Comments to Nuclear Waste Technical Review Board regarding the Joint Panel Meeting on Seismic Issues, 24 February 2003

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General: The ground motions resulting from the Probabilistic Seismic Hazard Analysis (PSHA) for the Yucca Mountain site fall into two categories, preclosure (100 to 300 years) and postclosure (up to 10,000 years). As to whether the two sets of ground motions are realistic or appropriate for their intended use, the preclosure ground motions seem fairly realistic in that they are within the range of what's been observed, although for the extensional tectonic setting of Yucca Mountain it could be argued that these motions (e.g., peak horizontal ground acceleration PGA) are a factor of two, or so, too high. For the postclosure motions, the annual exceedance probabilities (AEP) are very low and the PSHA results are quite spectacular primarily because of the uncertainties that resulted from the expert elicitation process and the amount of extrapolation involved to unusually low AEP. As will be discussed below, these low-probability ground motions seem implausible for at least several reasons and are well out of the range of what's been observed, especially in circumstances approximating those at the Yucca Mountain site.

Several alternative approaches were discussed at the meeting. The first involves consideration of limits to the peak ground motion based on the local geology, such as precarious rocks that have presumably been in place for more than 10,000 years and the absence of evidence for high dynamic strains in the Yucca Mountain tuffs that would limit levels of peak ground velocity (PGV) in the geologic past. Second, it turns out that the seismic source needed to cause the levels of ground motion resulting from the PSHA has a high stress character that has never been observed and may be thoroughly implausible because of the finite strength of the seismogenic crust. Thus, local geological observations and analyses of the seismic sources of the PSHA ground motions might both provide arguments for caps on the ground motion that are significantly below the PSHA results.

The following comments, in response to the 12 questions (in itlaics) posed for the consultants, address, in more detail, the issues related to postclosure ground motions because these results are more unusual and, thus more controversial, than those for the preclosure time frame.

Question 1. *Are the proposed ground motions within the range of the worldwide instrumental record?*

Silva and Wong, in their presentation *Proposed Ground Motions for Postclosure Analysis*, reviewed some of the highest ground motions recorded during the past 60 years, or so, for comparison with the results from the PSHA analysis. As I understand it, the table (p. 11) in the presentation of Silva and Wong, showing estimated PGV's, gives an approximation to the PSHA results (Stepp et al., 2001) for Point B, which is 300 m below the surface of Yucca Mountain, in tuff with a shear wave speed of 1900 m/s. If this site were at the surface, it would qualify as a rock site in category A. (The Uniform Building

Code has five site categories, A through E, progressing from rock with high shear wave speed to very soft soil with quite a low shear wave speed.) Because of its depth, the PGV's listed in this table are reduced approximately a factor of two compared to a surface PGV's. Accordingly, the PGV's in this table should be doubled before being compared with the ground motions recorded on rock listed in the table on p. 29 and the Cape Mendocino data in the tables listing the largest PGA's and PGV's, pp. 32 and 33. Of those ground motions at rock sites, the largest PGV is for Cape Mendocino at 1.27 m/s and the second largest is from the San Fernando record at Pacoima Dam at 1.12 m/s. At an AEP of 10^{-6} the PGV's listed in the table on p. 11 of the presentation of Silva and Wong, after being doubled, are nearly a factor of four greater than the largest PGV recorded at a rock site. At an AEP of 10^{-7}, the estimated PGV from the PSHA, as would be recorded at the surface, is more than a factor of eight greater than what's been recorded at a rock site.

It is worth noting that nearly all of the largest PGV's have been recorded on the hanging walls of major thrust earthquakes, the most spectacular examples being category C (soil, low shear wave speed) sites on the immediate hanging wall near the north end of the 1999 Chi-chi earthquake (the table on p. 33 of the presentation of Silva and Wong listing the largest PGV's). This is, of course, a highly unlikely tectonic scenario for Yucca Mountain and environs where normal faulting takes place in an extensional tectonic regime. That is, a more appropriate comparison with the probabilistic PGV's on p. 11 of Silva/Wong would be with ground motions from earthquakes in extensional tectonic settings, in which case the differences would be much more dramatic than those just described.

To summarize, the PGV's recorded on rock sites are many times lower than the equivalent estimates from the PSHA for the postclosure period, even at an AEP of 10^{-6} Accordingly, the observational ground motion database recorded worldwide during the past 60 years provides no precedent for the PSHA results at the low AEP's used for the postclosure analysis.

Question 2. *Are there physical constraints that might limit surface and subsurface ground motions at the Yucca Mountain site?*

The physical constraints that would limit the surface and subsurface ground motion at the Yucca Mountain site are associated with the response of the tuffs to high levels of dynamic strain associated with the estimated PGV's from the PSHA. If the shear wave speed is 1900 m/s and if the threshold for fracturing in the tuffs is a cyclic strain of 0.1 % (p. 34 of the presentation by Silva and Wong *Proposed Ground Motions for Postclosure Analysis*) then even the ground motion from the PSHA for 10^{-6} annual probability of exceedance would be expected to result in some evidence for fracture. That is, if the tuffs were subjected to a PGV of 2.4 m/s, the corresponding strain would be roughly 0.13 %, which is somewhat into the range for fracturing. As I understood the presentations, there does not appear to be any geological evidence for such high strains having affected the repository tuffs.

The absence of evidence for damaging levels of dynamic strain suggests that over the lifetime of the tuffs at Yucca Mountain (at least 11 million years), PGV's have been less than those from the PSHA analysis even at an AEP of 10^{-6}. Thus, the PSHA PGV estimates are not consistent with the observed nature of the tuffs at Yucca Mountain.

Question 3. *What kind of studies/analyses can be carried out that could help determine whether there is a limit?*

The types of studies that would indicate limits or bounds to peak ground motion fall into several categories. The first is evidence from the local surface geology at Yucca Mountain, such as the precarious rocks, discussed by Brune and Anderson in their presentation *Precarious rocks, Shattered Rock, and Seismic Hazard at Low Probabilities for Yucca Mountain,* that have the potential to limit peak ground motion for at least the past 10,000 years to fairly modest levels. The absence of shattered rocks in the cliff faces there has similar, though less stringent, implications for bounding the peak ground motion. There may be other geological indicators of paleo-ground motion in the tuff formations exposed underground, especially in the lithophysal units where delicate crystalline, needle-shaped features are found; these features may be susceptible to failure at high levels of ground motion and so shake table testing of them might be interesting.

The second type of evidence involves limitations associated with the earthquake source. The table *Fracture Strain Scaling Point A* on p. 21 of the presentation by Silva and Wong *Proposed Ground Motions for Postclosure Analysis* shows a good example of this. For the uniform hazard spectrum (UHS) at an AEP of 10^{-7} at point A (the surface site with the same rock properties as those at Point B at the repository depth), the most important contribution at 1 Hz is from the M7.7 earthquake at an epicentral distance of 51 km and for 10 Hz is from a M6.5 earthquake 1 km away. To fit the UHS 1 Hz level of 5.47 g requires a stress drop of 15 kilobar and at 10 Hz, with a spectral level of 13.76 g, the stress drop must be about 2.5 kilobars. (My colleague Dave Boore confirmed this result at my request.) In contrast, stress drops derived from ground motion spectra are generally close to 100 bars. Thus, from the stochastic point source modeling, the PSHA results at an AEP of 10^{-7} require highly unusual stress drops that are far higher than any that have been observed. Moreover, at the assumed source depths of 8 km, the strength of the crust estimated for this extensional tectonic setting is many times lower than these stress drops.

In summary, neither the local geological evidence nor the seismic source implications lend support to the ground motions resulting from the PSHA. Both types of evidence suggest caps to the ground motion that are much lower than the PSHA outcomes for any of the AEP's considered for postclosure.

Question 4. *What can be learned from earthquake motions in mines that would help address this problem?*

The underground recording of ground motion due to mining-induced earthquakes in South Africa has yielded some key insights regarding the seismic hazard to underground facilities. I mention several examples here. First, from these data, it is abundantly clear that PGV is a far more robust indicator of damage potential than PGA. In one instance, a PGA of 12 g, showing a predominant frequency of several hundred Hz, recorded in boreholes extending from a test tunnel at depth 3000 m, caused no damage whatsoever, an outcome consistent with the corresponding PGV of about 0.06 m/s. The PGA of 12 g recorded underground in the deep gold mine has no relevance for the PGA's listed in the table *Summary of Point A Peak Values* on p. 16 of the presentation by Silva and Wong because the circumstances are completely different. In the case of the mine event, the hypocentral distance was about 150 m and the magnitude was about 2.

Second, the near-source ground velocities for the mining-induced earthquakes are approximately several m/s but the stope support is designed to accommodate these levels of PGV. It appears that the strength of the seismogenic rock mass is the factor that controls the near-source PGV for these mining-induced events. Specifically, $PGV \leq 0.25\beta\tau/G$, where β is the shear wave speed, τ is the bulk shear strength of the rock mass, and G is the modulus of rigidity. For example, various types of evidence suggest that τ is limited to about 61 MPa and so, with β=3.7 km/s and G=3.7x10^4 MPa, the PGV is limited to about 1.5 m/s in the near field of a mining-induced earthquake. This result probably has no direct relevance to the issue of peak ground motion at Yucca Mountain because the ground motion affecting this facility would not be in the near-field of a seismic source unless a fault intersecting the repository slipped seismically. If such a scenario were to occur, the resulting PGV would be substantially less than in the South African example because the repository tuffs, at a depth of about 300 m, are much weaker than the Witwatersrand quartzites at depths of several km.

Question 5. *What can be learned from ground motions related to nuclear testing that would help address this question?*

As was suggested at the meeting by Dr. Hendron, the tunnels excavated at the Nevada Test Site (NTS), in association with some of the larger underground tests, could yield key information regarding the susceptibility of these tunnels to damage (e.g., rockfall) due to high levels of ground motion, for which there is presumably excellent documentation. The likelihood of seismically-triggered rockfall in the repository drifts seems to be a major unknown in the hazard assessment and so some NTS tunnel investigations might yield useful information for addressing this uncertainty that would complement the modeling efforts.

Question 6. *How do these ground motions compare to those assumed at other projects?*

Nothing to report here.

Question 7. *Have the site conditions, including rock properties, been characterized properly and appropriately taken into account?*

Almost everything I know about site conditions at Yucca Mountain I learned because of this meeting, but from the discussion, it appears that the lower, lithophysal units are relatively poorly characterized at this stage.

Question 8. *Are the models of drift stability (seismic and thermal) suitable and have they been used appropriately?*

Again, I am anything but an expert in modeling drift stability. Although I was impressed by the modeling results in the presentation by Mark Board *Drift Stability: Seismic and Thermal*, I have the impression that some validation of these outcomes (e.g., by studying other tunnels elsewhere at the NTS) is needed if we are to have confidence in this modeling.

Question 9. *Have the rockfall analysis, drip shield structural response, and waste package structural response to seismic ground motions been adequately modeled?*

No comment because of my lack of experience in this area.

Question 10. *Is the "failed area abstraction " the appropriate way to address waste package failure?*

As an earth scientist, I have no comment on this.

Question 11. *If the ground motion estimates remain the same, are there methods to mitigate potential problems in drift stability and repository operations and maintenance*?

I have no opinion on this.

Question 12. *If the ground motion estimates remain the same, are there means of mitigating adverse effects on waste packages?*

I'll leave this question to the engineers, also.

Closing remarks: The joint meeting on February 24 was very stimulating and highly useful for exposing some major discrepancies between the low-probability PSHA ground motion outcomes and observational experience. At numerous points during the meeting, speakers referred to "physically unrealistic ground motion", although nobody defined exactly what was meant by this. Was the PSHA outcome somehow tainted? As one of the ground motion experts in the PSHA process, I would say that the expert elicitation process was handled very competently. At the same time, however, we, as a group of experts, did not explore the long-term, low-probability implications of our results. Moreover, we did not consider the possibility of using geological or physical considerations to cap the ground motion parameters. As I recall, precarious rock evidence, for instance, was discussed but not incorporated into our elicitation procedure in any formal way.

I'll end by mentioning a few things about some potential effects of directivity in the context of the PSHA ground motion expert elicitations. First, directivity was not taken into account in our analyses of ground motion attenuation relations because, at that time, there were no formal procedures in place to account for this effect. In the meantime, Somerville et al. (Seismological Research Letters, v.68, No. 1, p. 199, 1997) have described a procedure to include effects of directivity in ground motion attenuation relationships. If this description had been available at the time the PSHA was in progress would this capability of including the possible effects of directivity have made a significant difference? In principle, taking account of directivity might have reduced our uncertainties because of a supposedly more detailed understanding of the earthquake source process. In practice, however, the list of well-defined observational examples of clear-cut directivity effects is fairly short, the Lucerne record of the 1992 Landers earthquake being perhaps the most unequivocal example. Additionally, the magnitudes of directivity effects are controversial as described by Somerville et al. (1997) and, in any event, seem to be negligible for frequencies above about 1 Hz. According to Somerville et al., directivity effects on PGV might be as high as a factor of 1.5, but are essentially zero for PGA. My sense is that taking directivity into account would not have made any material difference to our PSHA outcomes.