REVIEW OF BECHTEL SAIC COMPANY, LLC REPORT TITLED "PEAK GROUND VELOCITIES FOR SEISMIC EVENTS AT YUCCA MOUNTAIN, NEVADA, ANL–MGR–GS–000004, Rev. 00"

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1.0 Background

Potential seismic hazards at Yucca Mountain affect both preclosure seismic safety assessments and postclosure performance calculations. During the preclosure period, structures, systems, and components important to safety must maintain radiological safety within prescribed limits during and after earthquake events. For postclosure evaluations, seismicity is an important input to total-system performance assessments, which must include effects on pertinent features, events, and processes on the natural and engineered barrier systems. Large earthquake-induced ground motions could (i) accelerate rockfall and degradation of the drifts, thereby damaging the drip shields; (ii) damage internal components of the waste packages, including cladding; and (iii) cause the waste packages collide with one another or other components of the engineered systems, leading to damage or rupture of the waste packages.

To assess the potential effects of seismicity, the DOE conducted a probabilistic seismic hazard assessment using an expert elicitation (CRWMS M&O, 1998). Results of this assessment included probabilistic hazard curves that plot increasing levels of vibratory ground motion as a function of annual exceedance probability. The use of these hazard curves led to unrealistically large estimates of ground motions at small annual exceedance probabilities (i.e., below 10^{-6}).

In addition to concerns raised by NRC staff (e.g., Kokajko, 2005; NRC, 2005, 1999; Schlueter, 2000), the 2003 Nuclear Waste Technical Review Board's Panel on the Natural System and Panel on the Engineered System meeting devoted to seismic issues (United States Nuclear Waste Technical Review Board, 2003) focused on the very large vibratory ground motions estimated by the DOE probabilistic seismic hazard assessment at annual exceedance probabilities below 10^{-6} per year. In a letter from the Nuclear Waste Technical Review Board to DOE (Coraddini, 2003), the Board expressed concern that

> "... although the probabilistic seismic hazard assessment is, in general, sound, extending it to very low probabilities results in ground-motion estimates about which there are serious technical questions. These relate to the lack of physical realism and the implication of these unrealistic estimates for performance assessment, design, and scientific confidence."

The Nuclear Waste Technical Review Board noted that application of a physically unrealistic or highly conservative approach, even if acknowledged as such by DOE, could lead to a number of problems including a distorted understanding of repository behavior and the significance of different events, consideration of events for which there is little or no understanding or engineering practice, and undermined confidence in the scientific basis of the process under consideration (Coraddini, 2003). In its recent Technical Basis Document No. 14 (Bechtel SAIC Company, LLC, 2004a), DOE came to the same conclusion, that

> "Large ground motion predicted by the PSHA [probabilistic seismic hazard assessment] at annual exceedance probabilities of 1.0×10^{-6} and below overestimates the severity of low-probability ground motion at Yucca Mountain."

To address these concerns, DOE proposes to define a limit or cap to the level of seismic ground motion at the emplacement horizons (Bechtel SAIC Company, LLC, 2005). DOE proposed defining the ground motion limit in terms of a bounding peak ground velocity applicable for assessing the performance of the engineered barrier system under earthquake loads (Bechtel

SAIC Company, LLC, 2005). The DOE analysis for establishing the technical basis for the proposed bounding peak ground velocity consisted of four steps.

- First, DOE estimated a threshold finite shear strain that is expected to produce mechanical failure of lithophysal units of the Paintbrush Group nonwelded tuffs. Lithophysal rock that does not exhibit geologically observable deformation, including fracturing, would be suggestive of finite shear strain smaller than the threshold. Conversely, geologically observable deformation would suggest shear strain equal to or greater than the threshold shear strain.

- Second, DOE deduced that the lithophysal rocks at the repository site have not experienced any shear strain greater than the threshold. This deduction is based on their interpretation that the majority of fractures in the lithophysal rock resulted from cooling of the tuff soon after emplacement, along with an interpretation that the lithophysae shapes reflect a relatively undeformed state.

- Third, DOE determined the values of horizontal peak ground velocity necessary to generate a shear strain greater than the threshold shear strain.

- Fourth, DOE concluded that the Yucca Mountain site has not experienced values of horizontal peak ground velocity greater than the threshold since the formation of the Topopah Spring Tuff lithophysal zones (approximately 12.8 million years ago).

2.0 Staff Review

This review identified two fundamental problems with the DOE analysis. First, DOE did not account for the non-homogeneity of geologic deformation at Yucca Mountain in its analysis to estimate the maximum ground motion that the repository host rock may have experienced in the past using calculated maximum shear strains. As explained by DOE (Bechtel SAIC Company, LLC, 2005, p. 6-3), a key element of the DOE approach consists of "using the geologic data collected in the ESF and the ECRB Cross-Drift to determine whether pervasive seismically-induced fracturing and other rock damage has occurred at Yucca Mountain." The DOE analysis includes an implicit assumption that such fracturing would be uniformly distributed. The NRC staff concluded that the analysis would have resulted in a totally different conclusion if the non-homogeneity of tectonic deformations had been considered. Second, DOE did not provide the empirical data necessary to establish a reliable threshold shear strain representing failure of the lithophysal rock under the in situ conditions at the proposed emplacement level.

2.1 Non-Homogeneity of Tectonic Deformation

Deformation processes in rocks are intrinsically non-homogeneous. Even rocks that appear to be pervasively deformed may in fact be composed of zones of high strain separated by zones of unstrained material (e.g., Turner and Weiss, 1963; Ramsay, 1967; Jaeger and Cook, 1979). This is true of rocks that have deformed by quasi-ductile means such as pressure-solution, and it is especially true of rocks deformed by brittle mechanisms (fracturing and faulting). Once a zone of weakness, such as a fault or fracture, has formed, it tends to become the primary locus of future strain, if it is appropriately oriented to accommodate such strain. This is the very essence of faulting. Faults with large displacements—on the order of tens to hundreds of meters—do not develop displacement in a single slip event, but accumulate displacement over successive increments. Each slip increment exploits the same or closely similar path through the rock. The rock material between major faults (i.e., fault blocks) may contain faults and fractures, but these will typically accommodate much smaller displacements. Similarly, at a scale of millimeters to meters, rock material between faults or fractures may be completely undeformed, any bulk strain having been accommodated by the surrounding fractures (e.g., Turner and Weiss, 1963, Ramsay and Huber, 1983; Ramsay and Lisle, 2000).

The distribution of tectonic deformations at Yucca Mountain is non-homogeneous for the same reason, as evidenced by DOE analysis (Bechtel SAIC Company, LLC, 2003, p. 5-2):

> "The structural geology of Yucca Mountain is controlled by block-bounding normal faults spaced 1 to 4 km apart. In the site area, these north-striking faults include (from west to east) the Windy Wash, Fatigue Wash, Solitario Canyon, Bow Ridge, and Paintbrush Canyon faults. The Dune Wash and Midway Valley faults are also block-bounding faults, but differ from the other block-bounding faults in that they have no evidence of Pleistocene movement. The block-bounding faults commonly dip 50 to 80 degrees to the west. A subordinate component of left-lateral displacement is commonly associated with these block-bounding normal faults, as determined from slickenside orientations. The orientation, amount of offset, and nature of the associated deformation varies from north to south (and to some degree from west to east) within the site area. Displacement is transferred between block-bounding faults along relay faults, which intersect block-bounding faults at oblique angles, providing an intrablock kinematic link between the bounding structures. As such, the relay faults are significant components of the block-bounding fault systems, particularly, but not exclusively, in the southern half of Yucca Mountain. Within structural blocks, small amounts of strain are accommodated along intrablock faults. In many cases, intrablock faults appear to represent local structural adjustments in response to displacements on the block-bounding faults."

Thus, although DOE has reported the occurrence of structural features within which tectonic deformations have been accommodated at Yucca Mountain, DOE did not account for the occurrence of such features in its analysis to determine the maximum ground motion that the repository host rock may have experienced in the past. More than 30,500 fractures have been identified in the Exploratory Studies Facility, and approximately 825 of these are faults with displacements that range from a few millimeters to greater than 100 m (DTN: MO9904MWDFPG16.000 as cited in Nieder-Westermann, 2000). Furthermore, 77 of the 1,800 fractures documented in the Enhanced Characterization of the Repository Block Cross-Drift exhibit measurable displacements from a few millimeters to 175 m (Mongano, et al., 1999).

Seismic ground motions consist of up to three parts: rigid body motions and elastic and inelastic deformations. Only the inelastic deformations may leave geologically observable evidence such as faults, fractures, slickenside, and other such features. Whereas faults and fault zones may experience mostly inelastic deformations during a seismic event, the fault blocks typically experience mostly rigid body motion and elastic deformation, which would not leave any geologic evidence within the fault block [e.g., Ofoegbu and Ferrill, 1998, Figure 4(B)]. The magnitude of previous geologic deformation on a fault block, therefore, represents only a small part of any previous ground motion and cannot be used to determine the magnitude of such ground motion.

2.2 Lack of Empirical Data

The DOE analysis to determined a threshold shear strain representing mechanical failure of the lithophysal rock was hampered by a lack of necessary empirical data. Stress-strain data for rocks show that strain at the peak stress state increases with confining pressure (e.g., Ofoegbu and Curran, 1992; Wawersik and Brace, 1971; Wawersik and Fairhurst, 1970). DOE performed laboratory testing of lithophysal rock under zero confining pressure (unconfined) conditions, but did not perform any tests under confined (triaxial) conditions because of technological difficulties in conducting triaxial tests on large samples of lithophysal tuff (Bechtel-SAIC Company, LLC, 2003, p. 9-1). The DOE strain data for lithophysal rock, therefore, indicate failure strain under zero confining pressure, whereas the confining pressure at the proposed emplacement level may lie in the range of 2–4 MPa (Bechtel-SAIC Company, LLC, 2004b, p.4-7). To address this problem DOE calculated strains from numerically simulated biaxial compression testing based on micromechanical modeling using PFC2D and UDEC computer codes (Bechtel SAIC Company, LLC, 2005, p. B-1). The validity of such calculated strains for quantitative characterization of rock strain behavior is doubtful, however, because the calculation approach has not been appropriately calibrated.

A parametric study by Cho, et al. (2004) of PFC2D-calculated dilation strain using simulated uniaxial compression and Brazilian testing demonstrates the importance of appropriate calibration. The results indicate the calculated dilation decreases as the particle contact friction increases, but increases as the contact stiffness ratio or mean particle size increases. Also, the calculated dilation increases as the maximum cluster or clump size increases, for a PFC model based on particle clusters or clumps instead of individual particles. Cho, et al. (2004) concluded that geometrical factors (particle size and clump or cluster size) are more important than particle contact parameters (friction, bond strength, and stiffness) in controlling the calculated dilation in PFC2D modeling. "The clustered and clumped material," Cho, et al. (2004) noted, "all showed an order of magnitude larger amount of dilation ... compared with all other cases."

The main point to be derived from the Cho, et al. (2004) study is that a PFC model needs to be calibrated against empirical strain data in order to be used to quantify strain. Such calibration would be used to determine an appropriate choice of particle geometry and the particle contact properties. Cho, et al. (2004) indicate that particle clumps are better than individual-particle models. In contrast, the particle contact properties used for the DOE analysis were chosen by calibrating PFC2D and UDEC micromechanical models against strength and elastic stiffness based on unconfined compression testing. The models were not calibrated against any measured inelastic strain results. Furthermore, the models were used to calculate triaxial stress and strain conditions, although the calibrations were for unconfined conditions. Using such calculations as a basis to quantify strain behavior under seismic loading is, therefore, inappropriate.

3.0 Conclusions and Recommendation

In spite of the technical obstacles faced, the overall aim of DOE to develop realistic estimates of low probability earthquake ground motions is consistent with NRC policy (e.g., Ward, 1991) and regulatory requirements in 10 CFR Part 63. In particular, 10 CFR §63.114(b) states that "Any performance assessment used to demonstrate compliance with §63.113 must: Account for uncertainties and variabilities in parameter values and provide for the technical basis for parameter ranges, probability distributions, or bounding values used in the performance assessment." Regulations in §63.21(c)(15) require performance assessment models to be supported by information "representative of field conditions."

Seismologists and engineers have highlighted the need for and difficulty in developing reliable and technically defensible technical bases to define upper bounds on earthquake ground motions at relatively low annual exceedance. Bommer (2002) identified upper limits on earthquake ground motions as the "missing piece" in seismic hazard assessments. Bommer, et al., (2004) discussed the need to evaluate upper bound constraints on all components of the seismic hazard including: (i) source effects; (ii) path effects, including ground motion attenuation; (iii) site effects, including strength of near surface materials; and (iv) consistent interpretation and bounds on uncertainties. At present, however, there is little consensus within the engineering or seismological communities on the information and means needed to develop technically defensible upper bounds on seismic ground motions. Even the recently completed probabilistic seismic hazard assessment for nuclear power plants in Switzerland (e.g., Abrahamson, et al., 2002) wrestled with challenges of unrealistically large ground motions estimated at small annual exceedance probabilities. The staff concerns summarized in this review regarding the current DOE approach to cap peak ground velocity exemplify this challenge.

One possible solution is to reconvene an expert panel in which all the methods proposed by Bommer et al., (2004) are considered. As stated in NUREG-1563 (NRC, 1996) expert elicitation or expert judgment should be "employed when other means of obtaining requisite data or information have been thoroughly considered and it has been concluded that such means are not practical to implement." Given the current debate among seismologists and engineers, the immaturity of various approaches discussed by Bommer, et al. (2004), and the difficulty in deriving the necessary information from the DOE site-specific data from Yucca Mountain (as documented in this review), an expert elicitation to address determination of an upper bound on seismic ground motions may be appropriate. Although other approaches may be considered, expert elicitation has three advantages: (i) it is consistent with NRC guidance and practice concerning incomplete or unattainable information; (ii) it is consistent with the development of the overall seismic hazard assessment for Yucca Mountain, which also was achieved using an expert elicitation; and (iii) if done properly, the elicitation would quantify both the consensus opinion and associated uncertainty among experts.

Consistent with staff review of other expert elicitation results relied on by DOE, staff would review an elicitation of capping seismic ground motions against the guidance provided in NUREG–1563 (NRC, 1996), the review methods and acceptance criteria outlined in section 2.5.4 of NUREG–1804 (NRC, 2003), and the regulatory requirements of §63.21(c)(19).

Specific recommendations with respect to the elicitation include:

(1) Clearly defined elicitation objectives regarding low probability ground motions that are directly applicable to a demonstration of repository performance within the regulatory requirements in 10 CFR Part; in contrast to the original DOE seismic hazard elicitation, which was elicited prior to NRC 10 CFR Part 63 rulemaking.

(2) Selection of normative experts who represent a broad spectrum of expertise in seismology, structural geology, geotechnical engineering, and earthquake engineering, and who are clearly free of any real or perceived conflict of interest.

(3) Preelicitation training in the elicitation process per NUREG–1563 (NRC, 1996) guidance, including a complete and comprehensive explanation of the regulatory and programmatic context within which the DOE will apply the elicitation results.

4.0 References

Abrahamson, N.A., P. Birkhauser, M. Koller, D. Mayer-Rosa, P. Smit, C. Sprecher, S. Tinic, and R. Graf. "PEGASOS: A Comprehensive Probabilistic Seismic Hazard Assessment for Nuclear Power Plants in Switzerland." Proceedings of the Twelfth European Conference on Earthquake Engineering. Paper No. 633. London, England: Elsevier. 2002.

Bechtel SAIC Company, LLC. "Peak Ground Velocities for Seismic Events at Yucca Mountain, Nevada." ANL–MGR–GS–000004. Rev. 00. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2005.

———. "Technical Basis Document No. 14: Low Probability Seismic Events." Rev. 01. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2004a.

———. "Drift Degradation Analysis." ANL–EBS–MD–000027. Rev. 03. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2004b.

———. "Subsurface Geotechnical Parameters Report. 800-K0C-WIS0-00400-000-00A. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2003.

Bommer, J.J. "Deterministic vs. Probabilistic Seismic Hazard Assessment: An Exaggerated and Obstructive Dichotomy." Journal of Earthquake Engineering. Vol. 6. pp. 43–73. 2002.

Bommer, J.J., N.A. Abrahamson, F.O. Strasser, A. Pecker, P-Y Bard, H. Bungum, F. Cotton, D. Fäh, F. Sabetta., F. Scherbaum, and J. Studer. "The Challenge of Defining Upper Bounds on Earthquake Ground Motions." *Seismological Research Letters.* Vol. 75. pp. 83–95. 2004.

Cho, N., C.D. Martin, D.C. Sego, and R. Christiansson. "Modeling Dilation in Brittle Rocks." Gulf Rocks 2004—6th North American Rock Mechanics Symposium (NARMS): Rock Mechanics Across Borders & Disciplines. ARMA/NARMS Paper 04–483. Houston, Texas. June 5–9, 2004.

Coraddini, M.L. "Board Comments on February 24, 2003 Panel Meeting on Seismic Issues." Letter (June 27) to Dr. Margaret S.Y. Chu, DOE, Office of Civilian Radioactive Waste Management. Washington, DC: United States Nuclear Waste Technical Review Board. 2003. <www.nwtrb.gov/corr/mlc010.pdf>

CRWMS M&O. "Probabilistic Seismic Hazard Analyses for Fault Displacement and Vibratory Ground Motion at Yucca Mountain, Nevada, Final Report." I.G. Wong and J.C. Stepp, Report Coordinators. Report SP32IM3, WBS 1.2.3.2.8.3.6. Three Volumes. Oakland, California: CRWMS M&O. 1998.

Jaeger, J.C. and N.G.W. Cook. "Fundamentals of Rock Mechanics." Third Edition. London, England: Chapman and Hall Ltd. 1979.

Kokajko, L.E. "Pre-Licensing Evaluation of Key Technical Issue Agreements: Structural Deformation and Seismicity 2.01, 2.01 Additional Information Needed-1, 2.02, 2.04, 2.04 Additional Information Needed-1; Repository Design and Thermal Mechanical Effects 2.01, 2.02, 3.03; Container Life and Source Term 3.10; and Total System Performance Assessment and Integration 3.06 in *Technical Basis Document 14, Low Probability Seismic Events*." Letter (April 13) to J.D. Ziegler, DOE. Washington, DC: NRC. 2005.

Mongano, G.S., W.L. Singleton, T.C. Moyer, S.C. Beason, G.L.W. Eatman, A.L. Albin, and R.C. Lung. "Geology of the ECRB Cross Drift—Exploratory Studies Facility, Yucca Mountain Project, Yucca Mountain, Nevada." [Deliverable SPG42GM3]. Denver, Colorado: U.S. Geological Survey. ACC: MOL.20000324.0614. 1999.

Nieder-Westermann, G.H. "Fracture Geometry Analysis for the Stratigraphic Units of the Repository Host Horizon." Office of Civilian Radioactive Waste Management Analysis. Model Report ANL–EBS–GE–000006. Rev. 00. 2000.

NRC. NUREG–1762. "Integrated Issue Resolution Status Report." Rev. 1. Washington, DC: U.S. Nuclear Regulatory Commission. 2005.

———. NUREG–1804. "Yucca Mountain Review Plan." Rev. 2. Washington, DC: U.S. Nuclear Regulatory Commission. 2003.

———. "Issue Resolution Status Report, Key Technical Issue: Structural Deformation and Seismicity." Rev. 2. Washington, DC: U.S. Nuclear Regulatory Commission, Division of Waste Management. 1999.

———. NUREG–1563. "Branch Technical Position on the Use of Expert Elicitation in the High-Level Radioactive Waste Program." Washington, DC: U.S. Nuclear Regulatory Commission. 1996.

Ofoegbu G.I., and J.H. Curran. "Deformability of Intact Rock." *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*. Vol. 29(1). pp. 35–48. 1992.

Ofoegbu G.I. and D.A. Ferrill. "Mechanical Analyses of Listric Normal Faulting with Emphasis on Seismicity Assessment." Tectonophysics. Vol. 284. pp. 65–77. 1998.

Ramsay, J.G. "Folding and Fracturing of Rocks." New York, New York: McGraw-Hill Book Company, Inc. 1967.

Ramsay, J.G. and M.I. Huber. "The Techniques of Modern Structural Geology. Volume 1: Strain Analysis: Orlando, Florida: Academic Press, Inc. 1983.

Ramsay, J.G. and R.J. Lisle. "The Techniques of Modern Structural Geology. Volume 3: Applications of Continuum Mechanics in Structural Geology." San Diego, California: Academic Press, Inc. 2000.

Schlueter, J. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Igneous Activity (August 29–31, 2000)." Letter (October 23) to S. Brocoum, DOE. Washington, DC: Nuclear Regulatory Commission. 2000. <www.nrc.gov/waste/hlw-disposal/public-involvement/mtg-archive.html#KTI>

Turner, F.J. and L.E. Weiss. "Structural Analysis of Metamorphic Techtonites." New York, New York: McGraw-Hill Book Company, Inc. 1963.

United States Nuclear Waste Technical Review Board. "Joint Meeting of Site Characterization and Repository Panels on Seismic Issues, February 24, 2003." Transcript of meeting. Las Vegas, Nevada: Nuclear Waste Technical Review Board. 2003. <http://www.nwtrb.gov/meetings/meetings.html>

Ward, D.A. "The Consistent Use of Probabilistic Risk Assessment." Letter to the Honorable Ivan Selin, Chairman, U.S. Nuclear Regulatory Commission. July 19, 1991.

Wawersik W.R. and W.F. Brace. "Post-Failure Behaviour of a Granite and Diabase." Rock Mechanics. Vol. 3. pp. 61–68. 1971.

Wawersik W.R. and C. Fairhurst. "A Study of Brittle Rock Fracture in Laboratory Compression Experiments." *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts.* Vol. 7. pp. 561–575. 1970.