EVALUATING THE SEISMIC HAZARDS AND DEVELOPING DESIGN GROUND MOTIONS FOR YUCCA MOUNTAIN, NEVADA, U.S.A.

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ABSTRACT:

Yucca Mountain, Nevada has been recommended and approved for development as the site of the United States' first permanent repository for the disposal of spent nuclear fuel and high-level radioactive waste. As part of the development process, a license application has been prepared and submitted to the U.S. Nuclear Regulatory Commission. The license application describes earthquake ground-motion parameters for the subsurface waste emplacement facility (repository block) and for surface facilities. The ground-motion parameters are used for design of the subsurface and surface facilities, to evaluate safety during the preclosure period, and to assess repository performance during the postclosure period. Development of the ground motion parameters has been performed in three phases: (1) probabilistic seismic hazard analyses (PSHA) for both ground shaking and fault displacement; (2) geotechnical, geophysical, and geologic site characterization of the repository block and Surface Facility Area (SFA) to acquire site-specific data for site-response analysis; and (3) site-response analyses to modify reference rock outcrop ground motions from the PSHA to site-specific conditions and to develop design ground motions. The PSHA was the largest and most comprehensive analysis ever conducted for ground-shaking hazard and was a first-of-a-kind assessment of probabilistic fault displacement hazard. Formal expert elicitation was used to develop inputs for the PSHA. The hazard from the PSHA was conditioned to establish an upper range of extreme ground motions based on geologic and seismological arguments. An integrated program of borehole logging, geophysics, and velocity surveys, spectral-analysis-of-surface-wave surveys, and dynamic laboratory testing was performed to characterize the lithologic, velocity, and dynamic material properties for input into the site-response analysis. Variabilities in site properties were quantified and are accommodated in the ground-motion estimates. Site-response analyses were performed to calculate hazard-consistent ground motions using a random vibration theory-based equivalent-linear approach. Response spectra, time histories, and strain-compatible properties (SFA only) for preclosure analyses were calculated for mean annual frequencies of exceedance (AFE) of 10^{-3}, $5x10^{-4}$, and 10^{-4}. For postclosure analyses, ground motions were calculated for mean AFEs between 10^{-4} and 10^{-8}.

KEY WORDS: Yucca Mountain, seismic hazard, design ground motions, site-response analysis

1. INTRODUCTION

The Yucca Mountain site about 145 km northwest of Las Vegas, Nevada, has been designated for development as the United States' first permanent repository for spent nuclear fuel and high-level radioactive waste (Figure 1). Since the 1980s, the U.S. Department of Energy (DOE) has undertaken the most extensive and comprehensive seismic hazard evaluation of any site in the U.S. Ground-motion parameters have been developed for both a subsurface location, where waste will be emplaced, and for a surface location, where receipt and handling of waste will take place. Ground-motion parameters are used for both design analyses and to assess the performance of the repository during its operation (preclosure) and after it has been filled and sealed (postclosure). Development of ground motions has been performed in three phases: (1) probabilistic seismic hazard analyses (PSHA) for both ground shaking and fault displacement; (2) geotechnical, geophysical, and geologic site characterization of the repository block and Surface Facility Area (SFA) to acquire data for site-response analysis; and (3) site-response analyses to modify the ground motions from the PSHA to site-specific conditions and develop design ground motions. Stepp et al. (2001), Stokoe et al. (2003; 2004), and Wong et al. (2006) have described various aspects of the process of developing the seismic design ground motions. In this paper, we summarize the above process and the recent calculation of supplemental ground motions for preclosure design and safety analyses using additional site characterization data and a hazard-consistent site-response analysis approach.

Figure 1. View of Yucca Mountain from the north.

Yucca Mountain is a moderately eroded and tilted fault block, 3 to 8 km wide and about 35 km long, located in the north-central part of the Basin and Range Physiographic Province (Figure 1). The crest of Yucca Mountain ranges in elevation from about 1,500 to 1,930 m. Yucca Mountain consists of stacked layers of tuffs, approximately 11.5 to 14 million years old, that formed by eruptions of volcanic ash from a large caldera complex to the north. Individual layers of volcanic tuff, therefore, get progressively thinner from north to south. Most of the rocks are welded and nonwelded ash flow tuffs. The waste emplacement area is located within the Yucca Mountain block at an approximate depth of 300 m. The SFA, located on the eastern margin of Yucca Mountain, will be the site of the waste handling facilities, which will receive the incoming shipments of nuclear waste (Figure 2).

Ground motions (response spectra and time histories) for preclosure seismic design are determined for the planned underground waste emplacement tunnels and for the SFA. The waste emplacement tunnel ground motions are used to evaluate tunnel stability and to support preclosure waste package design and analyses. The SFA ground motions are used for design of the surface facilities, including soil-structure interaction analyses. Time histories for postclosure performance assessment are determined for the waste emplacement level only.

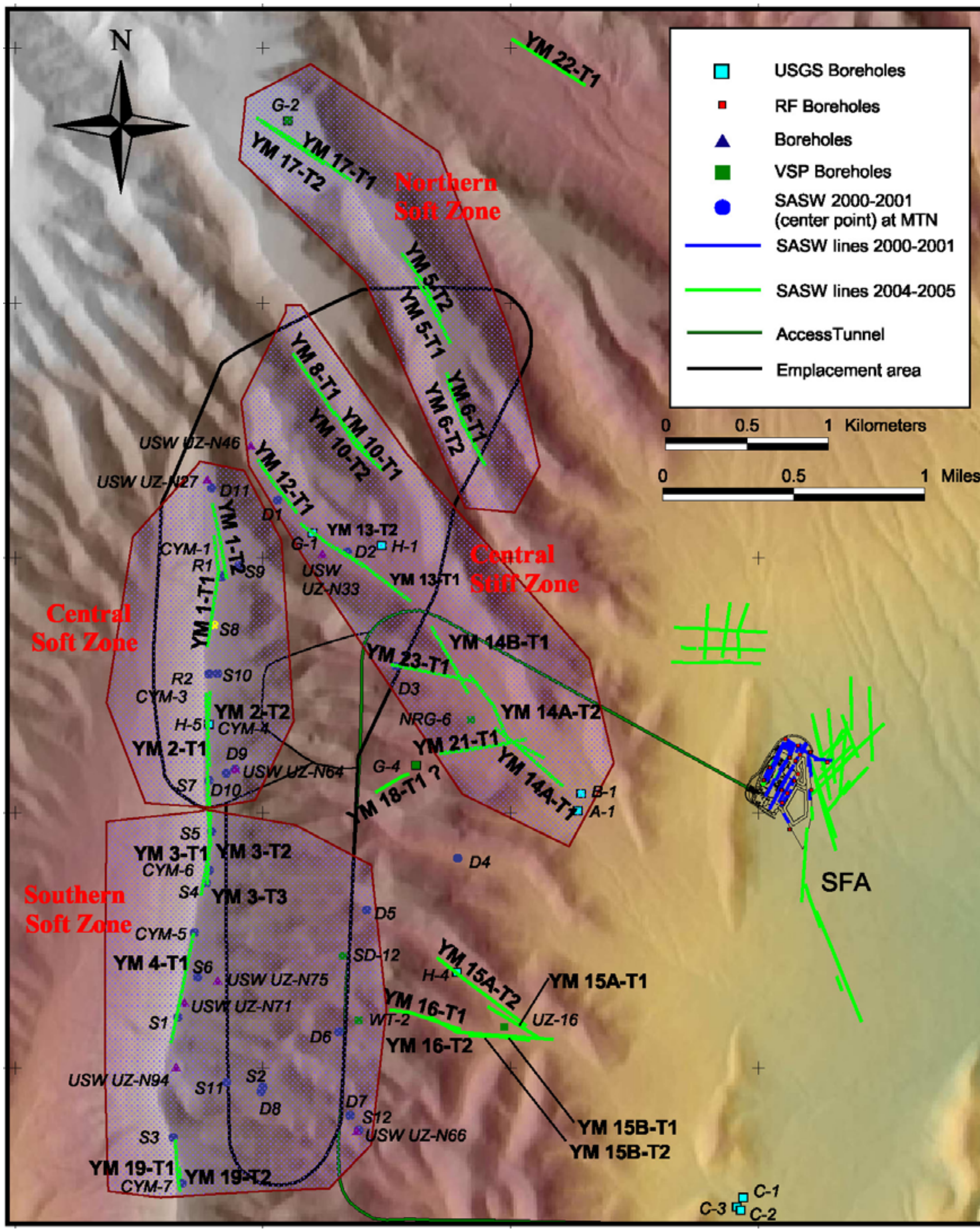

Figure 2. Map of repository block zones and SFA showing boreholes with downhole, sonic velocity, VSP, and SASW surveys.

The preclosure seismic design approach for the repository at Yucca Mountain is a risk-informed methodology for establishing design basis hazard levels for systems, structures, and components important to safety. Two design-basis ground-motion levels are used: Level 1 has a mean annual frequency of exceedance (AFE) of 1×10^{-3}, while Level 2 has a mean AFE of 5×10^{-4}. Beyond-design-basis ground-motion analyses and high-confidence-of-low-probability-of-failure analyses will be carried out, as appropriate. For these analyses, beyond-design-basis ground motions with a mean AFE of 1x10^{-4} are used. For postclosure analyses, the focus is on ground motions for AFEs between 10^{-4} and 10^{-8}. These ground motions are larger than those used for preclosure design and address the regulatory requirement to consider events with a 10^{-4} chance of occurring in 10,000 years.

2. PROBABILISTIC SEISMIC HAZARD ANALYSES

PSHAs were conducted to estimate both ground motion and fault displacement hazards at Yucca Mountain (Stepp et al., 2001). The study is the largest and most comprehensive analysis ever conducted for ground-shaking hazard at a single site and is a first-of-a-kind assessment of probabilistic fault displacement hazard. An expert elicitation process involving structured workshops, consensus identification of parameters and issues to be evaluated, sharing of all data and information among the experts, and open discussions about the basis for preliminary interpretations was implemented in general agreement with the Senior Seismic Hazard Analysis Committee (1997) and Kotra et al. (1996) guidelines. An 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. Ground-shaking hazard was computed for a hypothetical hard rock outcrop ("reference rock outcrop") with shear-wave velocity (V_S) of 1,900 m/sec, the V_S found at a nominal depth of 300 m. Fault displacement hazard is not discussed further herein.

Within the site region (within about 100 km), approximately 100 Quaternary faults were identified as potential seismic sources. With the exception of the Death Valley – Furnace Creek fault system, these faults are interpreted to have low slip rates (less than 0.1 mm/yr) and to be experiencing dominantly normal displacement in the extensional tectonic stress regime that characterizes the Basin and Range Province. The repository block is bounded on the west by the Solitario Canyon fault and on the east by the Bow Ridge fault. Both faults show evidence of slip during the Quaternary period. The objective of evaluating and characterizing seismic sources for the ground-shaking PSHA was to describe the source geometries, earthquake recurrence, and maximum magnitudes of seismic sources capable of producing earthquakes significant for ground-shaking hazard at the site. The seismic source teams characterized the faults in terms of probability of activity, location, rupture length, sense of slip, fault dip, maximum seismogenic depth, maximum moment magnitude, and earthquake recurrence.

Differences exist in properties of the seismic sources, regional crustal paths, and shallow sites for the Yucca Mountain region compared to the western U.S. strong-motion data set. Since the available attenuation relations are primarily based on California strong-motion data, the ground-motion experts evaluated the need to modify them for the Yucca Mountain site region. The seven ground-motion experts estimated median ground motions, aleatory variability (standard deviation), and epistemic uncertainty for a matrix of earthquake magnitudes, source-to-site distances, and faulting styles (normal and strike-slip), and for a suite of structural response frequencies. 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 developed by the experts to adapt western U.S. ground-motion relations for Yucca Mountain site-specific conditions.

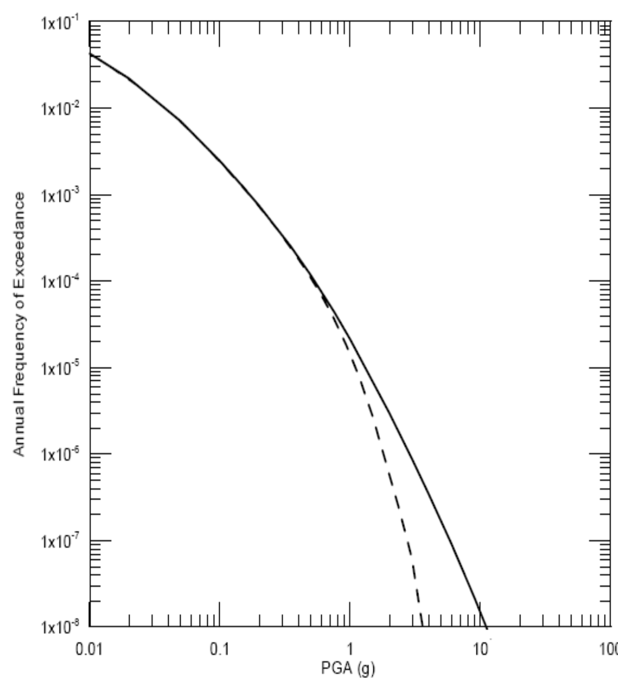

Figure 3. Conditioned (dashed line) and unconditioned (solid line) reference rock outcrop mean horizontal PGA hazard curves.

Ground-motion hazard was calculated for peak ground acceleration (PGA) (Figure 3), peak ground velocity (PGV), and spectral accelerations at selected structural response frequencies. The computations were based on equal weighting of the six seismic source expert team interpretations and the seven ground motion expert interpretations. Deaggregation of 5 to 10 Hz spectral acceleration shows that the hazard with a mean AFE of 10^{-4} is dominated by earthquakes smaller than moment magnitude (**M**) 6.5 at distances less than 15 km from Yucca Mountain (Figure 4). The sources of these earthquakes are background source zones and the local faults. At 1 to 2 Hz, **M** 7 and larger earthquakes from the Death Valley-Furnace Creek fault system beyond a distance of 50 km are significant contributors to hazard with a mean AFE of 10^{-4}.

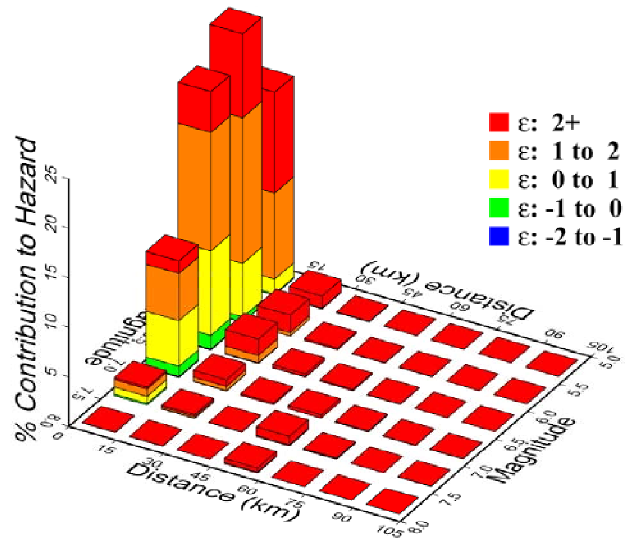

Figure 4. Contribution to mean hazard by magnitude, distance, and epsilon (ε) for the 5 to 10 Hz horizontal ground motions, 10^{-4} AFE.

Large epistemic uncertainty in the PSHA estimates of median ground motions as well as untruncated aleatory variabilities about median estimates resulted in extreme ground motions at AFEs of 10^{-6} and smaller (solid line in Figure 3). Two analyses indicate such results are inconsistent with the geologic setting at Yucca Mountain. One analysis combined geological observations in underground excavations at Yucca Mountain, laboratory rock testing, numerical simulations of rock mass deformation, and site-response analyses to estimate a level of PGV that has not been exceeded at Yucca Mountain in 12.8 million years. This nonexceedance observation over 10^7 years was taken as a reasonable bound to ground motions at Yucca Mountain and was used to condition the repository level PGV hazard curve to an AFE of 10^{-8}. More recently, the analysis to determine nonexceedance levels, updated to reflect current site-response model inputs, has been combined with an assessment of extreme source processes (probability distribution for extreme stress drops). The combined approaches are used to condition horizontal hazard curves for the hypothetical hard rock outcrop for a range of structural response frequencies (0.3 to 100 Hz), as well as horizontal-component PGV. Figure 3 shows the conditioned and unconditioned PGA hazard curves. The conditioned hazard curves for the hypothetical hard rock outcrop were then used to develop horizontal and vertical ground motions for the repository block and SFA.

3. SITE CHARACTERIZATION

The PSHA ground motions do not include the response of soil and rock that overlie rock with a shear-wave velocity of 1,900 m/sec. Hence site-response analyses were performed. Inputs into the site-response ground-motion model consist of small-strain seismic velocities, densities, nonlinear dynamic material properties, and the angles of incidence of the control motions. A comprehensive geotechnical, geological, and geophysical site characterization program was conducted to determine these inputs. Field investigations performed principally in 2000 to 2001 and 2004 to 2005 included: (1) borehole logging and downhole and suspension logging of P-wave velocity (V_P) and V_S in 15 boreholes at the SFA; the boreholes ranged in depth from 30 to 204 m; (2) caliper and gamma-gamma wireline surveys in selected boreholes; (3) 70 spectral-analysis-of-surface-wave (SASW) surveys over the repository block and across the SFA, and numerous SASW surveys in underground exploratory tunnels (Stokoe *et al.* 2003, 2004) (Figure 2); (4) dynamic laboratory testing (resonant column and torsional shear) of tuff and alluvium samples; and (5) test pits and standard static laboratory tests of collected samples from the SFA. In addition, pre-existing vertical seismic profiling (VSP) data from seven deep borings and deep sonic velocity data from 16 boreholes were considered in the analyses.

For the repository block, two base case V_S and V_P profiles were developed to represent the variability in mean velocities observed in the data, which indicate both “soft” and “stiff” zones exist at Yucca Mountain. For the SFA, a single base case profile for both V_S and V_P is used for the area northeast of a Miocene fault called the Exile Hill fault splay, which exhibits up to about 100 m of vertical offset. Three base case profiles are used for the area south of the fault. To accommodate the effect of the varying thickness of alluvium, site-response analyses were carried out for multiple values of alluvium thickness. The base case profiles are used, along with information on the statistical correlation of layer thicknesses and layer velocities, to develop a suite of random velocity profiles that are used as analysis input.

A similar procedure was used to represent the nonlinear dynamic properties of site materials. Multiple base case curves of normalized shear modulus reduction (G/Gmax) and hysteretic damping, as a function of cyclic shear strain, were developed to represent epistemic uncertainty in the mean values of these properties. The results of the dynamic laboratory testing were used to develop the site-specific dynamic property curves. Two sets of mean curves, representing either more linear or more nonlinear behavior, are developed each for the tuff and alluvium at the site. For input to the site-response analyses, the curves for all materials are randomized to represent random (aleatory) variability in properties within and across the site.

4. SITE-RESPONSE ANALYSES

The site-response analyses used for Yucca Mountain follow Approach 3 as described in NUREG/CR-6728 (McGuire *et al*. 2001) and provided hazard-consistent site-specific ground motions for the SFA and repository block. Ground motions were computed on soil at the SFA and for a tuff interface at the repository block emplacement level. In calculating the site-specific probabilistic ground motions at Yucca Mountain, the goal was to develop hazard-consistent motions, i.e., the AFE of the site-specific tuff or soil uniform hazard spectra (UHS) should be the same as the UHS for the hypothetical hard rock outcrop defined in the PSHA. Deaggregation of the PSHA results for a range of AFEs to identify controlling earthquakes for structural response frequency ranges of 1 to 2 Hz and at 5 to 10 Hz was used to develop ground motion input for the site-response model. Response spectra for appropriate controlling earthquakes were scaled to PGA values ranging from 0.1 to 10 g to cover the range of ground motions for AFEs of 10^{-2} to 10^{-8}. Site-response modeling, using these scaled response spectra as input, results in a database of site transfer functions (amplification factors) for horizontal motions. Empirical relations for the ratio of vertical-to-horizontal ground motion (V/H) and ground-motion analyses using a stochastic point-source ground-motion model along with the site-response model provide the basis to develop a database of site-specific V/H transfer functions.

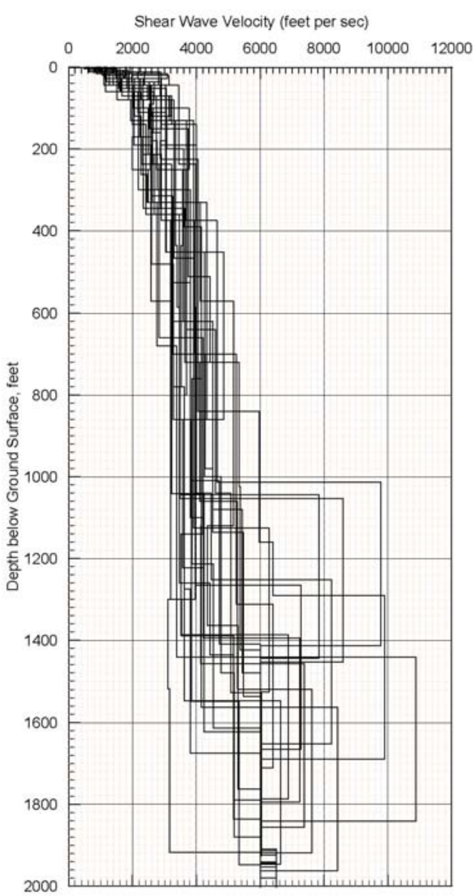

Figure 5. Sample of Randomized V_S Profiles for SFA

In implementing Approach 3 using the full integration method (Bazzurro and Cornell, 2004), the following steps were taken: 1) base case mean site properties were used to produce a randomized suite of velocity profiles as well as G/Gmax and hysteretic damping curves that are used to incorporate site variability in site-response modeling (Figure 5); 2) site amplification transfer functions were computed using a random vibration theory (RVT)-based equivalent-linear site-response model; 3) V/H transfer functions were developed from empirical relations and from combined point-source ground-motion and site-response modeling; 4) the conditioned PSHA reference rock outcrop fractile (percentile) and mean hazard curves were integrated with the transfer functions to arrive at a distribution of site-specific horizontal and vertical hazard curves; and 5) site-specific UHS were computed. The RVT-based equivalent-linear site-response model involves a computational method (i.e., equivalent-linear) that has been widely employed to evaluate 1D site response using vertically-propagating plane S-waves (Silva *et al.* 1997). Both P-SV (vertically polarized S-wave) and SH (horizontally polarized S-wave) waves are incorporated into the analyses and have specified angles of incidence based upon expected seismic source depths and distances.

5. SEISMIC DESIGN AND PERFORMANCE ASSESSMENT GROUND MOTIONS

Based on Approach 3, hazard-consistent site-specific design ground-motion inputs for preclosure analyses were determined for the repository block waste emplacement tunnels. Preclosure inputs also were determined for the SFA. As previously stated, two design basis ground-motion levels are used. For preclosure seismic safety analyses, the site-specific hazard curves and associated UHS are used. Ground motions for design analyses (response spectra, time histories, and strain-compatible material properties) were developed for AFEs of 10^{-3}, $5x10^{-4}$, and 10^{-4}. Hazard curves and associated UHS were also developed for AFEs from 10^{-3} to 10^{-7} for the SFA and from 10^{-3} to 10^{-8} for the repository block. Key results and products for preclosure design analyses are listed in Table 1 and shown in Figure 6.

At an AFE of 10^{-4} (i.e., beyond-design-basis), the horizontal PGA and PGV values are 0.91 g and 74.13 cm/sec for the SFA and 0.37 g and 41.40 cm/sec for the emplacement level, respectively. The lower ground motions for the emplacement level compared to the SFA are due to the reduction from depth effects and differences in site conditions, i.e., alluvium versus hard rock.

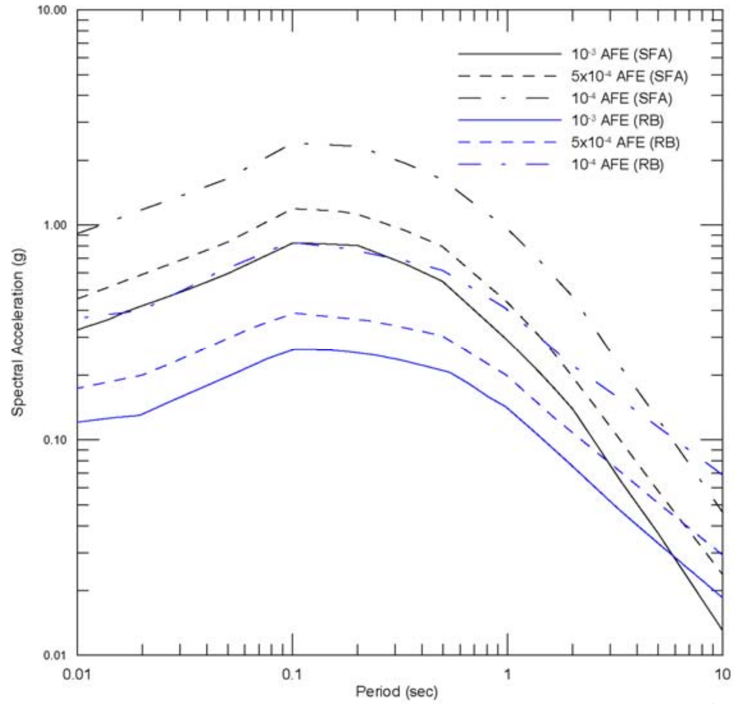

Figure 6. 5%-damped horizontal design spectra for 10^{-3}, $5x10^{-4}$, and 10^{-4} AFEs for the SFA and repository block.

6. ACKNOWLEDGMENTS

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Table 1. Preclosure Seismic Ground Motions for Design Analyses

AFE	**Site**	**Design Response Spectra**	**Time Histories**	**PGA (g)**		**10 Hz SA (g)**		**1 Hz SA (g)**		**PGV (cm/sec)**	
				H	**V**	**H**	**V**	**H**	**V**	**H**	**V**
10^{-3}	SFA	Horizontal and Vertical	5 three-component sets spectrally matched	0.33	0.22	0.82	0.55	0.29	0.15	23.19	—
$5x10^{-4}$	SFA	Horizontal and Vertical	5 three-component sets spectrally matched	0.45	0.32	1.17	0.86	0.43	0.23	34.13	—
10^{-4}	SFA	Horizontal and Vertical	5 three-component sets spectrally matched	0.91	0.72	2.40	2.22	0.96	0.52	74.13	—
10^{-3}	RB EL	Horizontal and Vertical	1 three-component set spectrally matched	0.12	0.07	0.27	0.14	0.10	0.082	13.48	6.96
$5x10^{-4}$	RB EL	Horizontal and Vertical	1 three-component set spectrally matched	0.17	0.12	0.39	0.23	0.15	0.12	19.54	10.10
10^{-4}	RB EL	Horizontal and Vertical	1 three-component set spectrally matched	0.37	0.32	0.84	0.59	0.30	0.25	41.40	21.51
Seismic hazard curves for the SFA: Horizontal and vertical SA at 0.3, 0.5, 1, 5, 10, 20, and 100 Hz (PGA), Horizontal PGV											
Seismic hazard curves for the RB EL: Horizontal and vertical SA at 0.3, 0.5, 1, 5, 10, 20, and 100 Hz (PGA), PGV											

NOTES: SA = spectral acceleration; RB EL = Repository block emplacement level; SFA = Surface facilities area; H, V = Horizontal, vertical