Probabilistic Seismic Hazard Analyses for Ground Motions and Fault Displacement at Yucca Mountain, Nevada

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Probabilistic seismic hazard analyses were conducted to estimate both ground motion and fault displacement hazards at the potential geologic repository for spent nuclear fuel and high-level radioactive waste at Yucca Mountain, Nevada. The study is believed to be the largest and most comprehensive analyses ever conducted for ground-shaking hazard and is a first-of-a-kind assessment of probabilistic fault displacement hazard. The major emphasis of the study was on the quantification of epistemic uncertainty. Six teams of three experts performed seismic source and fault displacement evaluations, and seven individual experts provided ground motion evaluations. State-of-the-practice expert elicitation processes involving structured workshops, consensus identification of parameters and issues to be evaluated, common sharing of data and information, and open exchanges about the basis for preliminary interpretations were implemented. Ground-shaking hazard was computed for a hypothetical rock outcrop at -300 m, the depth of the potential waste emplacement drifts, at the designated design annual exceedance probabilities of 10^{-3} and 10^{-4}. The fault displacement hazard was calculated at the design annual exceedance probabilities of 10^{-4} and 10^{-5}.

INTRODUCTION

The Nuclear Waste Policy Amendments Act of 1987, as amended, assigns to the U.S. Department of Energy (DOE) the responsibility for evaluating Yucca Mountain as a potential geologic repository for the nation's first permanent disposal facility for spent nuclear fuel and high-level radioactive waste. Yucca Mountain is located about 160 km northwest of Las Vegas, Nevada, in the Basin and Range Province. This portion of the Basin and Range Province is tectonically active in extension at a low strain rate, and characterized by late-Quaternary normal faulting, paleoseismic evidence for the occurrence of earthquakes up to about moment magnitude (M_w) 7.5, and a moderate level of historical seismicity.

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Probabilistic seismic hazard analysis (PSHA) is now established practice as the basis for determining seismic design ground motions for important nuclear facilities. Consistent with this practice, PSHAs for ground motion and fault displacement have been performed for the Yucca Mountain site. The methodology used for the PSHAs incorporated multiple expert evaluations of seismic sources, the potential for fault displacement, and ground motion estimation. The experts provided weighted alternative evaluations to characterize uncertainties in their interpretations. Based on these alternative interpretations, hazards were calculated and expressed as the annual probability at which levels of ground motion or fault displacement are expected to be exceeded. These results form the basis for developing seismic design ground motion and fault displacement parameters and provide estimates of the ground motion and fault displacement hazards for assessment of long-term waste containment and isolation performance of the potential repository.

The assessment of seismic hazards at Yucca Mountain was based upon the results of scientific investigations carried out principally over the past 20 years, many by the U.S. Geological Survey. Building upon earlier investigations of the Nevada Test Site (NTS) region, studies of the Yucca Mountain site included (1) evaluations of faults within about 100 km for evidence of Quaternary activity; (2) detailed paleoseismic fault-trenching studies of active faults near Yucca Mountain to determine the history and characteristics of past earthquake displacements; (3) monitoring of contemporary earthquake activity; (4) compilation of a catalog of historical and instrumentally recorded earthquakes in the Yucca Mountain region; (5) development of ground motion attenuation relationships for extensional tectonic regimes, which includes the Yucca Mountain region; (6) investigation of local site attenuation characteristics; (7) numerical modeling of ground motions from scenario earthquakes; (8) evaluation of the tectonic stresses from hydrofracture measurements and earthquake focal mechanisms; (9) collection and analysis of geophysical data to assess tectonic models and identify subsurface faults; and (10) collection and analysis of geodetic data to measure ongoing crustal deformation. Results of some of these studies have been summarized in Civilian Radioactive Waste Management System, Management and Operating Contractor (CRWMS M&O 2000). Together with the numerous studies performed by nonproject scientists and the already existing literature and information, this extensive data base formed the basis for the Yucca Mountain seismic hazard analyses.

The objective of the PSHAs was to provide ground motion and fault displacement hazard results for both determining preclosure (up to 300 years) seismic design requirements and for postclosure (10,000 years or more) performance assessment. The proposed governing regulation requires consideration of two categories of design basis events (NRC 1999). Category-1 events are expected to occur 1 or more times during the preclosure operational period of the facility. For ground motion, the target hazard for Category-1 events has been established at 10^{-3} annual probability of exceedance (DOE 1997). For Category-2 events, ground motion will be based on hazard at an annual exceedance probability of 10^{-4}. Because experience with the design of engineered structures for fault displacement is limited, corresponding target hazard levels for Category-1 and Category-2 fault displacement design basis events have been established at annual exceedance probabilities of 10^{-4} and 10^{-5}, respectively. Although criteria have been defined for fault displacement design, the primary approach will be to avoid faults capable of significant movement (DOE 1997).

The PSHA Project began in August 1994 and was concluded in June 1998 with the issuance of the final report (CRWMS M&O 1998). In this paper, we summarize the process followed in the PSHAs, the expert evaluations that formed the inputs for hazard calculations, and the hazard results.

APPROACH

The approach that was implemented to perform the PSHAs for Yucca Mountain is generally consistent with state-of-the-practice guidance for a Level 4 PSHA as defined by the Senior Seismic Hazard Analysis Committee (SSHAC 1997). A Level 4 PSHA involves evaluations of the inputs by multiple experts in a series of workshops and individual elicitation meetings facilitated by a technical facilitator/integrator (TFI). The Level 4 approach was implemented because of the perceived technical complexity of the required evaluations, the first-of-a-kind evaluations of fault displacement potential for probabilistic analysis, the desire to include a sufficiently broad range of diverse technical interpretations to represent the epistemic uncertainty of the scientific community, and the public and regulatory importance of the project. Implementation of the project departed from the recommended Level 4 approach in one respect: throughout the project it was strongly emphasized that primary ownership of the PSHA results rests with the expert evaluators instead of the TFI. This emphasis ensured full compliance with regulatory procedures and practice while implementing the scope of a Level 4 evaluation. The PSHAs were performed in three strongly integrated parallel activities, as shown in Figure 1: (1) evaluation and characterization of seismic sources including the potential for fault displacement; (2) evaluation and characterization of ground motion attenuation, including the effects of earthquake source, wave propagation path, and site rock properties; and (3) probabilistic calculations of both fault displacement and ground motion hazards (Stepp et al. 1996).

The method to calculate probabilistic ground motion hazard at a site is well established in the literature (Cornell 1968, McGuire 1976). Basic inputs are (1) an interpretation of seismic sources that contribute to the site hazard, from which conditional probability distributions of the distances of earthquakes from the site can be obtained; (2) an interpretation of earthquake recurrence for each source, including the mean annual rate of occurrence and magnitude distribution of earthquakes; and (3) an evaluation of ground motion attenuation for the site region, including the mean and standard deviation of ground motion amplitude as a function of magnitude and distance. Given the input evaluations, the hazard calculation method integrates over all values of the variables and produces an estimate of the mean frequency of exceedance of ground motion amplitude at the site. A graphical representation of these results is the well-known seismic hazard curve, which quantifies the aleatory (random) uncertainty in earthquake occurrence and ground motion attenuation. Aleatory uncertainty is the uncertainty naturally inherent in the earth and earthquake process, which in principle, cannot be reduced with additional data or information. The basic calculation method can thus be thought of as the aleatory seismic hazard model.

In addition to the aleatory uncertainty in seismic hazard, is epistemic uncertainty about the seismotectonic environment of a site. Epistemic uncertainty is due to incomplete scientific knowledge about earthquake processes and ground motion attenuation and to incomplete data available for evaluating these processes. Significant advances in the development of the methodology for quantifying epistemic uncertainty in seismic hazard have been made during the past 20 years (Bernreuter et al. 1985, Electric Power Research Institute [EPRI] 1986, SSHAC 1997). These advances involve the development and weighting of alternative interpretations of the seismotectonic environment of a site by one or more experts to provide a structured characterization of epistemic uncertainty suitable for seismic hazard computation. Evaluations by multiple experts are made within a structured expert elicitation process, which is designed to minimize uncertainty due to uneven knowledge among experts and due to experts using different, possibly incomplete data. These

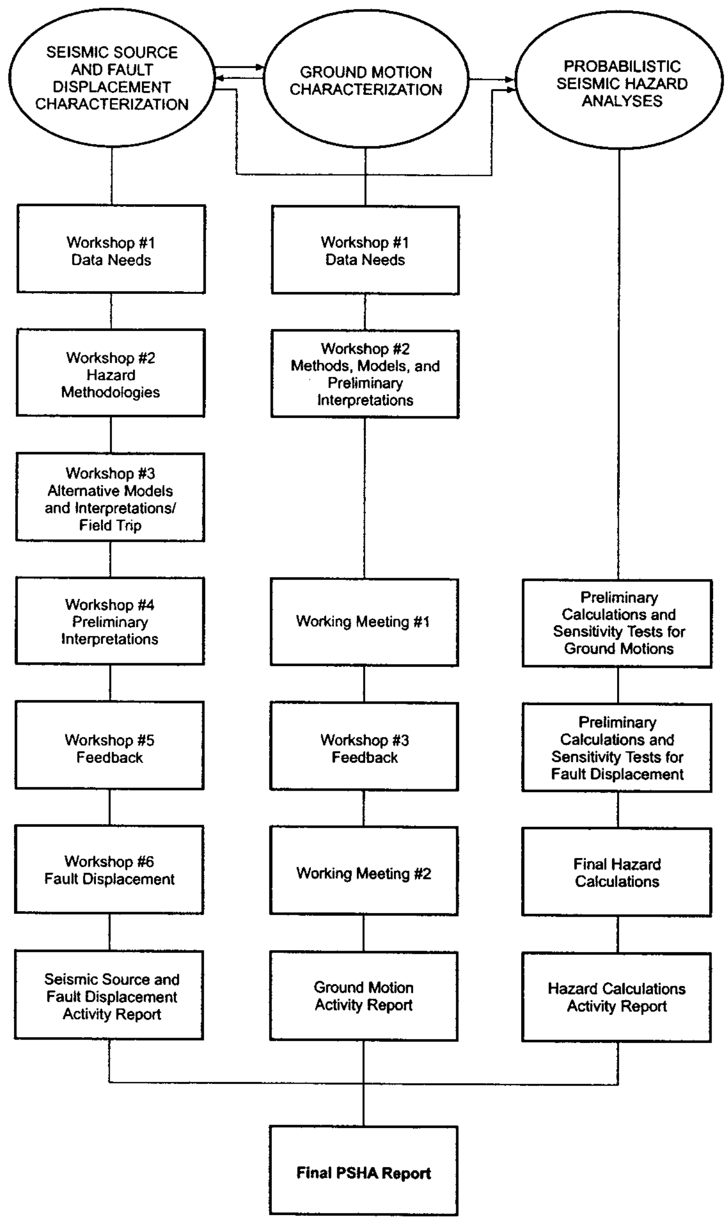


Figure 1. Probabilistic Seismic Hazard Analyses Project process for Yucca Mountain.

developments have been evaluated and important guidelines for the use of experts in PSHA have been developed (SSHAC 1997).

The weighted alternative interpretations can be expressed by use of logic trees (Kulkarni et al. 1984, EPRI 1986). Each pathway through the composite logic trees represents a complete interpretation of the seismotectonic environment of the site for which an aleatory seismic hazard curve is computed. Each pathway is associated with a probability equal to the product of the conditional probabilities of all the branches along the way. The result of computing the hazard for all pathways is a family of hazard curves, each with an associated weight, representing the full aleatory and epistemic uncertainty in the hazard at a site. Figure 1 shows the process followed for the development of the seismotectonic interpretations and seismic hazard results.

To capture the state of knowledge of the informed scientific community, epistemic uncertainty was evaluated by six teams of three earth science experts. Each team characterized seismic sources in the Yucca Mountain site region (generally within a distance of about 100 km) and fault displacement potential at the site. Preliminary hazard computations using conservative ground motion attenuation relationships had shown that sources beyond about 100 km from the site would not significantly contribute to the ground-shaking hazard (Wong et al. 1996). Similarly, to capture epistemic uncertainty in ground motion, seven ground motion experts characterized ground motion attenuation in the site region.

The integrity of the seismic hazard results rests principally on the scientific quality and thoroughness of the experts' interpretations that are input to the hazard calculation. Calculation methodological developments were introduced as needed to accommodate the experts' interpretations specific to the Yucca Mountain site. An example of such software modification was to provide for the capability to calculate the ground motion hazard from simultaneous rupture of multiple faults. These modifications were incorporated into the computer code FRISK88 (Risk Engineering 1998), which was used to compute the ground motion hazard at the Yucca Mountain site (CRWMS M&O 1998). Concurrently, the code was modified to compute fault displacement hazard using multiple expert interpretations of fault displacement potential as input.

Ground motion hazard was computed for a defined reference rock outcrop (discussed later) indicated by Point A in Figure 2. (Points B, C, and D are locations where seismic design ground motions are currently being calculated through a site response analysis using

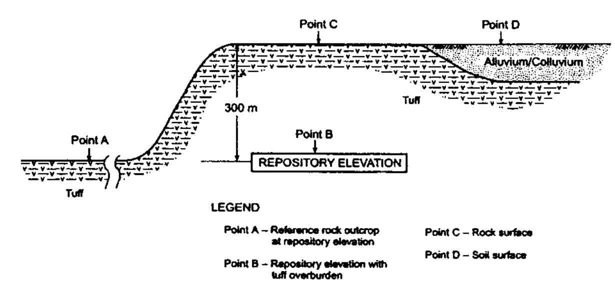


Figure 2. Locations of specified design earthquake ground motions. Point A is a hypothetical site and does not correspond to an actual location at Yucca Mountain.

ground motions derived at Point A as control motions.) Fault displacement characterizations were carried out for faulting conditions at nine locations within the potential repository facility area, identified in Figure 3. These locations were selected to span the range of known faulting conditions within the repository facility area for which fault displacement hazard is needed. Faulting conditions at the nine locations ranged from primary block-bounding faults to unfaulted rock and included secondary faults and fractures.

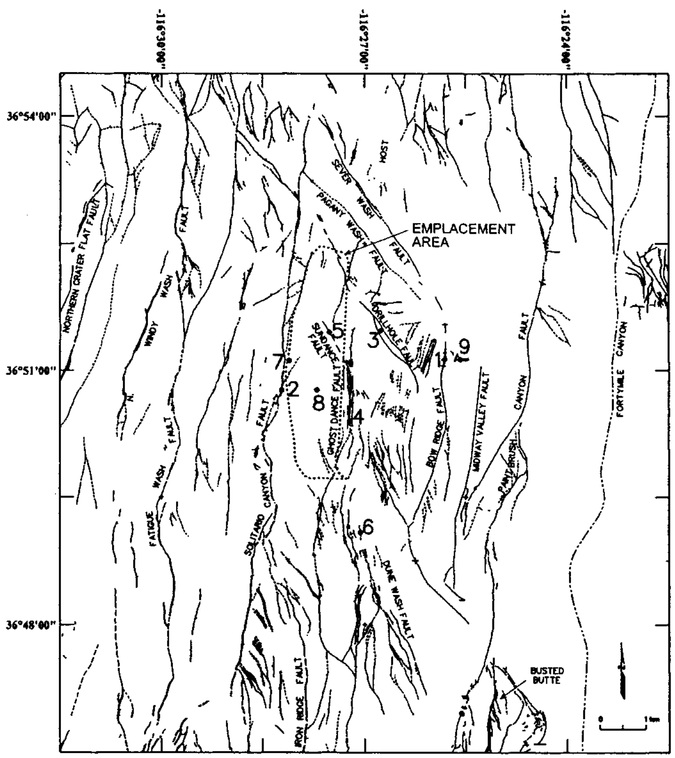
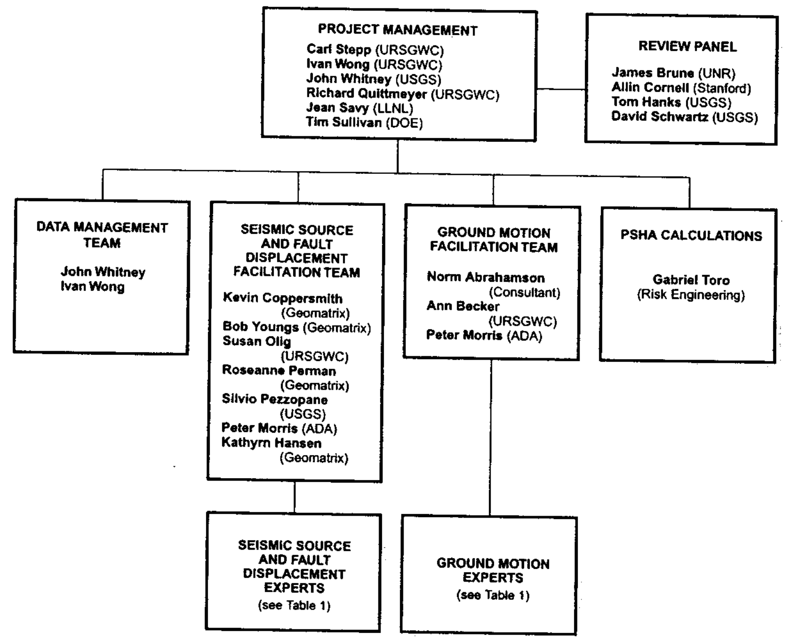


Figure 3. Nine locations for demonstration of fault displacement hazard assessment. Yucca Mountain is bounded on the west by the Solitario Canyon fault and on the east by the Bow Ridge fault. Potential waste emplacement area is also shown.

PROJECT ORGANIZATION

The organizational components of the Yucca Mountain PSHA Project are shown in Figure 4. Four technical teams were formed to compile a common data base, to plan, organize, and lead the technical workshops, to facilitate the expert interpretations, and to perform hazard calculations. These teams included (1) seismic source and fault displacement (SSFD) facilitation, (2) ground motion (GM) facilitation, (3) data management, and (4) PSHA hazard calculations. As depicted in Figure 1, the SSFD and GM evaluations were facilitated through a series of workshops, individual facilitation meetings, and working

meetings, each of which was planned and structured to accomplish an element of the overall required evaluations. One workshop was held in common to facilitate consistent evaluations of earthquake source stress drop, maximum magnitude, and interpretations of fault geometry of fault specific sources at and near Yucca Mountain. The SSFD and GM facilitation teams planned, organized, and led the workshops, which ranged progressively from defining the basic issues that required evaluation and identifying needed data and information, feedback, and final interpretations.



URSGWC – URS Greiner Woodward-Clyde

LLNL – Lawrence Livermore National Laboratory

UNR – University of Nevada, Reno

USGS – U.S. Geological Survey

ADA – Applied Decision Analysis

Figure 4. Project organization.

Six three-person expert teams performed seismic source and fault displacement potential evaluations and provided interpretations for hazard calculations (Table 1). The team approach was taken to ensure the composite scope of knowledge required to evaluate earthquake processes and the range of data relevant to the evaluations. The aggregate expertise of each team spanned (1) seismic geology, (2) regional tectonics, and (3) seismology of Yucca Mountain and the Basin and Range Province. Individuals in each of these three areas of expertise were randomly combined to form the six teams. Each team performed as a virtual expert by expressing uncertainty in their interpretations as the team's consensus uncertainty.

Seven individual GM experts provided evaluations of ground motion attenuation for input to the PSHA (Table 1). 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.

Table 1. SSFD and GM experts

SSFD Expert Teams	Affiliation
Walter J. Arabasz (AAR)	University of Utah
R. Ernie Anderson	U.S. Geological Survey
Alan R. Ramelli	Nevada Bureau of Mines & Geology
Jon P. Ake (ASM)	U.S. Bureau of Reclamation
D. Burton Slemmons	Consultant
James McCalpin	GEO-HAZ Consulting, Inc.
Diane I. Doser (DFS)	University of Texas, El Paso
Christopher J. Fridrich	U.S. Geological Survey
Frank H. (Bert) Swan	Geomatrix Consultants, Inc.
Albert M. Rogers (RYA)	GeoRisk Associates, Inc.
James C. Yount	U.S. Geological Survey
Larry W. Anderson	U.S. Bureau of Reclamation
Kenneth D. Smith (SBK)	University of Nevada, Reno
Ronald Bruhn	University of Utah
Peter L. K. Knuepfer	Binghamton University
Robert B. Smith (SDO)	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	URS Greiner Woodward-Clyde
Marianne C. Walck	Sandia National Laboratories

Experts were selected based on the following criteria: (1) strong relevant expertise as demonstrated by professional reputation, academic training, experience, and peer-reviewed publications and reports; (2) 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; (3) availability and willingness to commit the time required to perform the evaluations needed to complete the study; (4) specific knowledge of the Yucca Mountain area, the Basin and Range Province, or ground motion characterization; (5) 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; and (6) 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. In addition to these individual qualifications, the Project Management Team selected experts to obtain a range of organizational representation and to capture the diversity of scientific opinion.

To minimize spurious data uncertainty, the Data Management Team compiled all data relevant to the performance of the PSHAs and distributed it uniformly to all experts. An important component of this work was the identification of data gaps. This task was performed by the experts in the first workshop, who identified the evaluations to be performed and the data sets needed in the evaluations, and identified and discussed the issues that required evaluation. To the extent achievable, the identified data were compiled and provided to the experts. All data used by any expert were incorporated into the data base and made available to the other experts.

The PSHA Calculations Team performed preliminary hazard calculations based on the experts' preliminary interpretations. These preliminary results were provided to the experts and were then discussed in a feedback workshop (Figure 1) to allow them to understand how their characterizations of uncertainty in their interpretations were reflected in the seismic hazard results. The PSHA Calculations Team performed and reported the final hazard calculations.

A participatory peer review was implemented in which the Review Panel provided technical review and guidance at every stage of the project (SSHAC 1997). Members of the Review Panel were selected to provide expertise in PSHA methodology and the required input evaluations covering all elements of the project. Panel members attended all workshops, participated and made informal comments during the workshops, and made formal recommendations following each workshop. This process of participatory review allowed adjustments to be made and corrective actions to be taken as needed throughout the conduct of the work. The panel also reviewed the final report and made formal recommendations. This review process was accepted as being in compliance with the Project's Quality Assurance Program.

TECTONIC SETTING AND QUATERNARY FAULTING AT YUCCA MOUNTAIN

Yucca Mountain lies within the southern Basin and Range Province (CRWMS M&O 2000). The mountain is located on the southern flank of a large complex of Miocene calderas. It is considered to be an erosional remnant of a 14.0 to 11.4 Ma volcanic apron, which now is an irregularly shaped upland, 6 to 10 km wide and about 40 km long. The crest of the mountain reaches an elevation of 1,500 to 1,930 m, about 650 m higher than the floors of adjacent washes in Crater Flat, which bounds the mountain on the west and Jackass Flats, which bounds it on the east. Structurally, the mountain is composed of and flanked by subparallel north-trending and east-dipping fault blocks (CRWMS M&O 2000) (Figure 3). The blocks are bounded by typical Basin-and-Range high-angle, normal faults formed by east-west extension during the waning phases of most active volcanism. Secondary intrablock faults are common in the mountain. The potential repository site is located within the central block of Yucca Mountain, which is bounded on the west by the Solitario Canyon fault and on the east by the Bow Ridge fault (Figure 3). Secondary intrablock faults include the Ghost Dance, Sundance, and Drill Hole Wash faults.

Although Yucca Mountain is structurally similar to other fault-bounded ranges in the Basin and Range Province, it lies within the Walker Lane tectonic zone (CRWMS M&O 2000). The Walker Lane is a 100-km-wide structural belt along the western edge of the Basin and Range Province, which is characterized by long strike-slip faults that are interpreted to have accommodated much of the early extension in this region. The peak phase of this rapid tectonism took place 12.7 to 11.6 Ma, and the region has since experienced a decreasing strain rate. The Walker Lane appears to have been an important locus of tectonic deformation in the past; however, its role in the current tectonic framework of the southern Basin and Range is uncertain. The current pattern of Quaternary structural deformation at Yucca Mountain mimics the Middle Miocene normal faulting deformation, however at substantially lower strain rate (Fridrich et al. 1998).

Within the site region, approximately 100 Quaternary faults were identified as potential seismic sources (Piety 1996, McKague et al. 1996). With the exception of the Death Valley – Furnace Creek fault system, these faults are interpreted to have low slip rates and to be experiencing dominantly normal movement in the extensional tectonic stress regime that characterizes the Basin and Range Province.

EVALUATION AND CHARACTERIZATION OF SEISMIC SOURCES

The objective of evaluating and characterizing seismic sources for the ground-shaking PSHA was to describe alternative seismotectonic models of the site region that expressed the SSFD teams' uncertainties in source geometries, earthquake recurrence, and maximum magnitudes. The evaluations involved identifying and characterizing the seismic sources capable of producing earthquakes significant for ground-shaking hazard computation at the site.

The contribution of a seismic source to probabilistic ground-shaking hazard depends to the first order, on the source-to-site distance, its maximum earthquake, and its rate of earthquakes. The assessed maximum magnitude (M_{max}) for a seismic source represents the largest earthquake, regardless of its frequency of occurrence. It defines the upper limit of the earthquake recurrence distribution for a source. M_{max} is an uncertain source parameter that is normally assessed as a distribution. Approaches used to estimate M_{max} may vary depending on the type of source and on the types of data available. The earthquake recurrence relationship for a seismic source describes the frequency at which earthquakes of various magnitudes occur. It is determined by estimating the overall frequency of earthquakes and probability density function of earthquake size between a specified lower-bound magnitude of engineering interest (M_w 5.0 for this project) and the estimated maximum earthquake for the source. The parameters of the earthquake recurrence relationship are also uncertain.

Evaluations of seismic sources were performed following the structured elicitation process that was adopted for the project (Figure 1). The SSFD elicitation process included six workshops and a 1-day elicitation meeting with each team. The evaluations included alternative interpretations, each weighted to express the teams' epistemic uncertainties.

The teams used two types of interpretations to express their epistemic uncertainties in seismic sources: fault-specific sources and areal source zones. Faults were characterized when earthquake activity (either through paleoseismic evidence or historical seismicity) could be confidently associated with a specific fault or fault zone. Alternative total fault lengths, alternative fault dips, and possible linkages with other faults express uncertainties in the geometry of fault-specific sources. Earthquake ruptures were typically interpreted to occur with equal likelihood at any point on a fault and the size of the rupture was specified by an empirical relationship between earthquake magnitude and rupture area (e.g., Wells and Coppersmith 1994). The approximately 100 faults or fault zones identified as potential seismic sources within the site region were evaluated by the SSFD teams and incorporated into their seismic source interpretations.

Areal seismic source zones were used to represent distributed seismicity not apparently associated with known specific faults or to model groups of faults interpreted to have the same earthquake potential, at sufficiently large distances from the site such that the details of the individual faults are not significant for hazard calculation. Uncertainties in areal seismic source zones were expressed by weighted alternative interpretations of source boundaries. The teams interpreted the spatial distribution of earthquakes within areal source zones to be either homogeneous or nonhomogeneous.

LOCAL FAULTS

Detailed geological and structural mapping within about 10 km of the Yucca Mountain site was performed as part of extensive investigations conducted over a number of years (CRWMS M&O 2000). These investigations included trenching of faults that had evidence of Quaternary displacement and detailed logging of the trenches to determine the history of displacements. The mapping identified local faults that fall into one of three categories: (1) north-striking, block-bounding faults on which multiple displacements have occurred in the Quaternary, (2) northwest-striking faults that do not show evidence of displacement during the Quaternary, and (3) intrablock faults that also do not show evidence of displacement during the Quaternary (Figure 5). The observed close spacing between faults, their anastomosing pattern, and their relatively short lengths indicate that the local faults may be structurally interconnected either along strike or at depth and, thus, may rupture either partially or fully together. Eight of the mapped local faults show evidence of multiple surface-rupturing earthquakes during the Quaternary. Fault lengths shorter than 26 km together with preferred slip rates of 0.001 to 0.05 mm/yr, and preferred average recurrence intervals of 10,000 to more than 100,000 years, characterize these faults. Paleoseismic data from trenching studies indicate similar ages for ruptures on subparallel faults within the age-dating resolution. These observations suggest that simultaneous ruptures of two or more of the Yucca Mountain faults may have occurred several times during the Quaternary. The results of the detailed geologic and structural mapping of the site area formed the principal database for the experts' evaluations of local faults for ground motion hazard calculation.

The SSFD teams characterized local faults in terms of their probability of activity, locations, rupture lengths, sense of slip, fault dips, maximum seismogenic depths, M_{max}, and earthquake recurrence. Recognizing that some interpretations of local faults depend on operative tectonic models that can explain the structure of the crust in the site area, the teams evaluated credible tectonic models and incorporated the evaluations into their alternative interpretations of the structural relationships among the local faults. Parameters of the most significant local faults, which include the block-bounding Paintbrush Canyon, Bow Ridge, Stagecoach Road, and Solitario Canyon faults (Figure 5), are shown in Table 2. These parameters represent either the average or range of parameter values interpreted by the teams. Because the teams' interpretations varied particularly in regards to interpretations of independent single seismic sources and linked and combined fault sources, the parameters listed in Table 2 are composite.

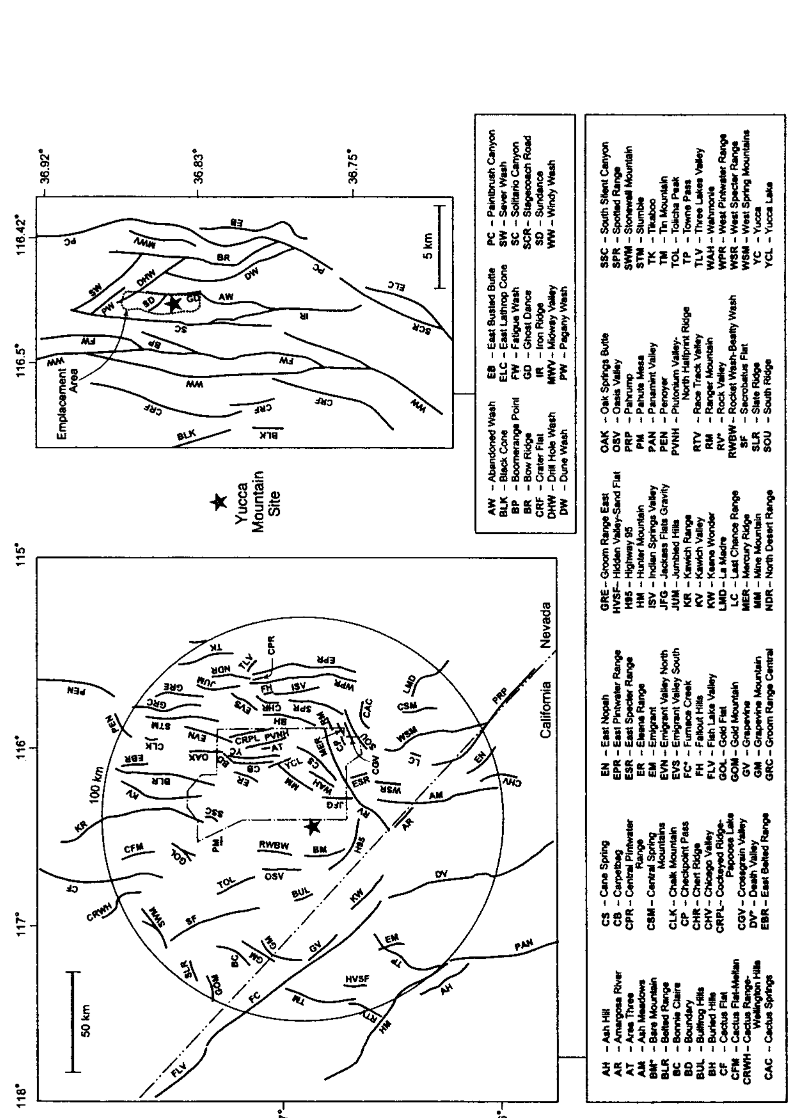


Figure 5. Known or suspected Quaternary faults within 100 km of Yucca Mountain. Local faults are shown on right. Boundary of NTS is also shown.

Table 2. Fault parameters of significant local faults considered by SSFD experts

Fault Name	Rupture Length (km)	Distance[1] (km)	Sense of Slip	Fault Dip[2]	Slip Rate[2] (mm/yr)	Probability of Activity
Solitario Canyon	16-19	1	LL-N	60°	0.01-0.03	1.0
Iron Ridge	6-9	2.5	LL-N	60°	0.002-0.004	0.1-1.0
Bow Ridge	6-8	2.5	LL-N	60°	0.002-0.003	0.4-1.0
Fatigue Wash	9-17	3.5	LL-N	60°	0.002-0.009	0.9-1.0
Paintbrush Canyon	12-19	4	LL-N	60°	0.002-0.017	1.0
Windy Wash	5-27	4.5	LL-N	60°	0.003-0.03	0.6-1.0
North Crater Flat	6-13	6	LL-N	60°	0.001-0.003	0.5-1.0
South Crater Flat	6-8	8	LL-N	60°	0.001-0.008	0.5-1.0
Stagecoach Road	4-10	10	LL-N	60°	0.016-0.05	1.0

1. Approximate shortest distance to repository.
2. Range or average of best estimate values interpreted by the expert teams.
LL = Left-lateral strike-slip
N = Normal

The experts evaluated M_{max} for faults using empirical relationships between magnitude and surface rupture length, rupture area, and/or maximum and average displacement (e.g., Wells and Coppersmith 1994). The preferred M_{max} values for the local faults ranged from M_w 5.7 to 6.8 across the teams with typical within-team uncertainties of ± ½ magnitude unit for individual sources. The higher values were for faults linked as single seismic sources.

Earthquake recurrence rates for the faults were quantified using recurrence intervals and/or slip rates. Most teams used the latter due to the lack of recurrence interval information. Best estimate slip rates ranged from 0.0001 mm/yr (Ghost Dance fault) to 0.05 mm/yr (Stagecoach Road fault). Some of the linked faults were assessed at slightly higher slip rates. The teams gave weights to four recurrence models: characteristic, truncated exponential, modified truncated exponential (described in Youngs et al. 1987), and maximum magnitude (Wesnousky 1986). The characteristic model was given the highest composite weight.

The teams considered dependence of faulting on credible tectonic models for the site area in their evaluations of alternative faulting to capture the range of complex rupture patterns and fault interactions. The close spacing of the local Yucca Mountain faults (Figure 5), the possible interactions suggested by their down-dip geometry, and the complexities of rupture patterns indicated by paleoseismic data led the teams to consider a wide range of alternative faulting behavior and tectonic/structural models. These models included subparallel planar faults extended through the seismogenic crust; planar faults merging down-dip into master faults; and faults soling into a detachment, which may itself be seismogenic. The potential for superimposed regional dextral shear resulting in buried strike-slip faulting was considered by all teams. Four teams included a buried large-scale strike-slip seismic source (with low probability) and two teams interpreted buried strike-slip faulting to be at the scale of earthquakes modeled by the areal source zones. The teams included the potential for along-strike linkages of some faults into single seismic sources and the occurrence of coseismic rupture of parallel faults. The latter rupture behavior necessitated the development of ground motion models for comparable levels of seismic energy release on parallel faults.

REGIONAL FAULTS

Evaluations of regional faults within the Yucca Mountain site region focused on structures considered capable of generating earthquakes of M_w 5 or greater based on fault length and those with a Quaternary history of multiple surface-rupturing earthquakes. These faults, shown in Figure 5, were evaluated as potential seismic sources. Paleoseismic data from Piety (1996) were used together with data from Anderson et al. (1995a, 1995b) and S. Pezzopane (USGS, written communication, 1996). McKague et al. (1996) found 52 faults within the site region to have evidence of displacement in the Quaternary and sufficient length to be potentially significant seismic sources. All of these studies were considered by the SSFD teams in their evaluations of seismic sources. The teams interpreted some of the faults to be linked and grouped them into a single fault source. A number of the shorter faults identified by McKague et al. (1996) were included in the teams' regional areal seismic source interpretations, because of their relatively small maximum earthquake potential.

The interpretations and the relative weights given by the teams to regional faults varied, reflecting the epistemic uncertainty. The number of regional faults interpreted to be seismic sources ranged among teams from 11 to 36, reflecting the teams' evaluations regarding fault activity and maximum magnitude. The seismic parameters of the more significant regional faults are shown in Table 3. All teams modeled the regional faults as planar faults to maximum seismogenic depths (11 to 20 km) with dips depending on the style of faulting (preferred values of 90° for strike-slip faults, 60° or 65° for normal faults). The evaluations of maximum seismogenic depths relied on observations of contemporary seismicity, including some of the better-studied large surface-faulting earthquakes in the Basin and Range Province (e.g., 1983 Borah Peak earthquake). Alternative fault lengths were included to express uncertainty in their mapped lengths. Faults were assessed probabilities of activity as low as 0.1. Slip rates less than 0.001 mm/yr were characterized by the experts and included in their model of regional seismic sources (Table 3).

The Furnace Creek – Death Valley faults are particularly significant for ground-shaking hazard assessment at Yucca Mountain because of their high slip rates (4 to 8 mm/yr) and potential to generate earthquakes of M_w 7 or larger, despite their relatively long distances from the Yucca Mountain site, beyond about 50 km (Figure 5).

AREAL SEISMIC SOURCE ZONES

The experts defined boundaries of areal source zones based on seismotectonic province considerations, including the distribution of historical earthquakes (Figure 6), and assessed M_{max} and recurrence. Some teams developed alternative areal source zone interpretations for the site region and some defined areal source zones beyond 100 km to completely express uncertainty in their seismic source interpretations. Several teams defined a local background areal source zone representing the area near Yucca Mountain within which detailed mapping and fault investigations were conducted as part of the site investigation. Because the mapping of faults is more complete within this local background source zone, the experts gave a large weight to the interpretation that sources of larger earthquakes were well identified by the local faults. Thus, they gave a large weight to a smaller maximum earthquake for this areal source zone than to more distant areal source zones that had less detailed mapping. An example of one team's areal seismic source zone interpretation is shown in Figure 7.

Table 3. Fault parameters of significant regional faults considered by the SSFD experts

Fault Name	Rupture Length (km)	Distance[1] (km)	Sense of Slip	Fault Dip[2]	Slip Rate[2] (mm/yr)	Probability of Activity
Mine Mountain	20-23	11	LL-N	70°-90°	0.01-0.03	0.6-1.0
Bare Mountain	20-23	14	N	60°	0.01-0.1	1.0
Wahmonie	14-15	22	N-LL	65°-90°	0.001-0.04	1.0
Ash Meadows	27-42	24	N	65°	<0.01-0.04	1.0
Rock Valley	30-62	27	LL-N	90°	0.02-0.16	1.0
Cane Spring	20-26	29	LL-N	90°	0.01-0.03	0.6-1.0
West Specter Range	8-19	33	N	60°	0.004-0.01	1.0
Amargosa River	12-25	34	N-RL	90°	0.01-0.05	1.0
Yucca Lake	13-19	36	N-RL	60°-90°	0.005-0.2	0.5-1.0
Eleana Range	11-15	37	N	60°	0.0002-0.2	1.0
Yucca	25-32	40	RL-N	65°-90°	0.02-0.2	1.0
Keane Wonder	23-27	43	N	65°	0.005	0.6-0.8
Furnace Creek	105-118	50	RL	90°	4.0-8.0	1.0
West Springs Mountains	29-52	53	N	65°	0.02-0.09	1.0
Death Valley	45-71	55	N-RL	65°-90°	2.5-5.0	1.0
Belted Range	21-50	55	N	65°	0.01-0.1	1.0
Kawich Range	24-84	57	N	65°	0.001-0.03	1.0
Pahrump	35-65	68	RL-N	90°	0.005-0.07	1.0
West Pintwater Range	37-82	76	N	60°	0.008-0.2	1.0

1. Approximate shortest distance to repository
2. Range or average of best estimate values interpreted by expert teams
LL = Left-lateral strike-slip
RL = Right-lateral strike-slip
N = Normal

M_{max} distributions for the areal seismic source zones represent the teams' uncertainties in the largest background earthquake in the site region that does not cause surface faulting or the estimated M_{max} for a geologic structure that was not explicitly included as a fault-specific source.

Earthquake recurrence for the areal seismic source zones was derived using the historical earthquake catalog developed for the region (Figure 6). The catalog was compiled from all available sources (e.g., USGS, University of Nevada, Reno, California Institute of Technology, etc.) for the region within a radius of 300 km of the Yucca Mountain site (CRWMS M&O 1998). Known underground nuclear explosions and other forms of blasting were removed from the catalogs. Dependent events (e.g., foreshocks and aftershocks) were deleted using the declustering algorithms of Veneziano and van Dyck (1985) or Youngs et al. (1987). The two declustered historical earthquake catalogs plus the full catalog were then provided to the experts for their review. Experts were required to consider the reservoir-induced earthquakes beneath Lake Mead and earthquakes induced by nuclear explosions at the NTS (Figure 6). All teams used the truncated exponential model to estimate earthquake recurrence rates within the areal seismic source zones. Alternative interpretations of the spatial distribution of earthquakes within areal seismic sources included (1) uniform smoothing (uniformly distributed in space) and (2) nonuniform smoothing using Gaussian kernels having different degrees of smoothing representing the teams' interpreted degrees of spatial stationarity. The latter interpretation utilized a technique similar to that developed by Frankel (1995).

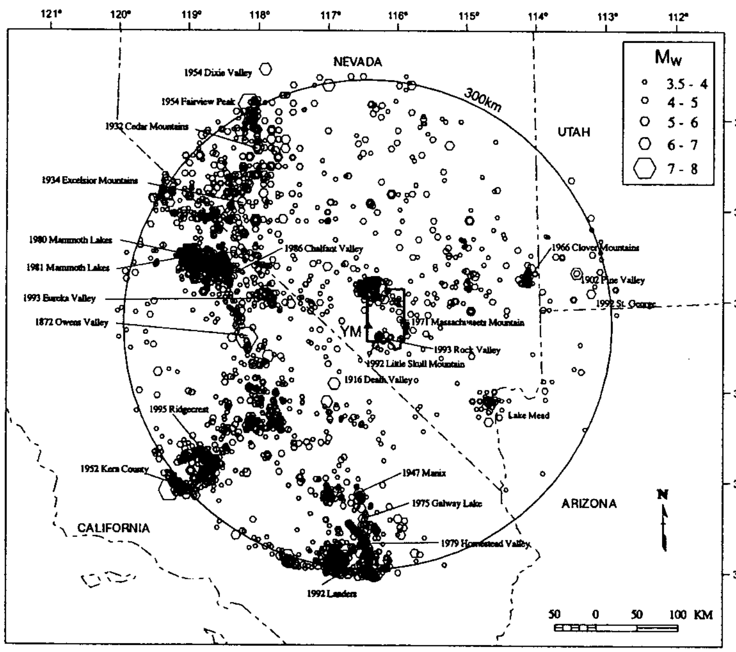


Figure 6. Historical seismicity (1868 to 1996) M_W 3.5 or Modified Mercalli Intensity III or greater within 300 km of Yucca Mountain. Significant earthquakes are noted.

Areal seismic source zones were modeled as distributed point sources in the probabilistic calculations. The distance measure for a point source was modified to "closest distance" where appropriate to account for the finite dimensions of fault rupture (CRWMS M&O 1998). The variability in the ground motion models was increased to incorporate the variability in the closest distance for a given hypocentral distance.

Earthquakes related to volcanic processes, particularly basaltic volcanism and dike-injection, were explicitly modeled in volcanic source zones by only two teams. Volcanic-related earthquakes were not modeled as a separate source by the other teams. Considering the low magnitude and frequency of volcanic-related seismicity, these teams concluded this earthquake activity to be accounted for in their areal source zones.

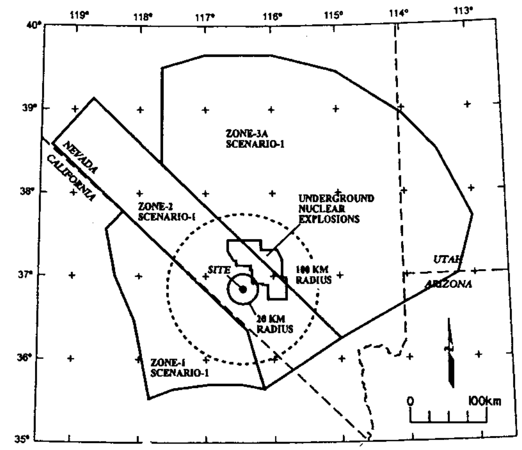


Figure 7. Alternative regional s urce zone models considered by one of the SSFD expert teams.

COMPARISON OF ESTIMATED AND OBSERVED EARTHQUAKE RECURRENCE

As discussed above, epistemic uncertainty in the seismic source characterization parameters was expressed by developing logic trees with branches weighted to represent each SSFD team's interpretations. These logic trees were structured to incorporate dependencies in the uncertainties, such as the types of seismic sources implied by a tectonic model, consistent down-dip widths for faults in a region, and use of a common earthquake catalog for assessing seismicity rates of areal source zones. The distributions for maximum magnitude and earthquake recurrence parameters were typically assumed to be independent from source to source. The uncertainties were propagated through the analysis by full enumeration of the suite of hazard model parameter sets represented by the end branches of the logic trees.

Figure 8 shows the results of this calculation in terms of the computed frequency of earthquakes occurring on the three types of seismic sources and on all seismic sources combined within a 100-km radius of the Yucca Mountain site. Curves are shown indicating the mean earthquake frequency computed using each SSFD team's source characterization model for (a) local faults, (b) regional faults, (c) areal source zones, and (d) combined results for all sources. The solid curves show the mean cumulative earthquake frequency and the 5th to 95th percentiles of the aggregate epistemic distribution for cumulative earthquake frequency across all six SSFD teams. The curves labeled by team are the mean cumulative frequencies computed using each team's seismic source characterization. These comparisons indicate the relative contribution of within-team expression of epistemic uncertainty and team-to-team variability in interpretations to the total uncertainty in earthquake recurrence. Where the mean results for the individual teams lie well within the aggregate 5th to 95th percentile curves, such as over most of the magnitude range for the local faults and for larger magnitude earthquakes on the regional faults (Figure 8a and b), the within-team epistemic uncertainty has a larger contribution to the total scientific uncertainty. Where the mean results for the individual teams fill the range between the aggregate 5th and 95th percentile curves, such as the results for the areal source zones and for smaller magnitude earthquakes on the regional faults (Figure 8b and c), the team-to-team variability in interpretation has a larger contribution to the total scientific uncertainty. The larger team-to-team variability in computed cumulative earthquake frequencies for the regional faults reflects differences in interpretations of the appropriate form of the magnitude distribution to extrapolate geologically-based earthquake recurrence estimates for large-magnitude earthquakes to the rate for small to moderate earthquakes. The team-to-team variability in computed cumulative earthquake frequencies for the areal source zones within 100 km of the site reflects differences in interpretation of the appropriate region over which areal sources should be defined, the degree of spatial stationarity in the observed seismicity, and the M_{max} for earthquakes not associated with the fault-specific sources.

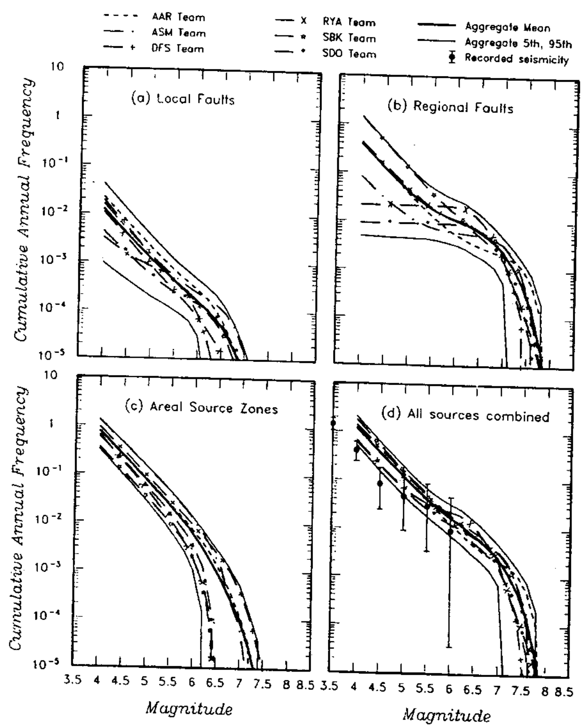


Figure 8. Computed cumulative earthquake frequencies for (a) local faults, (b) regional faults, (c) areal source zones, and (d) all sources combined within 100 km of the Yucca Mountain site. The curves for each team (abbreviations are listed in Table 1) are the mean cumulative frequency. The solid lines show the aggregate mean (heavy line) and the 5th and 95th percentiles of the aggregate distribution (light line) for cumulative earthquake frequency. Shown on (d) is the most likely cumulative earthquake frequency (solid points) and the 90-percent confidence interval on the cumulative earthquake frequency computed from the recorded seismicity within the 100 km of the site.

Also shown in Figure 8d are the cumulative earthquake frequencies computed from the recorded seismicity within 100 km of the site. As indicated by the large confidence intervals, the data are limited, with only 7 earthquakes of M_w 4.5 or larger recorded in the region (one more has occurred after completion of the study). Comparisons such as these were fed back to the SSFD teams to aid in their interpretations. The overprediction of the observed seismicity in the M_w 4 to 5 range results from extrapolation of large-magnitude earthquake rates to smaller-magnitude earthquakes on the regional faults and the interpretations by the SSFD teams that large areal sources are needed to properly represent the potential for random seismicity not associated with the faults characterized as individual seismic sources (e.g., Figure 7). It should be noted that the 90-percent confidence intervals for the cumulative earthquake frequencies computed from the SSFD teams' interpretations overlap the 90-percent confidence intervals computed from the recorded seismicity.

GROUND MOTION EVALUATION AND CHARACTERIZATION

The Basin and Range Province is a tectonic regime characterized by extensional deformation and a thin crust (35 km or less). Late-Quaternary faulting within 20 km of the potential repository is principally normal, both with and without an oblique component. Strike-slip faults that contribute to the potential ground motion hazard at the site have been identified at distances of 25 km and greater (Table 3). These features of the tectonic regime were taken into account by the GM experts in their evaluations of ground motion attenuation in the Yucca Mountain region.

Strong motion data from the Basin and Range Province, even when combined with the limited data from analog tectonic environments are insufficient to adequately constrain empirical attenuation models for normal faulting earthquakes. Consequently, a key issue with respect to characterizing ground motion attenuation in the Yucca Mountain region was the applicability to the Basin and Range Province of western U.S. empirical attenuation models, which are based on relatively large data sets. Most empirical attenuation relations in the western U.S. are based primarily on recordings in California from strike-slip and reverse-slip earthquakes (e.g., Boore et al. 1997, Abrahamson and Silva 1997). Because strong motion recordings of normal faulting earthquakes are sparse, separate style-of-faulting factors typically have not been estimated for normal faulting. Instead, the normal faulting data are usually grouped with strike-slip faulting data. The few normal faulting strong ground motion recordings have not been found to be statistically different from those predicted for strike-slip faulting in previous evaluations (Westaway and Smith 1989).

Differences exist in the seismic source, regional crustal path, and shallow site properties for the Yucca Mountain region compared to average source, path, and site properties represented in the western U.S. strong motion data set. Since these attenuation relations are primarily based on California strong motion data, the GM experts evaluated the need to modify them (median and/or standard deviation) to account for differences in the source, path, and site properties between California and Yucca Mountain site region. Alternative sets of conversion factors were developed to convert the California attenuation relations to conditions appropriate for the Yucca Mountain site region. The GM experts then evaluated which, if any, of the conversion factors should be applied to estimate the ground motion at Yucca Mountain.

SPECIFIC GROUND MOTION ISSUES

In addition to the general issue of evaluating the applicability of empirical strong motion models based largely on strong motion data recorded in California, several specific issues were identified by the GM experts and prioritized for the study. Most of these issues arose from a need to further evaluate an available data set. The three key issues are described in the following.

Reference Site

Initially, the reference site properties for this study were defined as the average properties of tuff at the surface of Yucca Mountain. Development of conversion factors to account for differences in the shallow site response requires detailed information on the shear-wave velocity and nonlinear dynamic properties of the shallow tuff at Yucca Mountain (primarily the top 50 m), which was not available at the time for the study. A preliminary velocity profile for the shallow tuff had been estimated as part of a scenario earthquake modeling project (J. Schneider, URSGWC, written communication, 1996), but this velocity profile is not well constrained. In addition, the laboratory testing studies available to determine the dynamic behavior of the site materials were very limited. Since the detailed geotechnical data would eventually be available, but not in time to be considered in this study, it was decided to redefine the reference site condition to be a hard-rock outcrop site and then use the detailed geotechnical data when it became available to propagate the hard-rock ground motion up through the shallow tuff. (A geotechnical investigation of the site is being undertaken during Summer 2000.) The reference rock outcrop was defined by removing the top 300 m from the shear-wave velocity profile used in the scenario earthquake modeling project. This reference site is represented by Point A in Figure 2. The mean shear-wave velocity at the surface for the reference hard-rock site is 1900 m/sec.

As part of the definition of the reference rock outcrop, the high-frequency spectral decay parameter for the site needed to be defined in addition to the shear-wave velocity. In this study, kappa, as defined by Anderson and Hough (1984) was used as the high-frequency spectral decay parameter. Kappa has been interpreted to represent the effects of the anelastic attenuation (low strain material damping) in the shallow crust (approximately the top 1 km); however, kappa is not a direct measurement of damping. Kappa is estimated by evaluating the high-frequency spectral decay compared to an assumed source model. The key to evaluating differences in kappa between California and Yucca Mountain is to estimate kappa using the same source model (e.g., omega-squared model). The average kappa for sites at the surface of Yucca Mountain was previously estimated to be 0.02 sec based on studies by Su et al. (1996). This kappa is for Point C (Figure 2) and not for the reference hard-rock site (Point A). The difference between the kappa at Point C and at Point A is due to the material damping in the top 300 m of tuff. To account for this difference, laboratory studies of the low-strain damping of the tuff in the top 300 m were conducted (Stokoe et al. 1998). The damping was found to be very low, implying that the top 300 m only contributed 0.0014 sec to the kappa estimated at the surface. Subtracting this shallow kappa from the estimated kappa at the surface leads to a kappa of 0.0186 sec for the reference hard-rock outcrop. The GM experts used this estimate of the median kappa as part of the reference hard-rock outcrop definition. Variability in the kappa over the repository facility area is accommodated in the standard deviation of the ground motion attenuation relations.

This definition of the reference hard-rock outcrop provided a well-defined reference for the GM experts to develop their ground motion estimates. With the change in the reference

site from the surface of the tuff (represented by Point C in Figure 2) to the reference hard-rock outcrop (represented by Point A), the nonlinear properties of the tuff were not needed for the development of the ground motions in this study. Nonlinearity is being addressed in the computation of the seismic design ground motions at Points B, C, and D through site-specific site response analyses.

Stress Drops for Normal Faulting Earthquakes

The ground motion study by Spudich et al. (1996) found lower ground motions for earthquakes in extensional regimes than for earthquakes in compressional regimes. Since their analysis was based on residuals from attenuation relations, it was not clear to what extent this difference could be due to earthquake source, path, or local site effects. Because high-frequency ground motions scale with stress drop (Brune 1970), the GM experts requested that stress drops, the difference in stress across a fault before and after an earthquake, be computed for the Spudich et al. (1996) data set to compare with stress drop data for California earthquakes This analysis was done in an effort to determine the causes of the ground motion differences.

Median Brune stress drops (Brune 1970) were computed for the normal faulting earthquakes in the Spudich et al. (1996) worldwide data base as well as for strike-slip earthquakes in California, using a consistent methodology. The stress drops for normal faulting earthquakes were found to be systematically lower than those for strike-slip earthquakes (Becker and Abrahamson 1997). The effect of the lower stress drops is a reduction of 15-55% in the high-frequency ground motion, depending on the approach used to compute the stress drops.

Numerical Simulations

Numerical simulations of ground motions at Yucca Mountain were available for the earthquakes considered in the scenario earthquake modeling project (J. Schneider, URSGWC, written communication, 1996). The experts, however, were required to estimate the ground motions for much larger ranges of magnitudes and distances than were considered in that study. To address this issue, numerical simulations were generated for the full set of events (point estimates) that the experts had to consider. Three preferred methodologies were identified by the experts from the six included in the scenario earthquake modeling project. The models of Zeng and Anderson, Silva, and Somerville were selected based on their perceived superior modeling ability as evidenced by comparisons included in the scenario earthquake modeling project (J. Schneider, URSGWC, written communication, 1996). Ground motions for the required point estimates were then generated for southern Basin and Range source and path properties and the reference rock outcrop properties.

GROUND MOTION EXPERTS' EVALUATIONS

Ground motion evaluations were performed using an expert elicitation process similar to that used for seismic source and fault displacement evaluations. The elicitation process was facilitated by the GM Facilitation Team; it included three workshops, two working meetings, and a 1-day elicitation meeting with each GM expert (Figure 1).

The seven GM experts estimated median ground motion, aleatory variability (standard deviation), and epistemic uncertainties for a matrix of earthquake magnitudes, source-to-site distances, and faulting styles (normal and strike-slip) and for a suite of spectral frequencies

(CRWMS M&O 1998). The ground motions were defined at the reference rock outcrop. These estimates were based on empirical and numerical simulation-based models and on combinations of conversion factors. The experts classified proponent models as empirical attenuation relations, hybrid empirical, point-source numerical simulations, finite-fault numerical simulations, and blast models (J. Schneider, URSGWC, written communication, 1996). A complete list of the models is shown in Table 4.

Table 4. Model classes and proponent models

Model Class	Proponent Models	Used For Final Estimates?
Empirical	Abrahamson and Silva (1997)	Yes
	Boore et al. (1997) (Vs model)	Yes
	Boore et al. (1994) (Class A)	No
	Boore et al. (1994) (Class B)	No
	Campbell (1997) (Soft Rock)	Yes
	Campbell (1997) (Hard Rock)	No
	Campbell (1993, 1994)* (Hard Rock)	No
	Campbell (1990, 1994) (Soft Rock)	No
	Campbell (1990) (Soil, Soft Rock)	No
	Idriss (1993) (Rock, Stiff Soil)	No
	Idriss (written comm., 1997) (Rock, Stiff Soil)	Yes
	Joyner and Boore (1988) (Rock)	Yes
	Sadigh et al. (1997) (Rock)	Yes
	Sabetta and Pugliese (1996) (Rock)	Yes
	Spudich et al. (1996) (Rock)	Yes
	McGarr (1984) (Rock)	Yes
Hybrid Empirical	Campbell (This Study)	Yes
Finite Fault Simulation	Silva (This Study)	Yes
	Somerville (This Study)	Yes
	Zeng and Anderson (This Study)	Yes
Point Source RVT	Silva (This Study)	Yes
Blast	Bennett Model 1 (J. Schneider, URSGWC, written communication, 1996)	No
	Bennett Model 2	Yes
	Bennett Model 3	No

* Campbell (1994) is Campbell and Borzognia (1994).

As described above, a fundamental issue that the experts evaluated is whether ground motions at Yucca Mountain differ significantly from the motions represented by the data set that forms the basis for empirical models and, if they differ, by how much. Differences could be caused by source, path, or site effects. The region- and site-specific aspects of the ground motion could be directly incorporated as input for the numerical simulations, but for the empirically based models, proponent conversion factors were developed to account for these differences. Suites of conversion factors were obtained using the results of (1) numerical finite-fault simulations, (2) stochastic point-source simulations, and (3) empirical attenuation relations. The conversion factors included corrections for the following:

- Source—ratio of western U.S. sources to Yucca Mountain region extensional sources (0.35 to 1.0)
- Crust—ratio of western U.S. crust to Yucca Mountain region crust (0.9 to 1.2)
- Site—ratio of reference rock outcrop to Yucca Mountain surface (1.1 to 2.2)

Due to the large number of estimates required, the experts used numerical weighting of proponent model estimates to develop their initial estimates. The weighting procedure applied two levels of weights. The models were first separated into classes, and weights were assessed for each class based on the experts' evaluations of the applicability of the class. Then for each range of magnitude, distance, and fault type, weights were assessed for the models within each class based on the experts' evaluations of the strengths and weaknesses of each model in terms of its applicability to the Yucca Mountain region. In general, each expert varied the class and model weights on a case-by-case basis to reflect his/her assessment of the applicability of each model. For example, an expert may have downweighted or eliminated an empirical relationship outside the magnitude range of the data on which the relationship was based.

The resulting matrix of point estimates consisted of 51 combinations of parameters that were considered to adequately define attenuation for the seismic sources developed by the SSFD expert teams. The matrix covered magnitudes ranging from M_w 5.0 to 8.0, distances ranging from 1 to 160 km, and strike-slip and normal faulting (both hanging wall and footwall). The range of spectral frequencies for which ground motion was evaluated was selected to span the range of interest for the potential Yucca Mountain SSCs: 0.3, 0.5, 1, 2, 5, 10, and 20 Hz in addition to peak ground acceleration (PGA) (defined at 100 Hz) and peak ground velocity (PGV). The GM experts also evaluated two special cases representing the SSFD experts' interpretations of fault sources near Yucca Mountain: multiple parallel fault rupture and a shallow detachment fault. The experts developed scaling rules to apply to their models specifically to represent these seismic sources (CRWMS M&O 1998).

A ground motion model estimates the median ground motion as a function of magnitude and distance and the aleatory variability (standard deviation) about the median. Both the median estimate and the standard deviation are uncertain. The experts used logic trees to characterize this epistemic uncertainty in their ground motion evaluations. In a typical logic tree, an expert's evaluation of alternative models is expressed by weighting branches of the logic tree representing the alternative models. The approach used to assess epistemic uncertainty in ground motion for this PSHA is somewhat different. Each GM expert evaluated the alternative models individually and developed his/her own composite model for their best estimates of the median and standard deviation for a given set of earthquake magnitudes and source distances. Thus, the experts' ground motion estimates consisted of four values for each magnitude-distance pair: median, aleatory standard deviation, epistemic uncertainty for the median, and epistemic uncertainty in the aleatory variability.

The GM experts' point estimates of the ground motion were parameterized by the GM Facilitation Team as attenuation equations for use in the hazard calculations. 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 to be 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 ground motion saturation at large magnitude and close distances.

As an example, the median PGA attenuation for a M_w 6.5 normal faulting earthquake is shown in Figure 9a and the epistemic uncertainty about the median (σ_μ) is shown in Figure 9b. The total epistemic uncertainty for the median ground motion is a combination of the range of the experts' estimates of the median (range in Figure 9a) and the uncertainty associated with each expert's estimate (Figure 9b). Note that if the median ground motion

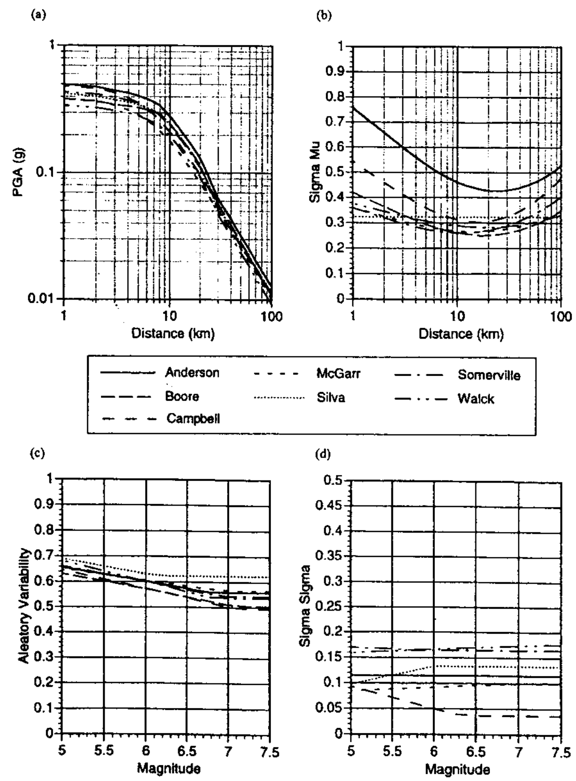


Figure 9. PGA characterization of a M_w 6.5 normal faulting earthquake in the hanging wall: (a) median attenuation of horizontal PGA, (b) epistemic uncertainty of the median values, (c) aleatory variability, and (d) the epistemic uncertainty in the aleatory variability. (b), (c), and (d) are in natural log units.

estimates are very similar, it does not mean that no epistemic uncertainty exists; that would be the case only if the epistemic uncertainty was zero. Similar plots for the best estimate of the standard deviation (σ) and epistemic uncertainty in the standard deviation (σ_σ) are shown

in Figures 9c and 9d. Consensus on the median values occurs when the experts' estimates of the median and standard deviation are within the epistemic uncertainty of the others. Significant differences occur when the experts' median estimates differ by more than their estimates of the epistemic uncertainty.

GROUND MOTION HAZARD CALCULATIONS AND RESULTS

Ground motion hazard was computed at the reference rock outcrop (Point A, Figure 2). The calculation was conducted in three steps. For each SSFD expert team, the calculation was performed for each seismic source for each combination of attenuation and seismic source parameters, resulting in an appropriately weighted aleatory hazard curve for each combination. The total hazard across sources was then aggregated for each team to obtain the teams' mean and fractile hazard curves. The integrated hazard across all SSFD teams was obtained by combining the expert teams' mean and fractile hazard curves giving each team equal weight. A minimum magnitude of M_w 5.0 was used as the lower bound for integrating the earthquake recurrence relationship in the hazard calculations (EPRI 1989, Appendix B). The aleatory uncertainty (the variability about the GM experts' median attenuation) in the ground motion attenuation equations was modeled using the unbounded lognormal distribution (no upper bound was assumed).

Ground motion hazard was calculated for the ground motion measures PGA, PGV, and spectral accelerations at 0.3, 0.5, 1, 2, 5, 10, and 20 Hz structural frequencies. The computations were based on equal weighting of the six SSFD expert teams' interpretations and the seven GM experts' interpretations. The results are presented in the form of summary hazard curves, which depict the mean, median, and 15th and 85th fractile of the calculated aleatory hazard curves. The mean and median convey the central tendency of the hazard results while the separation between the 15^{th} and 85^{th} fractile curves conveys the epistemic uncertainty on the calculated exceedance probability. Figure 10 shows summary hazard curves for PGA and 1 Hz spectral acceleration.

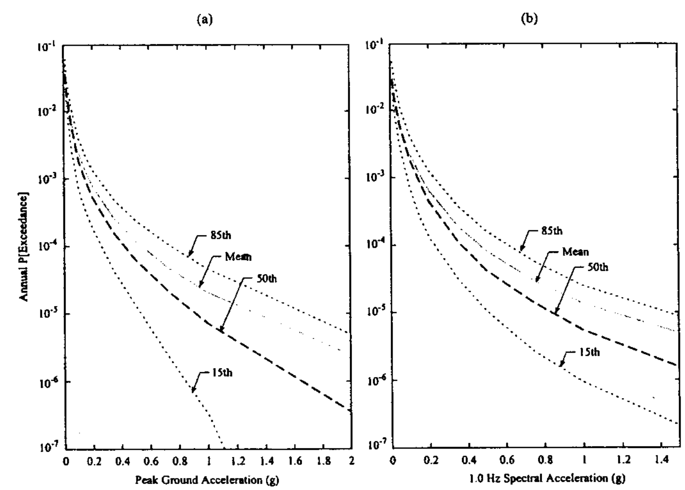


Figure 10. Summary hazard curves for horizontal (a) PGA and (b) 1 Hz spectral acceleration.

The uniform hazard across structural frequencies is expressed as mean, median, and 15th and 85th fractile uniform hazard spectra in Figure 11 for the target design annual exceedance probability of 10^{-4}. Note that this uniform hazard spectrum peaks at about 10 Hz unlike typical western U.S. spectra, which have their spectral peaks at about 2 to 3 Hz. This shift to higher frequencies reflects the lower kappa at Yucca Mountain, which is more typical of eastern U.S. sites (Silva and Darragh 1995). PGA, 0.3, 1.0, 5, and 10 Hz spectral acceleration values and PGV are summarized in Table 5 for target design basis hazard annual exceedance probabilities of 10^{-3} and 10^{-4}.

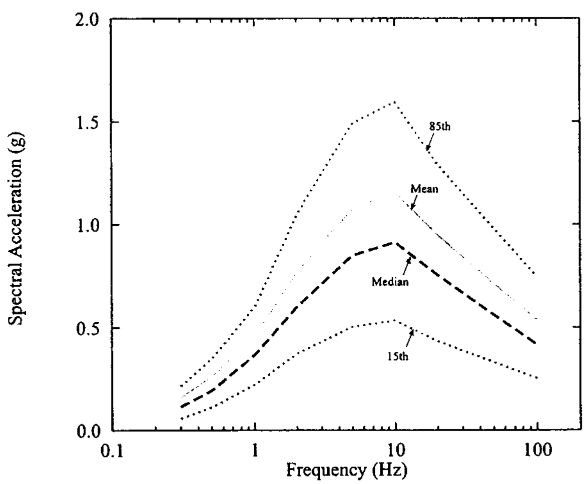


Figure 11. Horizontal uniform hazard spectrum for 10^{-4} annual exceedance frequency.

Table 5. Mean ground motion hazard at 10^{-3} and 10^{-4} annual exceedance probabilities

	Horizontal		Vertical	
Frequency (Hz)	**10^{-3}**	**10^{-4}**	**10^{-3}**	**10^{-4}**
PGA	0.17 g	0.53 g	0.11 g	0.39 g
0.3	0.05 g	0.17 g	0.03 g	0.11 g
1.0	0.16 g	0.47 g	0.07 g	0.22 g
5.0	0.35 g	1.10 g	0.20 g	0.66 g
10.0	0.36 g	1.20 g	0.25 g	0.91 g
PGV	15 cm/sec	48 cm/sec	7.6 cm/sec	25 cm/sec

GROUND MOTION HAZARD SENSITIVITY RESULTS

Extensive evaluations to determine the sensitivity of the hazard results to assessed input parameters were performed (CRWMS M&O 1998). The largest contributor to uncertainty in ground motion hazard was found to be uncertainty in ground motion attenuation. Specifically, experts' uncertainties about the median ground motion attenuation and the standard deviation of motion about the median, in that order, are the largest contributors. Expert-to-expert epistemic uncertainty is a smaller contributor to total hazard uncertainty.

Figure 12, which shows the mean hazard curves for individual SSFD teams, displays the team-to-team epistemic uncertainty in seismotectonic interpretations. This uncertainty can be considered a measure of the earth science community's uncertainty in characterizing the expected hazard at Yucca Mountain. We consider this uncertainty, which is generally less than a factor of 2, to be reasonably small, reflecting the large common information base used by the experts and the structured expert elicitation process that was followed. The expert elicitation process resulted in a common knowledge base.

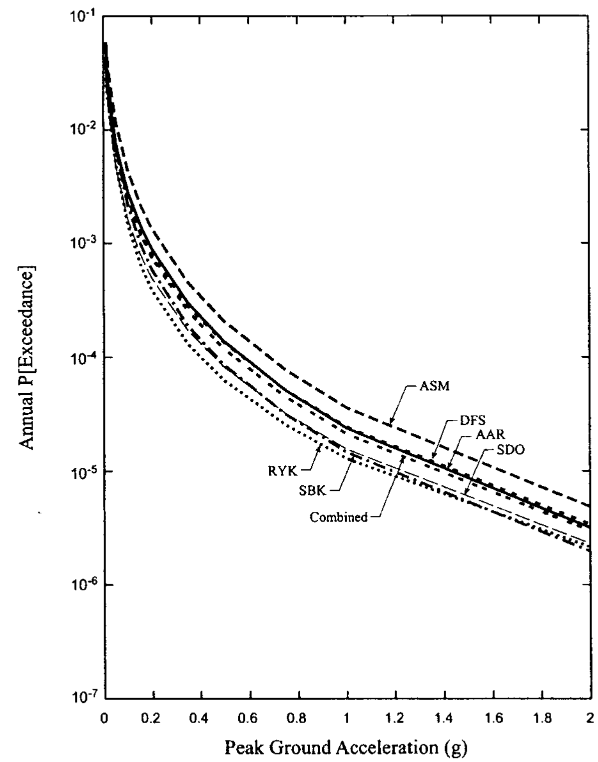


Figure 12. Mean hazard curves by team for horizontal PGA.

With respect to the seismic source characterizations, the earthquake recurrence values (either slip rates or recurrence intervals) and recurrence models (e.g., characteristic, exponential, or maximum moment) used were found to contribute the most to uncertainty in the ground motion hazard. M_{max} has a small effect on uncertainty especially for 10 Hz motions, because a large fraction of the hazard at this frequency is contributed by more frequent moderate-magnitude events at close distances. 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 significantly contribute to uncertainty in hazard results.

The composite mean hazard was deaggregated on magnitude, distance, and ground motion variability, as shown in Figure 13, to determine controlling earthquakes and provide engineering insights for development of design basis spectra (McGuire 1995). Deaggregation of the mean hazard for an annual exceedance probability of 10^{-4} shows that at intermediate frequencies (5 to 10 Hz), the ground motion hazard is dominated by earthquakes smaller than M_w 6.5 at distances less than 15 km (Figure 13a). The sources of these earthquakes are the Paintbrush Canyon – Stagecoach Road and Solitario Canyon faults (or alternative

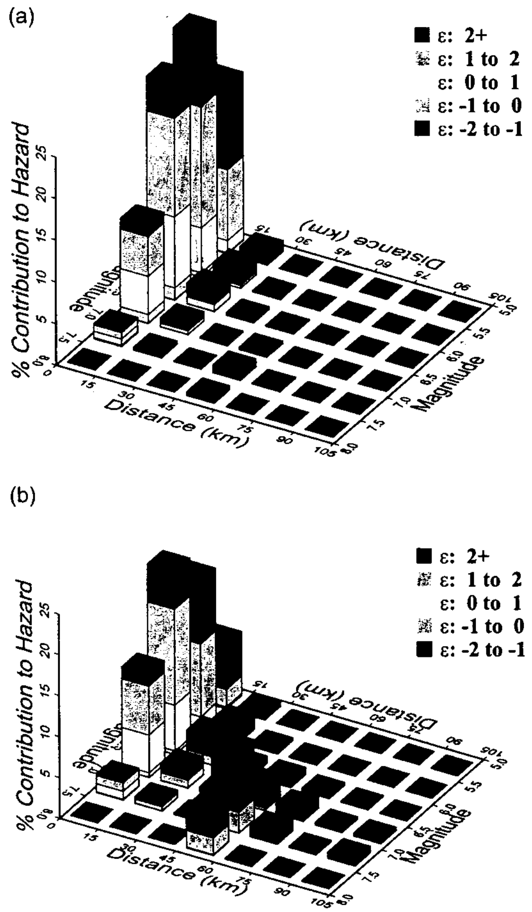


Figure 13. Magnitude-distance-epsilon deaggregation of mean seismic hazard for (a) 5 to 10 Hz and (b) 1 to 2 Hz horizontal spectral acceleration at 10^{-4} annual exceedance frequency.

interpretations of coalesced fault systems that include these faults) and the host areal seismic source zone. Dominant earthquake sources for low-frequency ground motions (e.g., 1 to 2 Hz) display a bimodal distribution with significant contributions to the total hazard from large nearby earthquakes, the three sources mentioned above, and from M_w 7 and larger earthquakes beyond distances of 50 km and ground motion variability larger than two standard deviations (Figure 13b). The latter contribution is mainly from the comparatively active 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 only a small contribution to the total hazard. Hypothesized buried strike-slip faults, volcanic seismicity, and proposed seismogenic detachment faults contribute negligibly to the total hazard.

EVALUATION AND CHARACTERIZATION OF FAULT DISPLACEMENT POTENTIAL

The SSFD expert teams developed original approaches to model and characterize fault displacement potential for input to the fault displacement hazard assessment (CRWMS M&O 1998). The approaches were primarily based on empirical observations of faulting characteristics during past earthquakes at Yucca Mountain and in the Basin and Range Province. Empirical data were fit by statistical models to quantify faulting parameters and their variability. These results were then used by the teams to develop forward alternative models to characterize their interpretations of fault displacement potential and to express their uncertainty.

The potential for fault displacement was categorized as either principal or distributed faulting. Principal faulting occurs along a main plane (or planes) that is the locus of release of seismic energy. 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 basic formulation of a probabilistic hazard model for fault displacement is analogous to that for computing ground-shaking hazard. The hazard can be represented probabilistically by a displacement hazard curve that is analogous to a ground motion hazard curve. The curve depicts annual occurrence of fault displacement values (i.e., the annual frequency of exceeding a specified amount of displacement). Thus, the hazard curve is a plot of the frequency of exceeding fault displacement value d, designated by $\nu(d)$. This frequency can be computed using the expression

$$\nu(d) = \lambda_{DE} P(D > d) \quad (1)$$

where λ_{DE} is the frequency of displacement events at a point of interest, and $P(D > d)$ is the conditional probability that the displacement D in a single event will exceed value d.

Several approaches were developed by the SSFD expert teams to characterize λ_{DE} and $P(D > d)$ (CRWMS M&O 1998). Approaches to characterize λ_{DE} fall into two categories: the displacement approach and the earthquake approach. The displacement approach provides an estimate of the frequency of displacement events directly using feature-specific or point-specific observed displacements. The earthquake approach relates the frequency of displacement events to the frequency of earthquakes on the seismic source using the seismic source characterization that was used as input to the ground motion hazard assessment. The earthquake approach was to characterize the potential for fault displacement from background earthquakes.

For principal 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.

APPROACHES FOR CHARACTERIZING FAULT DISPLACEMENT POTENTIAL

In aggregate, the six SSFD expert teams slightly preferred the displacement approach (aggregate weight ~ 0.6) over the earthquake approach for characterizing fault displacement potential at sites subject to principal faulting and at sites subject to only distributed faulting. For characterizing principal faults, four of the teams used only one approach. Three teams used only one approach for characterizing displacement potential on distributed faults.

Principal faulting hazard was assessed for points located on faults that the SSFD expert teams identified as being seismogenic. The preferred method for estimating λ_{DE} in the displacement approach used slip rate divided by the average displacement per event. The expert teams used a number of approaches to evaluate $P(D > d)$, based on empirical distributions derived from Yucca Mountain paleoseismic data (CRWMS M&O 1998). These distributions were normalized by various parameters, including the expected maximum displacement in the maximum event, the average displacement estimated from displacement data, and the average and maximum displacements estimated from the length of the fault.

To characterize λ_{DE} for assessing displacement hazard on principal faults using the earthquake approach, the teams used the frequency of earthquakes they had evaluated for the ground motion hazard assessment and multiplied it by the conditional probability that an earthquake 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 $P(D > d)$ 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 λ_{DE} on features subject only to distributed faulting used slip rate divided by the average displacement per event (displacement approach). The slip rates were derived using the cumulative displacement and slip history on the fault or feature. The teams used approaches for evaluating $P(D > d)$ similar to those used for principal faulting hazard. The empirical distributions were combined with a scaling relationship used to estimate the average displacement per event to obtain $P(D > d)$.

The SSFD expert teams were most uncertain in their characterizations of 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 (CRWMS M&O 1998). The widest variations in approaches were those for assessing the distribution for displacement per event on the distributed ruptures.

FAULT DISPLACEMENT HAZARD RESULTS

Probabilistic fault displacement hazard was calculated at locations on representative features within the potential repository facility area, shown in Figure 3 and described in Table 6. Two of the locations (7 and 8) have four alternative displacement histories specified to represent fault and fracture conditions that have been mapped at Yucca Mountain (2-m small fault, 10-cm shear, fracture, and intact rock; Table 6).

All of the teams considered locations 1 and 2 to be on principal faults. Two teams also considered some potential for principal faulting hazard at location 4 because they had interpreted some probability that the Ghost Dance fault is seismogenic. One team also made the interpretation that location 6 in Dune Wash lies on the West Dune Wash fault and is subject to principal faulting displacement.

Table 6. Mean displacement hazard at nine demonstration locations

Location	Location Description	Displacement (cm) Annual Exceedance Probability 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
7c	Fracture	<0.1	<0.1
7d	Intact rock	<0.1	<0.1
8	Between Solitario Canyon and Ghost Dance faults		
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

The teams varied widely in their assessments of the potential that distributed faulting could occur in future earthquakes at locations 3 through 9, which are away from the block-bounding faults and principal faults. These assessments were based on fault orientation, cumulative slip, and structural relationships. One team's interpretation is that all features with some evidence of cumulative displacement are capable of displacement in future earthquakes. Another team's interpretation is that for most of these features, the probability that they are capable of displacement in future earthquakes is low. All teams considered the potential for displacement at a point in intact rock due to the occurrence of a future earthquake to be either extremely low or zero.

The integrated hazard results depict fault displacement hazard and its uncertainty at the nine locations shown in Figure 3, based on the interpretations and parameters developed by the SSFD expert teams. Separate results were obtained for each location and presented as summary fault displacement hazard curves (e.g., Figures 14 and 15). Table 6 contains a summary of the mean displacement hazard results for the two target design basis annual exceedance probabilities, 10^{-4} and 10^{-5}, at the nine locations. These target design hazard levels are a factor of 10 lower that the targeted hazard design levels for ground motion, reflecting the limited engineering experience with design of facilities for fault displacement (DOE 1997).

With the exception of locations 1 and 2, which are on the block-bounding Bow Ridge and Solitario Canyon faults, respectively, the displacements are all 0.1 cm or less at a 10^{-5} annual exceedance probability. At these two locations at 10^{-5} annual exceedance probability, the displacements are 7.8 and 32 cm, respectively (Figure 14, Table 6). Thus, locations not on a block-bounding fault (i.e., locations on intrablock faults, other small faults, shear fractures, and intact rock) are assessed to have displacements of 0.1 cm or less at a 10^{-5} annual exceedance probability (Figure 15). Both hazard curves for locations 1 and 2 are flat between 0.1 to 10 cm (Figures 14a and 14b), implying that if a surface displacement occurs on either fault, it is likely to be greater than 10 cm.

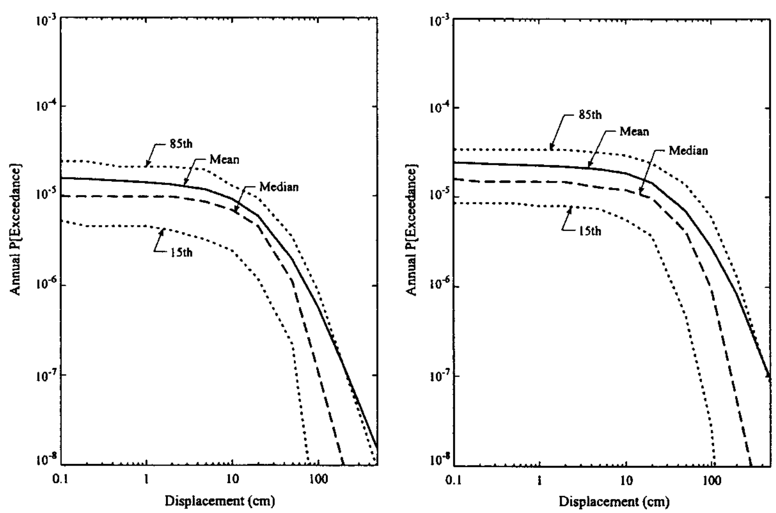


Figure 14. Summary hazard curves for (a) Location 1, Bow Ridge fault and (b) Location 2, Solitario Canyon fault.

Figure 16 illustrates the team-to-team epistemic uncertainty in the mean fault displacement hazard for location 1. This uncertainty is significantly larger than is found for ground motion hazard. We believe this relatively larger scientific uncertainty reflects the

earth science community's lack of experience with probabilistic assessments of fault displacement hazard. Epistemic uncertainty in distributed fault displacement hazard is larger than the uncertainty in displacement hazard on principal faults.

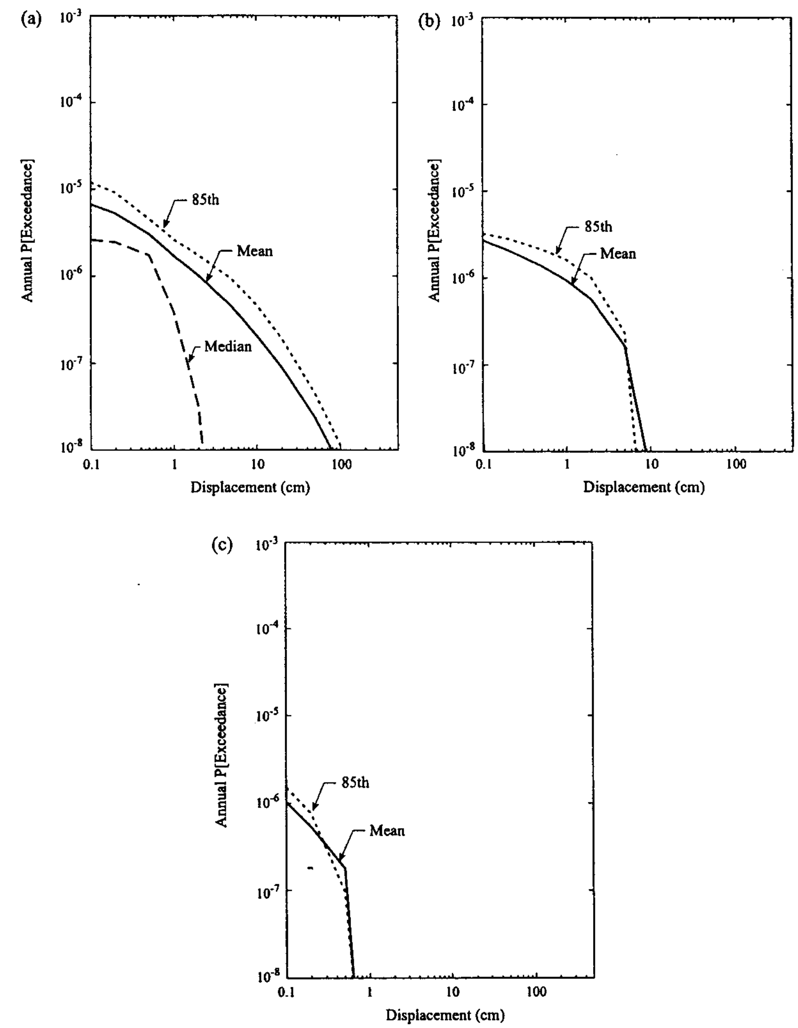


Figure 15. Summary hazard curves for Location 8, midway between Ghost Dance and Solitario Canyon faults: (a) 2 m cumulative displacement, (b) 10 cm cumulative displacement, and (c) no measurable cumulative displacement.

A positive correlation exists between the amount of geologic data available at a location and the uncertainty in the calculated fault displacement hazard at that location, as might be expected. For locations with significant geologic data, the team-to-team uncertainty is less than one order of magnitude. For locations with few or no data, the team-to-team uncertainty may span three orders of magnitude. The larger uncertainty at these locations is considered to be due to greater data uncertainty (i.e., less certain constraints on the team's fault displacement characterization models).

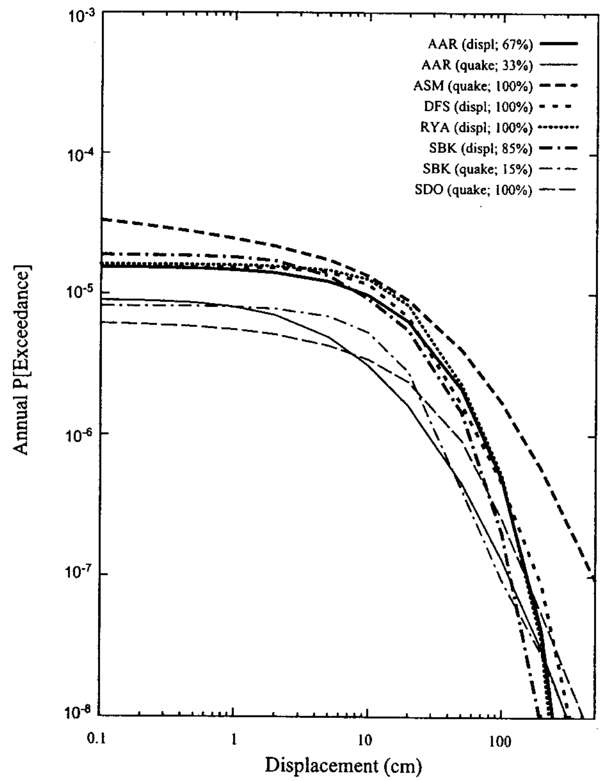


Figure 16. Mean hazard curves by team for Location 1, Bow Ridge fault.

While the fault displacement hazard results display large uncertainty, the hazard levels are quite low. Although these results overall have significantly greater uncertainty than the ground motion hazard results, they 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.

DISCUSSION AND CONCLUSIONS

The Yucca Mountain PSHA implemented state-of-the-practice guidance for a Level 4 PSHA as defined by the SSHAC (1997). A SSHAC Level 4 PSHA is complex and costly to implement, and generally, will not be justified except for projects that have a high level of public or regulatory importance. For these projects it is important to include a sufficiently broad range of diverse technical interpretations, and the additional complexity of project management and the planning and implementation of a structured expert elicitation may be justified.

A major objective of the Yucca Mountain PSHA was to obtain hazard results quantifying epistemic uncertainty that represents the state of knowledge of the informed scientific community about evaluations of earthquake sources, earthquake recurrence, ground motion attenuation, and fault displacement modeling. To achieve this objective we found it necessary to give a high level of attention and equal care to all aspects of project planning and implementation and to maintain flexibility to make adjustments during the execution of the project. From the beginning of the study we emphasized equal weighting of the experts for purposes of aggregating the hazard results. This objective heightens the importance of selection of experts and formation of the expert panels. For this important step we drew on the broad resources of the scientific community to identify SSFD experts with balanced experience and expertise in Basin and Range tectonics, paleoseismic investigations, and seismology to perform the SSFD evaluations. Because of the scope of expertise required, six teams were formed to independently perform SSFD evaluations by randomly combining a seismologist, a regional tectonics expert, and a paleoseismic expert. Each team functioned as a virtual expert by being expansive in characterizing uncertainty in the team's evaluations so as to include the composite of the individual team member's uncertainties. We consider this approach important to achieve full representation of epistemic uncertainty in the teams' interpretations: For the ground motion attenuation evaluations, we similarly drew upon the resources of the scientific community to identify a panel with balanced experience with the range of empirical and numerical ground motion attenuation models. The SSFD and GM Facilitation Teams provided the critical leadership for planning and implementing the expert elicitation workshops. Each of these teams had experienced leaders supported by resource experts who developed specific data sets and performed specific analyses in response to needs for information identified by the experts during execution of the project. A Data Management Team supported the project by compiling data and distributing data and data products to the expert evaluators in a consistent, standard format. We conclude that each of these project planning and management actions is equally important in assuring that the objective of the project is achieved.

We implemented a participafory peer review (SSHAC 1997). The peer review panel members together had experience and expertise in all elements of the project. The panel participated at every stage of the project. Panel members made presentations in workshops performing as resource experts, provided verbal and written comments and recommendations following each workshop, and reviewed project reports. This high level of participatory review had the important benefit of identifying adjustments that significantly improved the effectiveness of the elicitation process. The ongoing review led to an additional meeting of the GM Panel to refine methods of assessing uncertainty, a joint meeting of the GM and SSFD Panels to discuss common evaluations of earthquake source parameters and the geometry of faulting for local fault specific sources, and an additional workshop to provide additional feedback to the SSFD experts of fault displacement hazard results.

In summary, the level of ground motion hazard calculated for a defined rock condition at Yucca Mountain is comparable to the hazard assessed for other sites in low strain rate regions elsewhere in the Basin and Range Province, such as the Rio Grande rift (Wong and Olig 1998). It is lower than has been assessed in some other regions of the Basin and Range Province, for example, locations along the Wasatch fault in Utah. Uniform hazard spectra for the annual probability targeted seismic design of the Yucca Mountain facility SSCs that are relevant for off-site radiological safety, 10^{-4}/yr, indicate that seismic design motions will be within the range of experience with seismic design of nuclear facilities. We believe, in addition, that the hazard curves provide a stable basis for assessing the effects of ground motion on long-term radionuclide isolation and containment performance of the facility.

As typically observed, the mean hazard is higher than the median hazard and the difference increases with increasing ground motion level. This divergence between the median and mean hazard is interpreted to reflect the influence of the upper tails of the uncertainty distributions including the uncertainty in ground motion about the median attenuation. Indeed, at the very low annual hazard probabilities required for evaluation and design of nuclear facilities, the hazard is typically driven by the upper tails of the uncertainty distributions.

The approaches used to characterize fault displacement potential for probabilistic fault displacement hazard calculation were developed specifically for the Yucca Mountain site. The lack of experience with evaluating fault displacement potential for hazard calculation may explain part of the significantly large epistemic uncertainty in the hazard results, particularly for locations subject to distributed faulting. In part also, the large epistemic uncertainty can be attributed to the limited data available to constrain the modeling parameters. Even with the large epistemic uncertainty, the hazard results indicate that fault displacement hazard is not a seismic design issue for the repository, although significant faults including block-bounding faults will be avoided in the layout of the underground facilities. As is the case with the ground motion hazard results, the fault displacement hazard results provide a stable basis for assessing the effects of fault displacement on long-term waste isolation and containment performance of the repository facility.

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