APPENDIX B Memorandum received from Prof. Heaton after Workshop #2

Comments by Dr. Thomas Heaton (Caltech) on ground motion issues regarding probabilistic seismic hazards as applied to Diablo Canyon and Palo Verde Nuclear Generating Station.

B.1 Memorandum

From: Dr. Thomas Heaton

To: Dr. Norman Abrahamson

Subject: Comments on PSHA workshop of 22-24 October 2013

Date: 5 November 2013

These are general comments on the probabilistic seismic hazard analyses (PSHA) of Diablo Canyon and Palo Verde nuclear power generating stations. These comments follow my participation at the Southwestern U.S. Ground Motion Characterization SSHAC Level 3 Workshop 2 – Proponent Models and Alternative Interpretations that I attended on October 22-24, 2013 at Shattuck Plaza Hotel, Berkeley, California.

In general the PSHA is making steady progress towards establishing a framework to characterize response spectral amplitudes (rsa's) as a function of earthquake magnitude, rake, JB distance, and site factor. Within the assumption that rsa's are log-normally distributed about a geometric mean that can be characterized by the chosen parameters, I think that the analysis is careful and rigorous. That said, I have some concerns that the current methodology may not characterize potentially important earthquake features that might be pertinent to nuclear power plant design.

1) If low frequency motions are a concern (sloshing of storage pools?), then whatever systems are affected are almost certainly not linear systems for very large motions. This means that modal analysis is not appropriate. It is important for the design engineers to directly communicate with scientists about what types of ground motion time histories are plausible. I would strongly discourage the use of "spectrum compatible motions" to simulate non-linear long-period dynamics.
2) The spatial distribution of slip is the key parameter that determines the nature of near-source long-period ground motion. For example, two earthquakes of identical magnitude can have very different average slips. Furthermore the maximum slip can be much larger than the average slip. However, when considering low-probability long-period motion, it's critically important to characterize the statistical features of slip on segments of a fault that are close to

the site. The current analysis does this problem by characterizing the source with moment magnitude, which is an averaging parameter for an earthquake. Variability is handled by assuming that long-period motions are log-normally distributed about the mean appropriate for the magnitude. However, I am not aware of any evidence that shows that the slip at a point is log-normally distributed about the mean. Instead, I would guess that we are looking at a power law distribution (Pareto). For a variety of reasons, I would argue that these slip distributions are approximately fractal in nature. Unfortunately, power law distributions are very hard to deal with when using standard statistical analysis. It may be more appropriate to simply say that PSHA is not well suited for this problem. The key issue is to design structures that are robust with respect to long-period ground motions. (Please see Yamada, M., A. Olsen, and T. Heaton 2009, Statistical features of short- and long-period near-source ground motions, Bull. Seism. Soc. Am., 99: 3264 - 3274)

3) When it comes to high-frequency near-source shaking, the evidence is good that observations are compatible with the hypothesis that pga's saturate with magnitude and that they are approximately log-normally distributed about ½ g with a standard deviation of a factor of about 2. You argue that this variability can be decomposed into separate site and source variabilities; this seems to be convincing and I fully support this approach. However, I am concerned about using a log-normal distribution to catch the tails of the distribution. In particular, I am concerned that we have now seen several examples of near-source peak accelerations whose time histories are asymmetric about their zero line (see Yamada, M., J. Mori, and T. Heaton, 2008, The slapdown phase in high acceleration records of large earthquakes, Seismological Research Letters; 80: 559 – 564). It has been hypothesized that this may be an example of 'slap down," a phenomenon that was well studied by the nuclear explosion test community. Slap down is clearly a nonlinear phenomenon and I would expect its statistics to be independent of the log-normal distribution that are used to characterize most of the data. It's very difficult to put an upper limit on slap down accelerations. There are many examples of objects that have been launched through the air in violent shaking from past earthquakes. Slap-down seems to be a plausible phenomenon in the near source of earthquakes.

4) While I know that it was not the function of this group to address the problem, I am concerned that moderate to large nearby earthquakes are excluded for the analysis of the Palo Verde plant. Simple examinations of Google Earth images (*Figure B1*) show clear lineations, one of which is within 13 km of the site. While the geologic investigation may indicate that these structures have not offset Pleistocene deposits, I feel that it is not justified to conclude that these structures are known to be incapable of future activity. At the very least, these structures should be considered in a logic tree. Based on our current capabilities to fully characterize these geologic structures, I suspect that we will obtain a finite probability on a logic tree. I suspect that this could significantly change the PSHA numbers for Palo Verde. The figure below is looking to the southwest from Phoenix, AZ, and it shows remarkable lineations along the course of the lower Salt River (the lineation closest to the power station), and also along the course of the Gila River (the lineation that extends to California).

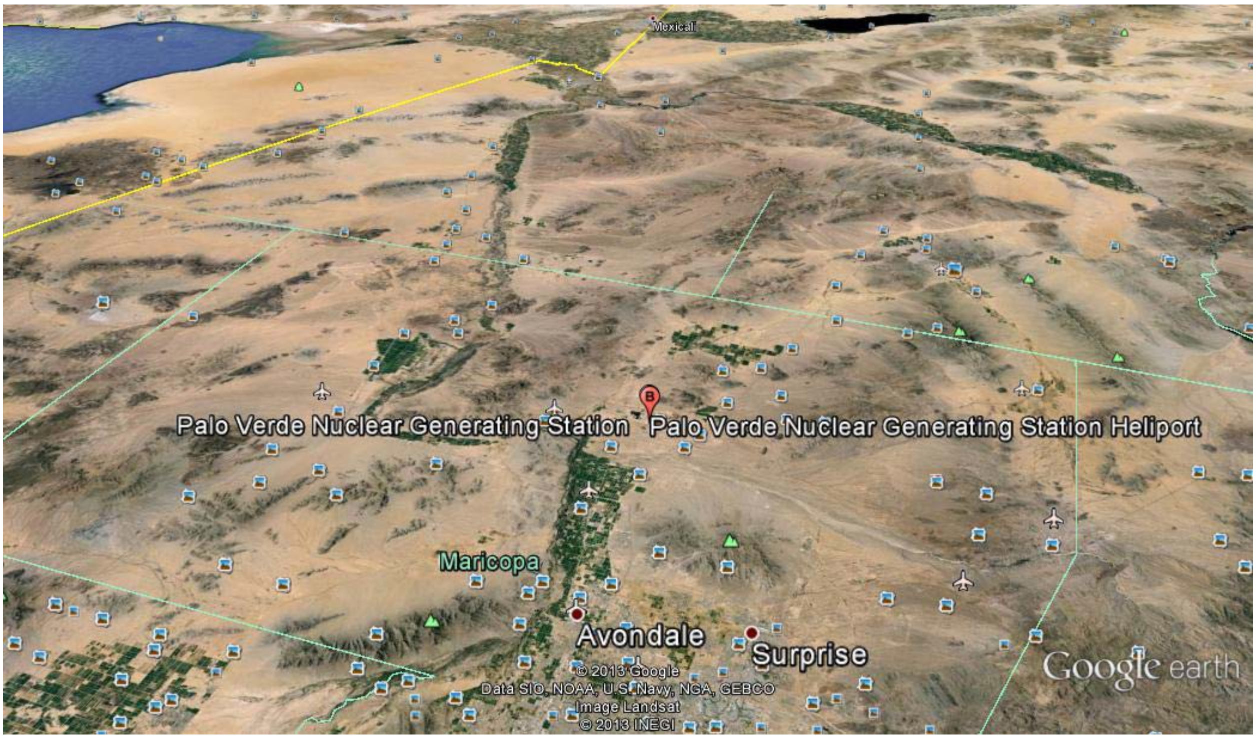

Figure B1: Google Earth image showing lineations around the PVNGS site