacement and ground motion characterizations, respectively. Chapters 4.0 and 6.0 describe the experts' evaluations of seismic source and fault displacement and ground motion, respectively. The probabilistic methodology used to quantify the ground shaking hazard at Yucca Mountain is presented, and the results along with sensitivity analyses are described, in Chapter 7.0. Chapter 8.0 presents the probabilistic hazard methodology for fault displacement and the results. References cited in the report are contained in Chapter 9.0. Appendix A contains biographies of both the SSFD and GM experts. Data packages distributed to both the SSFD expert teams and GM experts are listed in Appendix B. Appendices C and D contain the workshop summaries including a summary of the final project meeting where the final PSHA results were presented (Appendix C). The expert elicitation summaries are contained in Appendices E and F. Appendix G describes the development of the historical seismicity catalog. The development of the fault displacement hazard parameter distributions is discussed in Appendix H. Appendices I and J show the results of the attenuation regression analysis and the development of the hypocentral distance-based models for the areal sources, respectively.

TABLE 1-1

SSFD FACILITATION TEAM MEMBERS AND THEIR PRINCIPAL RESPONSIBILITIES

NAME	AFFILIATION	RESPONSIBILITIES
Kevin J. Coppersmith	Geomatrix Consultants, Inc.	Team leader, project planning and methodology development; facilitating workshops; documentation
Susan S. Olig	Woodward-Clyde Federal Services	Workshop and field trip coordination; workshop summaries; documentation
Roseanne C. Perman	Geomatrix Consultants, Inc.	Project planning and methodology development; documentation
Silvio Pezzopane	U.S. Geological Survey	Project planning and methodology development; data synthesis
Peter A. Morris	Applied Decision Analysis, Inc.	Review of project direction; expert elicitation methodologies and training
Robert R. Youngs	Geomatrix Consultants, Inc.	Project planning and methodology development; eliciting and formulating alternative models; documentation of results/sensitivity

Note: Kathryn L. Hanson, Geomatrix Consultants, Inc., assisted with documentation, review, and report preparation.

TABLE 1-2

GM FACILITATION TEAM MEMBERS AND THEIR PRINCIPAL RESPONSIBILITIES

NAME	AFFILIATION	RESPONSIBILITIES
Norm A. Abrahamson	Consultant	Team leader, project planning and methodology development; facilitating workshops; documentation
Ann M. Becker	Woodward-Clyde Federal Services	Project planning and methodology development; workshop summaries; documentation; data synthesis, elicitation
Peter A. Morris	Applied Decision Analysis, Inc.	Review of project direction; expert elicitation methodologies and training

Note: John Schneider was an original member of the Facilitation Team but left the Project in October 1996.

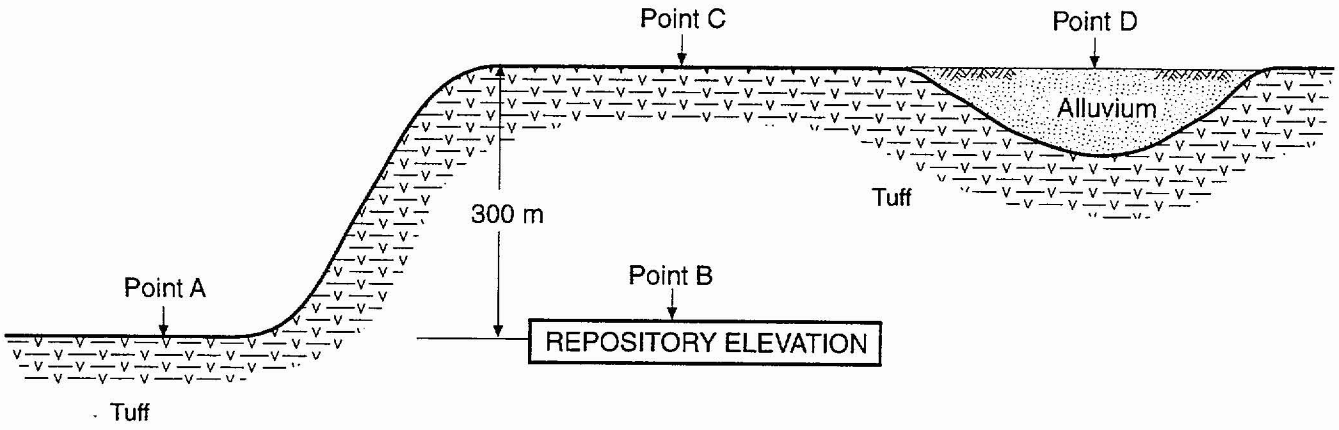
TABLE 1-3
SSFD EXPERTS

NAME	AFFILIATION	EXPERTISE
Jon P. Ake	U.S. Bureau of Reclamation	Seismology
R. Ernest Anderson	U.S. Geological Survey	Regional Geology and Tectonics
Larry W. Anderson	U.S. Bureau of Reclamation	Paleoseismology
Walter J. Arabasz	University of Utah	Seismology
Ronald Bruhn	University of Utah	Regional Geology and Tectonics
Craig dePolo	Nevada Bureau of Mines & Geology	Paleoseismology
Diane I. Doser	University of Texas, El Paso	Seismology
Christopher J. Fridrich	U.S. Geological Survey	Regional Geology and Tectonics
Peter L.K. Knuepfer	Binghamton University	Paleoseismology
Dennis W. O'Leary	U.S. Geological Survey	Regional Geology and Tectonics
James McCalpin	GEO-HAZ Consulting, Inc.	Paleoseismology
Alan R. Ramelli	Nevada Bureau of Mines & Geology	Paleoseismology
Albert M. Rogers	GeoRisk Associates, Inc.	Seismology
D. Burton Slemmons	Woodward-Clyde Federal Services	Regional Geology, Tectonics, and Paleoseismology
Kenneth D. Smith	University of Nevada, Reno	Seismology
Robert B. Smith	University of Utah	Seismology
Frank H. (Bert) Swan	Geomatrix Consultants, Inc.	Paleoseismology
James C. Yount	U.S. Geological Survey	Regional Geology and Tectonics

Note: Peter Knuepfer and Dennis O'Leary replaced Anthony J. Crone, USGS and Christopher M. Menges, USGS, respectively, during the course of the project.

TABLE 1-4
GM EXPERTS

NAME	AFFILIATION
John G. Anderson	University of Nevada, Reno
David M. Boore	U.S. Geological Survey
Kenneth W. Campbell	EQE International Inc.
Arthur F. McGarr	U.S. Geological Survey
Walter J. Silva	Pacific Engineering & Analysis
Paul G. Somerville	Woodward-Clyde Federal Services
Marianne C. Walck	Sandia National Laboratories



LEGEND

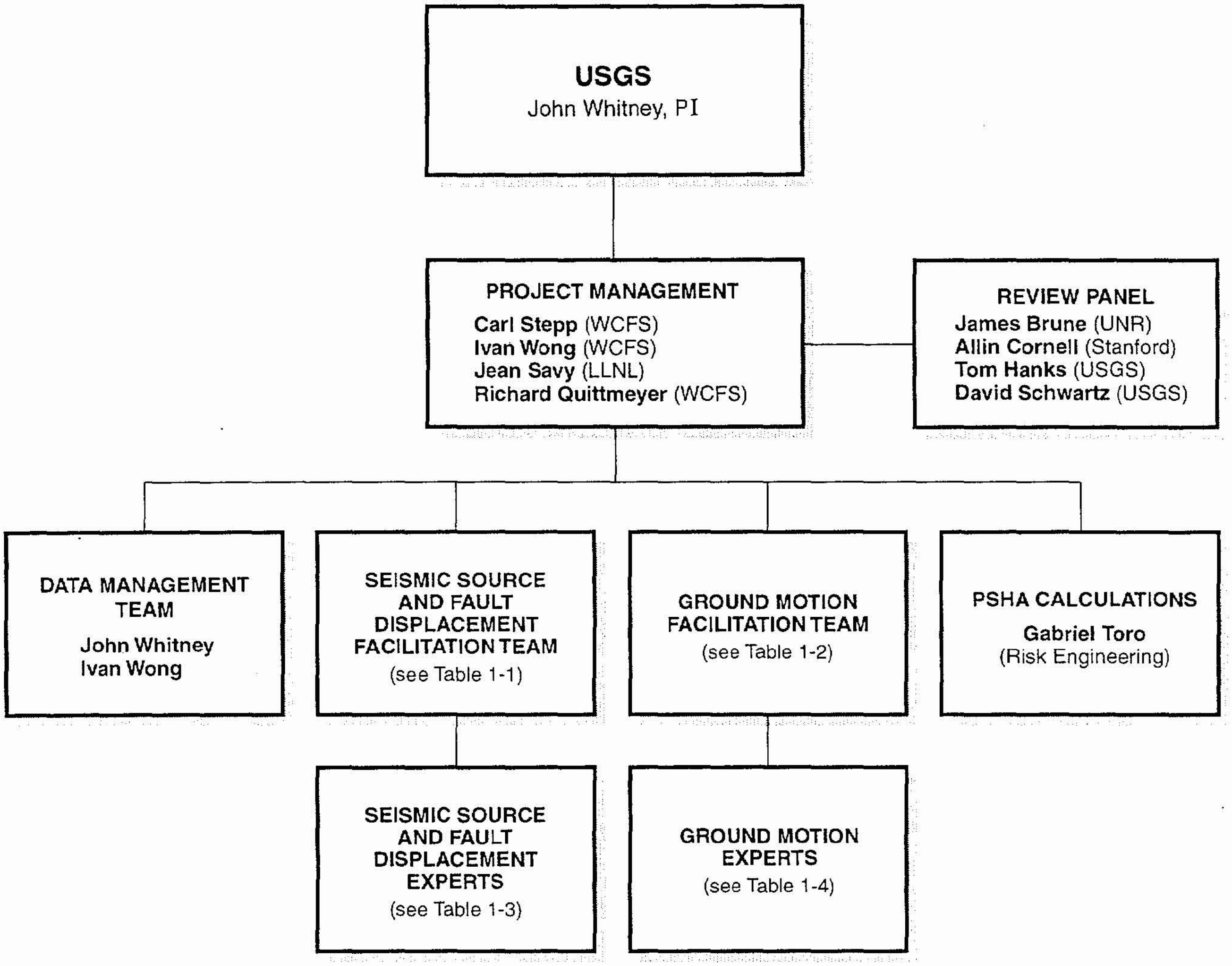
Point A – Reference rock outcrop at repository elevation

Point B – Repository elevation with tuff overburden

Point C – Rock surface

Point D – Soil surface

Figure 1-1 Locations of specified Design Basis Earthquake ground motions



WCFS – Woodward-Clyde Federal Services

LLNL – Lawrence Livermore National Laboratory

UNR – University of Nevada, Reno

USGS – U.S. Geological Survey

Figure 1-2 Project organization

2.0

GENERAL GUIDANCE, OVERVIEW OF EXPERT ELICITATION PROCESS, AND SELECTION OF EXPERTS

This chapter describes the criteria for being an expert, the expert selection process, and the general process followed in eliciting the evaluations of the experts. Experience has shown that to be credible and useful, technical analyses such as those performed for the seismic source, fault displacement, and ground motion characterizations must: (1) be based on sound technical information and interpretations, (2) follow a process that considers all available data, and (3) incorporate uncertainties (SSHAC, 1997). A key mechanism for quantifying uncertainties is the use of multiple expert evaluations.

In the PSHA Project, the term "elicitation" was used in a broad sense to include all of the processes involved in obtaining the technical evaluations of multiple experts. These processes include reviewing available data, debating technical views with colleagues, evaluating the credibility of alternative views, expressing interpretations and uncertainties in interviews, and documenting interpretations. In this sense, the elicitation process began with the first workshops and ended with the finalization of the expert elicitation summaries.

Because of the importance of the entire expert elicitation process, facilitation teams were established at the outset of the project. Facilitation team members had experience in developing guidance for and implementing multiexpert studies and in understanding the technical aspects of the project.

2.1 GUIDANCE REGARDING EXPERT EVALUATIONS

The procedures and approaches for expert elicitation developed through conducting many studies, have been formalized in guidance documents that were followed in this Project. DOE developed guidance for the formal use of expert elicitation by the Yucca Mountain Project (DOE, written communication, 1995), and the NRC staff issued a Branch Technical Position on use of expert elicitation in the high-level waste program (NRC, 1996). Comprehensive guidance on expert elicitation for seismic hazards assessments recently was set forth in a study sponsored by the DOE, the EPRI, and the NRC (SSHAC, 1997).

In this project, multidiscipline, multiexpert teams were used to evaluate seismic sources and fault displacement potential. Individual experts were used in the characterization of ground motion attenuation. Teams were used previously in a large probabilistic evaluation conducted to assess the seismic hazard at 37 commercial nuclear power plant sites in the central and eastern U.S. (EPRI, 1986). In the EPRI study, experts were arranged into six earth science teams, each having a range of expertise required for characterizing seismic sources, including seismology, geophysics, and geology/tectonics. Multiple workshops were held to evaluate technical issues, and each team developed seismic source characterizations, including their associated uncertainties. The technical basis for the assessments was documented in a final report (EPRI, 1986), and the study underwent extensive NRC review (EPRI, 1988). As with the EPRI study, each expert team in the seismic source and fault displacement characterization was expected to function as a virtual expert, expressing their evaluations and uncertainties as an individual expert. Teams were not asked to provide a single consensus evaluation, no more than an individual expert is asked to provide a single estimate. Rather, teams were asked to provide alternative interpretations expressing their range of uncertainties, just as individual experts are asked to provide their expressions of uncertainty.

The Senior Seismic Hazard Analysis Committee (SSHAC, 1997) defines the roles of expert *proponent, evaluator,* and *integrator*. An expert proponent advocates a particular technical hypothesis or interpretation, an expert evaluator considers the support for alternative hypotheses and interpretations in the available data and evaluates the associated uncertainties, and an expert integrator combines the evaluators' alternative interpretations into a composite distribution that includes uncertainties. The expert evaluators forego the role of proponent in making their interpretations and evaluating uncertainties. Proponents of specific hypotheses or interpretations participated as resources and presented their hypotheses or interpretations in workshops. Alternative proponent interpretations were presented to the experts and open scientific debate was facilitated by the integrator. Some expert evaluators also were proponents of a particular hypothesis or interpretation in a workshop.

Expert interactions are a central component of the elicitation process and must be properly facilitated (SSHAC, 1997). Experience from numerous seismic hazard studies has shown that experts interact frequently in their professional activities, and that workshops serve to provide information and interaction that facilitate their consideration of hypotheses and data and, ultimately, their evaluations and interpretations. Expert interactions in the PSHA Project were facilitated through multiple workshops and, for seismic source and fault displacement characterization, a field trip. Technical challenge and debate of alternative interpretations was the focus of these meetings, which included discussions of preliminary interpretations made by the experts.

The SSHAC (1997) process emphasizes the need to consider at the outset of a project the strategy for integration or aggregation of the experts' evaluations. This project at the outset defined a strategy to combine the evaluations of the experts using equal weights. The key procedural components of the project (ranging from the selection of experts to the dissemination of data sets) were designed to allow the equal-weights strategy to be implemented in a defensible manner. As noted by SSHAC (1997), the goal of a multiexpert evaluation of inputs to a PSHA is to capture and express the range of uncertainty such that the aggregated hazard results represent uncertainty of the informed technical community.

The PSHA Project followed the procedural guidance set forth in the SSHAC (1997) study, both in spirit (e.g., recognition of the importance of facilitated expert interactions) and, as applicable, in details of implementation (e.g., suggestions for conducting workshops and elicitation interviews). For example, the seismic source and fault displacement characterization elicitation was designed in accordance with SSHAC (1997) guidance. The expert teams were informed about and reminded of the need to express the full range of uncertainty, that is, they were asked to express alternative interpretations permitted by the available data weighted by the degree that each was considered to be supported by the data. The NRC Branch Technical Position (NRC, 1996) is generally consistent with the SSHAC guidance, providing the criteria for when expert elicitation should be used and outlining approaches for motivating, eliciting, and documenting expert evaluations. Other documents in the literature provide complimentary approaches to the formal or informal use of expert elicitation (e.g., Meyer and Booker, 1991).

2.2 GENERAL APPROACH

The general approach implemented by the PSHA Project for eliciting the evaluations of the experts is described in this section. The principal steps were:

(1) **Selection of Experts**. The Project Management Team established criteria for the selection of experts (see Section 2.3). These criteria were intended to insure that all the experts had proper professional stature and technical expertise. A list of candidates was developed by the Project Management Team with input from the facilitation team leaders. From this list of candidates, 18 SSFD and 7 GM experts were selected.

(2) **Development of Project Plan.** The Project Management Team developed a Project Plan that outlined the goals and key elements of the project, the scheduling of significant activities such as workshops, and the general topics to be covered by workshops and the field trip. Throughout the project, flexibility was maintained to address additional needs as they arose in order to assure that the project goals were achieved. For example, an additional feedback workshop was implemented to review fault displacement characterization methodologies, and additional feedback teleconferences were held to facilitate the finalization of fault displacement characterization. These additional activities are documented in this report.

(3) **Data Compilation and Dissemination.** The compilation and distribution of pertinent data, including published reference material, began early and continued throughout the project (Appendix B). Before the first workshops, the experts were sent a number of data sets and publications. Important data sets and publications identified during each workshop also were distributed. Experts were provided access, as needed, to all Yucca Mountain data gathered as part of the project and to data gathered by others (for example, the State of Nevada and the Center for Nuclear Waste Regulatory Analyses [CNWRA]).

(4) **Meetings of the Experts.** Structured, facilitated interaction among the experts took place during the workshops (and one field trip for the SSFD experts) and working meetings. The workshops were designed to identify the significant issues, review available data, debate alternative models, and review methods to quantify uncertainties in seismic source and fault displacement and ground motion interpretations. Proponents of particular technical positions provided their interpretations to the experts. Debate and technical challenge of alternative interpretations were facilitated to identify uncertainties. At these meetings, researchers from a variety of organizations engaged in studies relevant to the project, including the USGS, University of Nevada at Reno, Nevada Bureau of Mines and Geology, CNWRA, Lawrence Berkeley National Laboratory, and California Institute of Technology, presented pertinent data sets and alternative models and methods.

(5) **Elicitation Interviews.** One-day elicitation interviews were held between each of the three-member SSFD expert teams, GM experts, and representatives of the facilitation teams. Each expert or expert team provided their preferred and alternative evaluations, expressed their uncertainties, and specified the technical bases for their assessments. The facilitation teams documented the elicitation during the interview. The experts then independently prepared documentation of their evaluations, included as Appendices E and F in this report.

(6) **Feedback of Preliminary Results.** Following the elicitation interviews and the completion of preliminary interpretations, feedback workshops were held. The objectives of these workshops were to review, discuss, and debate the interpretations of each of the experts or expert teams, allowing them to understand the alternative approaches used by others as well as to technically defend their preliminary interpretations. Debate and technical challenge of the interpretations were encouraged to make sure that alternatives were understood and uncertainties were being appropriately incorporated. Facilitation and calculations team members presented preliminary analysis and sensitivity results. At the final workshops, the aggregation process was discussed.

(7) **Finalization of Expert Evaluations.** Following the feedback workshops, the experts revised and refined their interpretations and developed their final elicitation summaries. A series of technical reviews were conducted to insure that the sequence of models, components, and parameters was logical and complete and that the technical bases for the assessments were clearly provided.

(8) **Preparation of Activity Reports.** Activity Reports for seismic source and fault displacement characterization and ground motion characterization were prepared to document the process followed and the expert elicitation summaries.

2.3 SELECTION OF EXPERTS

The selection of experts involved four steps: (1) developing selection criteria, (2) obtaining a list of candidates, (3) selecting and inviting candidates to participate, and (4) for seismic source and fault displacement characterization, dividing the experts into six multidisciplinary teams. A selection panel, formed from members of the Project Management Team and other members of the project including the facilitation team leaders, was responsible for the selection process. The panel included Carl Stepp, John Whitney, Ivan Wong, Tom Hanks, David Schwartz, Silvio Pezzopane, Kevin Coppersmith, and Norm Abrahamson.

Expert selection was based on the following criteria:

- Strong relevant expertise as demonstrated by professional reputation, academic training, experience, and peer-reviewed publications and reports

- Willingness to forsake the role of proponent of any model, hypothesis, or theory and to perform as an impartial expert who considers all hypotheses and theories and evaluates their relative credibility as indicated by the data

- Availability and willingness to commit the time required to perform the evaluations needed to complete the study

- Specific knowledge of the Yucca Mountain area, the Basin and Range Province, or ground motion characterization

- Willingness to participate in a series of open workshops, diligently prepare required evaluations and interpretations, and openly explain and defend technical positions in interactions with other experts participating in the project

- Personal attributes that include strong communications skills, interpersonal skills, flexibility and impartiality, and the ability to explain clearly and succinctly the basis for interpretations and technical positions

The selection panel developed a preliminary list of candidates. Additional candidates were added to the preliminary list to form the final list of candidate experts. Candidates were nominated to capture the needed breadth of scientific expertise and technical knowledge and to obtain a range of organizational representation. Individuals who had expertise in each of three technical areas for seismic source and fault displacement were specifically nominated.

From the candidate list, 18 SSFD experts were initially selected in November 1994. Five of the seismic source and fault displacement candidates who were initially invited to become experts declined, stating schedule conflicts or perceived conflicts of interest. Additional individuals were contacted until the full complement of 18 experts was attained in January 1995.

In addition to the specific selection criteria, an important general requirement for the GM experts was to insure that the range of credible ground motion attenuation relations was represented. To that end, GM experts were selected from individuals knowledgeable in both the empirical approach to ground motions as well as numerical modeling techniques. Also, individuals knowledgeable in technical issues such as near-field source effects, crustal attenuation, path effects, site response, and ground motions from nuclear explosions were sought.

From the candidate list, six GM experts were selected by the panel in November 1994. In advance of their selection, the Project Management Team had concluded that the minimum number of experts necessary to provide diversity of knowledge was six (Geomatrix Consultants, written communication, 1997). A seventh GM expert was added to complete the representation of various ground motion models. All experts were contacted in late November and early December 1994 to determine whether they could participate in the PSHA Project. All seven selected GM experts agreed to participate.

Of the 18 SSFD experts who attended the initial April 1995 workshop, two subsequently resigned. Before the project resumed in October 1996, Dr. Tony Crone informed the Project Management Team that new commitments prevented him from continuing to serve as an expert. The selection panel chose Dr. Peter Knuepfer as a replacement. In early February 1997, the panel replaced Dr. Chris Menges, who withdrew for health reasons, with Dr. Dennis O'Leary. Dr. O'Leary is a member of the USGS Yucca Mountain geologic team and had been an active participant in all the seismic source and fault displacement workshops held to date.

The Project Management Team chose to form expert teams for seismic source and fault displacement characterization in order to incorporate the required scientific disciplines and diversity of knowledge. It was deemed essential that both geologic and seismologic disciplines were represented on the teams. Six three-person teams were formed, consisting of (1) an individual having particular knowledge and expertise about the paleoseismology and Quaternary faulting in the Yucca Mountain area, (2) an individual having particular knowledge and expertise about the regional geology and tectonics of the Yucca Mountain region and/or Basin and Range Province, and (3) an individual having experience or education in seismology and seismicity. The six individuals from each of the three technical areas were selected at random by the SSFD Facilitation Team and combined into teams. The acronyms for each team used in this report are given in order of area of expertise as follows: (1) seismology, (2) regional geology/tectonics, and (3) paleoseismology (e.g., the AAR team is composed of seismologist W. Arabasz, regional geologist E. Anderson, and paleoseismologist A. Ramelli) (see Section 4.3.1.1).

Consistent with the guidance of NUREG-1563 (NRC, 1996), all experts were asked to document any conflicts of interest relating to their roles as evaluators of seismic sources, fault displacement, and ground motion attenuation for Yucca Mountain. Each expert completed a conflict of interest statement, which is included as part of the records of the PSHA Project. None of the selected experts was precluded from participating in the Project on the basis of conflicts of interest.

3.0

SEISMIC SOURCE AND FAULT DISPLACEMENT CHARACTERIZATION FACILITATION APPROACH

In this chapter, the approach utilized by the SSFD Facilitation Team to elicit interpretations from the SSFD experts is described.

3.1 DATA COMPILATION AND DISSEMINATION

Data compilation and dissemination formed an important aspect of the seismic source and fault displacement characterization process. The goal was to ensure that the evaluations by the SSFD expert teams were based on a knowledge of all available data and existing interpretations in the published and unpublished literature. Initially during 1995, the USGS served as a clearinghouse for requests for and dissemination of data. In subsequent stages of the study, the SSFD Facilitation Team and the Data Management Team were responsible for receiving requests for data and for compiling and disseminating the data to the experts. The data distributed included journal articles, preprints of recently completed work, synthesis reports for Yucca Mountain work, digital data bases such as the fracture data base derived from the line-survey for the ESF, and empirical data compiled from literature. In some cases, compilations of data and simple analyses of the data (e.g., linear regressions) were performed by the SSFD Facilitation Team at the specific request of the expert teams. For example, Silvio Pezzopane conducted a number of analyses of empirical data regarding historical surface ruptures to fulfill requests made by the expert teams. These analyses are documented in the workshop summaries.

3.2 SEISMIC SOURCE AND FAULT DISPLACEMENT WORKSHOPS

The following sections summarize the workshops and field trips conducted during the project (Figure 3-1). These activities were the primary vehicles for expert interaction and review of technical issues. Detailed summaries of the workshops and field trip are provided in Appendix C.

3.2.1 Workshop #1-Data Needs

The Workshop on Data Needs, April 17-19, 1995, was the first of six workshops conducted for the seismic source and fault displacement characterization. The primary goals of the workshop were to identify key technical issues of importance to seismic source characterization and to specify the data required to characterize the seismic sources for vibratory ground motion and fault displacement hazards. Other objectives of the workshop were to provide information to the experts on the overall study, the products to be developed, the project schedule, the roles of various participants, alternative expert roles (evaluators, proponents, specialists), basic approaches to PSHAs and expressing uncertainties, and ground rules regarding communication and interaction throughout the study.

To accomplish these goals, the workshop included a series of presentations and discussion sessions that involved scientists from various organizations. The basic approach of the workshop was to (1) identify technical issues of most significance to seismic hazards at Yucca Mountain, (2) link those issues with the data most relevant to addressing the issues, (3) specify the available relevant data for the Yucca Mountain region, and (4) identify the data required by the experts to characterize seismic sources. During a discussion that followed workshop presentations by several technical specialists, the experts identified the issues deemed most important to characterizing seismic sources at Yucca Mountain. The identification of technical issues was essential for identifying the types of data needed, and to help create a common understanding among the experts of the important elements that directly or indirectly influence future seismic hazards at Yucca Mountain.

The major technical issues identified by the experts during the first workshop included (1) defining candidate seismic sources and associated maximum magnitudes for the background earthquake, (2) choosing recurrence models and weights for fault sources, (3) developing models for fault segmentation and multiple fault ruptures, (4) assessing the effects of triggering on earthquake recurrence, (5) characterizing fault geometry and kinematics, (6) characterizing distributive faulting, (7) assessing nonstationary and temporal clustering of earthquakes, and (8) assessing the importance of volcanic earthquakes and characterizing potential sources of such events. A complete list of the technical issues and required data identified by the experts is included as Table 2 in the workshop summary in Appendix C.