RAI Volume 3, Chapter 2.2.1.2.1, Second Set, Number 19, Supplemental Question 1:

Clarify the response by including the basis for proportional (2 to 1) relationship between static stress drop and water table elevation changes.

1. SUPPLEMENTAL RESPONSE

The original response to RAI 3.2.2.1.2.1-2-019 used a proportional relationship between static stress drop and water table elevation changes. The basis for this relationship is found in the model of Kemeny and Cook (1992) and the conclusions of the National Research Council (1992). Through the use of conservative assumptions, Kemeny and Cook (1990, Section 5.3) developed a simple mechanical model relating the static stress drop from a normal-faulting earthquake to water table rise. For a given depth of faulting, their model results in a proportional relationship between static stress drop and water table rise (Kemeny and Cook 1992, Equation 6-1). For a 100-bar static stress drop and a faulting depth of 10 km, this relationship yields a water table rise of 12 meters, or a ratio between static stress drop (in bars) and water table rise (in meters) of about 10-to-1. Based in part on the Kemeny and Cook model, and taking into account additional information on hydrologic properties and model sensitivities, the National Research Council (1992, p. 116) concluded that "only a modest rise in the water table of less than 50 m is likely to occur as the result of a nearby earthquake."

To assess the impact of a larger static stress drop in the original response to RAI 3.2.2.1.2.1-2-019, the proportional relationship between static stress drop and water table rise from the Kemeny and Cook model was retained, but combined with the 50-m water table rise that the National Research Council concluded likely bounds the effect, assuming a 100-bar static stress drop and faulting depth of 10 km. Thus, water table rise (in meters) is taken as half the static stress drop (in bars).

2. COMMITMENTS TO NRC

None.

3. DESCRIPTION OF PROPOSED LA CHANGE

None.

4. REFERENCES

Kemeny, J. and Cook, N. 1990. "Rock Mechanics and Crustal Stress." Section 5 of *Demonstration of a Risk-Based Approach to High-Level Waste Repository Evaluation*. McGuire, R.K., ed. EPRI NP-7057. Palo Alto, California: Electric Power Research Institute.

Kemeny, J.M. and Cook, N.G.W. 1992. "Water Table Change Due to a Normal Faulting Earthquake." Section 6 of *Demonstration of a Risk-Based Approach to High-Level Waste Repository Evaluation: Phase 2*. EPRI TR-100384. Palo Alto, California: Electric Power Research Institute.

National Research Council. 1992. *Ground Water at Yucca Mountain, How High Can It Rise? Final Report of the Panel on Coupled Hydrologic/Tectonic/Hydrothermal Systems at Yucca Mountain*. Washington, D.C.: National Academy Press.

RAI Volume 3, Chapter 2.2.1.2.1, Second Set, Number 19, Supplemental Question 2:

Clarify the rationale for how stress changes in the upper crust after an earthquake. The RAI response states that the static stress drop is assumed to be a drop in shear stress which induces an increase in horizontal compressive stress.

- Do you mean a change in deviatoric stress or normal stress?
- Do you consider the main driver in water table rise to be poroelastic effect or permanent deformation that reduces porosity?

1. SUPPLEMENTAL RESPONSE

The Yucca Mountain site is located in an extensional tectonic stress regime with the least principal stress oriented ESE-WNW (General Information, Section 5.2.1.5). Extensional strain is accommodated, in part, by repeated earthquake faulting events (recurrence time of tens of thousands of years) that cause periodic stress drops at the fault rupture accompanied by an increase in mean compressive stress in the adjacent crustal rocks. Continued extensional strain reloads the tensional stress and reduces the compressional stress (e.g., Sibson 1991, p. 2495).

Kemeny and Cook (1992, pp. 6-3 to 6-4) present the stress change following a normal-faulting earthquake in terms of a Mohr circle diagram. For a normal-faulting earthquake, the maximum principal stress is the vertical stress, and the minimum and intermediate principal stresses are horizontal. An earthquake results in a drop in the shear stress along the fault. As the vertical stress, to a first approximation, remains unchanged, the minimum horizontal stress increases (i.e., becomes more compressive) in response to tensional stress unloading associated with the earthquake.

For the simple poroelastic model used by Kemeny and Cook (1992, p. 6-6), the post-earthquake increase in mean compressive stress leads to an elastic reduction in pore volume from pores, cracks, joints, and faults. The reduced pore volume accommodates a reduced volume of water, and all the expelled water is assumed to move vertically into overlying unsaturated layers, thus raising the water table. Kemeny and Cook (1992, Equation 6-3) give the change in mean normal stress (Δp) as:

$$\Delta p = \frac{\Delta \tau (1+\nu)}{3 \sin\theta \cos\theta}$$

in which $\Delta\tau$ is the static stress drop, ν is Poisson's ratio, and θ is the fault dip. They assume that this stress change is uniform with depth (Kemeny and Cook 1990, p. 5-15). In the context of normal and deviatoric stresses, it is the normal stresses, which tend to change the volume of a body, that are important rather than the deviatoric stresses, which tend to distort a body. While deviatoric stresses in the earth's crust cause the deformation that leads to earthquakes, it is the increase in mean normal stress caused by the static stress drop associated with an earthquake that results in elastic reduction in porosity. In the Kemeny and Cook representation it is this poroelastic effect, not permanent deformation, that reduces porosity and causes a rise in the water table.

2. COMMITMENTS TO NRC

None.

3. DESCRIPTION OF PROPOSED LA CHANGE

None.

4. REFERENCES

Kemeny, J. and Cook, N. 1990. "Rock Mechanics and Crustal Stress." Section 5 of *Demonstration of a Risk-Based Approach to High-Level Waste Repository Evaluation*. McGuire, R.K., ed. EPRI NP-7057. Palo Alto, California: Electric Power Research Institute.

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Sibson, R.H. 1991. "Loading of Faults to Failure." *Bulletin of the Seismological Society of America*, *81*, (6), 2493-2497. El Cerrito, California: Seismological Society of America.

RAI Volume 3, Chapter 2.2.1.2.1, Second Set, Number 19, Supplemental Question 3:

> Are the water table elevation changes relatively long-lasting or transient? Are the relaxation times at the scale of the changes in tectonic stress, earthquake cycle or something more rapid?

1. SUPPLEMENTAL RESPONSE

The water table elevation changes resulting from seismic activity in the vicinity of Yucca Mountain are not long-lasting or permanent; they are transient. The relaxation times are short in comparison to the 10,000- and 1,000,000-year compliance periods relevant for postclosure performance assessment of the Yucca Mountain repository, and are short in comparison with the duration of cycles of extensional tectonic stress buildup and release, which are thousands to tens of thousands of years as recorded by the recurrence of crustal faulting events.

1.1 TECHNICAL BASES FOR SUPPLEMENTAL RESPONSE

DOE concurs with the comprehensive technical evaluation performed by the National Research Council (1992, p. 108), which concluded that there are two distinct categories of temporal responses of the groundwater system at Yucca Mountain to an earthquake: (1) a relatively rapid, short-lived dynamic response associated with the passing of earthquake waves, and (2) a long-term response associated with the volumetric strain in the rocks after the earthquake waves have passed through or an increase in permeability from dynamic ground motion. This categorization is similar to the approach taken by Montgomery and Manga (2003), who distinguished between (1) a transient response due to the passage of seismic waves, and (2) a sustained or permanent response arising from aquifer compression or dilation.

The duration of the dynamic response due to the passage of earthquake waves was noted by the National Research Council (1992, p. 108) to be a short-lived, transient phenomenon that is not relevant to the performance of a repository. Montgomery and Manga (2003) note that the transient response results in rapid oscillations in the water table ranging from seconds to minutes. Consistent with the National Research Council (1992) evaluation and descriptions from Montgomery and Manga (2003), the terms “transient” or “short-lived” in the context of water table response to a seismic event in the vicinity of Yucca Mountain relate to a time period of minutes.

The longer-term response of the water table as a result of a seismic event may be associated with poroelastic volumetric strain in the rocks, permeability changes, or compaction of unconsolidated deposits. While the effects of poroelastic volumetric strain are relevant to water table rise at Yucca Mountain following a seismic event, water level changes due to changes in permeability or compaction are not expected to be significant at Yucca Mountain. In the case of permeability changes, the National Research Council (1992, pp. 70 and 109) notes that, if the large hydraulic gradient in the saturated zone to the north of Yucca Mountain is caused by a low permeability barrier, then an increase in the permeability of that barrier following a seismic event could lead to a modest rise of the water table of about 40 m. The conceptual model of the saturated zone in the vicinity of the large hydraulic gradient consists of a large region of altered

rock associated with the Claim Canyon caldera (SNL 2007, Sections 6.3.1.4 and 6.3.1.11). This is consistent with the conceptualization of this caldera and the nearby Timber Mountain caldera as regions of low permeability in the Death Valley regional model (Belcher 2004, Figures F-17 and F-37). Because this low permeability zone is conceptualized as a region of thermally altered rock and not a discrete tectonic feature, potential local permeability changes associated with a seismic event are not expected to significantly alter the overall flow characteristics in this region. Therefore, the "dam break" scenario hypothesized by the National Research Council is not expected to occur at Yucca Mountain and significantly change the water table elevation. In addition, although Montgomery and Manga (2003) note that unconsolidated deposits that undergo compaction from seismically triggered events can result in sustained changes in water levels that reflect nonrecoverable deformation, this situation is not relevant at Yucca Mountain, where the stress drop and associated poroelastic compression and subsequent water table rise is occurring in stiff rocks with low porosity (such as the Paleozoic carbonate rocks) (National Research Council 1992, p. 113).

The duration of the water table changes associated with the volumetric strain in the rocks was not quantified by the National Research Council. However, they noted that the water table rise is a transient phenomenon that will gradually dissipate (National Research Council 1992, p. 115). In Appendix D of their report, the transient decay of hydraulic head following a hypothetical earthquake at Yucca Mountain was shown to return to ambient conditions in about 100 days (National Research Council 1992, pp. 220 to 221). Montgomery and Manga (2003, p. 2047) note that sustained hydrologic responses due to poroelastic deformation can persist for months. Consistent with the National Research Council (1992) evaluation and descriptions from Montgomery and Manga (2003), the terms "long-term" or "sustained or permanent" in the context of water table response to a seismic event in the vicinity of Yucca Mountain relate to a time period of months. The water table rise is dissipated primarily by the lateral flow of groundwater from areas with a higher water table elevation to the surrounding areas with a lower water table elevation.

Given that the short-lived dynamic seismic wave responses have relaxation times that last for minutes and longer-term poroelastic responses have relaxation times that last up to months, these time periods are both considered transient in comparison to the 10,000- and 1,000,000-year compliance periods relevant to the performance assessment of the Yucca Mountain repository. This use of the term "transient" to describe the potential water table rise following a seismic event is consistent with the assessment of the National Academy of Sciences in a report entitled *Technical Bases for Yucca Mountain Standards*, which concludes that "results indicate a probable maximum transient rise on the order of 20 m or less" (National Research Council 1995, p. 94). This 20 m value may be compared to the conclusions reached by the National Research Council (1992, pp. 115 to 116), where, for a 100-bar drop in shear stress "the models suggest that regardless of which approach is taken, only a modest rise in the water table of less than 50 m is likely to occur as a result of a nearby earthquake." This 50 m value was used in the screening of the feature, event, and process (FEP) described under FEP 1.2.10.01.0A, Hydrologic Response to Seismic Activity (SNL 2008). Consistent with these findings, for a possible 165-bar drop in shear stress, a transient water table rise of about 80 m was calculated as described in the original response to RAI 3.2.2.1.2.1-2-019. Subsequent analyses presented in the response to

Supplemental Question 6 indicate a potential range of transient water table rise of between 60 and 115 m, which is still below the waste emplacement areas of the repository.

The transient rise in the water table elevation due to poroelastic effects is expected to dissipate within a period of months as the pore pressures re-equilibrate following the seismic event. Transient effects are of insufficient magnitude or duration to significantly affect repository performance, which has resulted in the exclusion of FEP 1.2.10.01.0A from the total system performance assessment.

2. COMMITMENTS TO NRC

None.

3. DESCRIPTION OF PROPOSED LA CHANGE

None.

4. REFERENCES

Belcher, W.R. 2004. *Death Valley Regional Ground-Water Flow System, Nevada and California - Hydrogeologic Framework and Transient Ground-Water Flow Model*. Scientific Investigations Report 2004-5205. Reston, Virginia: U.S. Geological Survey. ACC: MOL.20050323.0070.

Montgomery, D.R. and Manga M. 2003. "Streamflow and Water Well Responses to Earthquakes." *Science, 300*, 2047-2049. Washington, D.C.: American Association for the Advancement of Science.

National Research Council. 1992. *Ground Water at Yucca Mountain, How High Can It Rise? Final Report of the Panel on Coupled Hydrologic/Tectonic/Hydrothermal Systems at Yucca Mountain*. Washington, D.C.: National Academy Press.

National Research Council. 1995. *Technical Bases for Yucca Mountain Standards*. Washington, D.C.: National Academy Press.

SNL (Sandia National Laboratories) 2007. *Saturated Zone Site-Scale Flow Model*. MDL-NBS-HS-000011 REV 03. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20070626.0004.

SNL 2008. *Features, Events, and Processes for the Total System Performance Assessment: Analyses*. ANL-WIS-MD-000027 REV 00. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20080307.0003.

RAI Volume 3, Chapter 2.2.1.2.1, Second Set, Number 19, Supplemental Question 6:

Clarify why the characteristic event on the Solitario Canyon fault was the only event used to constrain the likelihood of "an earthquake occurring"?

- Aren't there other faults near the repository (Windy Wash, Bow Ridge, Paintbrush Canyon, Stagecoach Road, Bare Mountain) most with fault planes that cross near or directly beneath the repository that are just as likely to produce a earthquake as the Solitario Canyon fault?
- If the stress drop is relatively independent of magnitude (as stated on page 9 of RAI response), then wouldn't other more frequent earthquakes on these faults also warrant consideration in the model?

1. SUPPLEMENTAL RESPONSE

In the response to RAI 3.2.2.1.2.1-2-019, a large earthquake on the Solitario Canyon fault was used to evaluate the average probability of occurrence for an earthquake that potentially could lead to a seismically induced water table rise beneath the repository. The specified earthquake was used for consistency with the extreme stress-drop approach to ground motion conditioning. In that approach, earthquakes on the Solitario Canyon fault with moment magnitudes of 6.0 and 6.5 were used in characterizing the distribution of extreme ground motion at the repository waste emplacement level (see Section 1.1 of response to RAI 2.2.1.1.1-1-008). In the original response to RAI 3.2.2.1.2.1-2-019, the shortest recurrence interval interpreted for the Solitario Canyon fault (35,000 years; SAR Table 2.2-17) was used to assess a point-source stress drop with an exceedance probability of 10^{-8}. It was assumed, following the National Research Council approach (1992, p. 114), that the entire seismogenic portion of the crust (i.e., 10 km) is affected by the increase in mean compressive stress related to the earthquake. This assumption is reasonable given the size of the earthquake considered.

1.1 IMPACT FROM CONSIDERATION OF MULTIPLE LOCAL FAULTS

Earthquakes on faults in the vicinity of Yucca Mountain other than the Solitario Canyon fault also potentially could cause an earthquake-induced water table rise at the site. Kemeny and Cook (1990, p. 5-15) assume the volume of rock affected by the change in mean stress extends laterally to a distance equal to the vertical extent of fault rupture. Manga and Wang (2007, p. 294) state that static stresses decrease as $1/r^3$, where r is distance from the earthquake. To evaluate potential earthquake-induced water table rise at Yucca Mountain from changes in static stress, local faults within about 20 km of the site are considered.

As part of the probabilistic seismic hazard analysis (PSHA) for Yucca Mountain, a recurrence relation was developed for aggregated local fault sources for the combined interpretations of all the seismic source characterization teams (CRWMS M&O 1998, Figure 4-74). In characterizing local fault sources, each team addressed faults within about 20 km of Yucca Mountain (CRWMS M&O 1998, Appendix E). Thus, this recurrence relation includes contributions from the Windy Wash, Bow Ridge, Paintbrush Canyon, Stagecoach Road, Bare Mountain, and other local faults. For moment magnitudes of 6.0 and 6.5, consistent with events considered in the extreme-stress-

drop approach to ground motion conditioning, the mean annual frequencies from this aggregate recurrence relation are approximately 1.3×10^{-4} and 5.0×10^{-5}, respectively. Taking the higher rate and a lognormal distribution for point-source stress-drop with a median value of 60 bars and a lognormal standard deviation of 0.5 (as in the original response to RAI 3.2.2.1.2.1-2-019), a point-source stress drop of 400 bars has a probability of exceedance of about 10^{-8} (1.3×10^{-4} times the lognormal complementary cumulative probability of about 7.4×10^{-5}). Using the relation between point-source stress drop and static stress drop derived in the original response to RAI 3.2.2.1.2.1-2-019, a 400-bar point-source stress drop corresponds to a static stress drop of 200 bars. Finally, using the relation between static stress drop and water table elevation given in the original response to RAI 3.2.2.1.2.1-2-019 (and further explained in response to Supplemental Question 1), a maximum water table rise of 100 m is estimated. For such a water table rise, there is still about a 90 m gap between the raised water table and the lowest waste emplacement drift (e.g., see response to Supplemental Question 9).

1.2 IMPACT FROM CONSIDERATION OF MORE FREQUENT EARTHQUAKES

The evaluations given above and in the original response to RAI 3.2.2.1.2.1-2-019 do not take into account the impact of either smaller moment magnitude earthquakes or variation in the vertical depth (h) over which fault rupture occurs. In the Kemeny and Cook (1992, Equation 6-1) representation, water table rise is dependent on h as well as static stress drop:

$$\Delta w = \left(1.2 \times 10^{-5}\right) \times \Delta\tau \times h$$

in which Δw is water table rise in meters, $\Delta\tau$ is static stress drop in bars, and h is depth of faulting in meters.

Kemeny and Cook (1992, p. 6-2) consider a case in which h is 15 km. In *Ground Water at Yucca Mountain: How High Can It Rise?* (National Research Council 1992, p. 114), a value of 10 km for h is inferred from their assumption that the seismogenic crustal thickness is 10 km. When considering the effect on the elevation of the water table of smaller magnitude earthquakes, the impact of the vertical extent of faulting must be considered. The annual frequency of smaller magnitude events is higher. Thus, based on the lognormal distribution, a larger point-source stress drop is needed to obtain a combined annual probability of exceedance of 10^{-8}. The larger stress drop tends to increase the predicted water table rise. However, the smaller magnitude earthquake has a smaller vertical extent of rupture, which tends to decrease the predicted water table rise. The seismically induced water table rise for different moment magnitudes is evaluated, taking into account the competing effects from increasing point-source stress drop and decreasing vertical extent of rupture.

As in the original response to RAI 3.2.2.1.2.1-2-019, the point-source stress drop with a 10^{-8} probability of exceedance is determined using the lognormal complementary cumulative probability distribution (median of 60 bars and a lognormal standard deviation of 0.5), conditional on an earthquake occurring. The probability of occurrence for different moment magnitude earthquakes is taken from Figure 4-74 in *Probabilistic Seismic Hazard Analyses for Fault Displacement and Vibratory Ground Motion at Yucca Mountain, Nevada* (CRWMS M&O

1998). For the point-source stress drop with a 10^{-8} probability of exceedance, a corresponding static stress drop is then determined using the general relation between median point-source stress drop and median static stress drop developed in the original response to RAI 3.2.2.1.2.1-2-019. The ratio between the resulting static stress drop and the static stress drop of 100 bars assumed in *Ground Water at Yucca Mountain: How High Can It Rise*? (National Research Council 1992, p. 114) provides a linear multiplicative factor, which varies as a function of moment magnitude, giving the water table rise relative to the rise for a 100-bar stress drop for the Kemeny and Cook representation.

The vertical extent of rupture is computed from an empirical relation between the logarithm of rupture width and moment magnitude (Wells and Coppersmith 1994, Table 2A). The Wells and Coppersmith regression based on normal faulting events is used. A fault dip of 60 degrees is assumed to convert down-dip rupture width to vertical extent of rupture. The ratio between the resulting vertical extent of faulting and the seismogenic crustal thickness of 10 km assumed in *Ground Water at Yucca Mountain: How High Can It Rise*? (National Research Council 1992, p. 114) provides a multiplicative factor giving the water table rise relative to the rise for a 10 km vertical extent of faulting for the Kemeny and Cook representation.

The combined impact of the static stress drop and vertical extent of faulting is then obtained by multiplying the static stress drop ratio and the vertical extent of faulting ratio. Finally, this combined factor is applied to the 50-m water table rise that the National Research Council concluded was unlikely to be exceeded in 10,000 years (National Research Council 1992, p. 116).

Table 1 summarizes the combined impact on water table rise of changes in the point-source stress drop with an annual probability of exceedance of 10^{-8} and vertical extent of faulting as a function of moment magnitude. Water table rise values of about 60 m (i.e., 1.15×50 m) and 115 m (i.e., 2.33×50 m) are obtained for moment magnitudes of 5.5 and 6.75, respectively. For a 115-m water table rise, a 75-m distance remains between the water table and the lowest waste emplacement drift (e.g., see response to Supplemental Question 9). For larger moment magnitudes, the vertical extent of faulting does not increase because the thickness of the seismogenic portion of the earth's crust provides a constraint. The National Research Council (1992, p. 114) used a value of 10 km for this thickness. Here a value of 15 km is used based on interpretations by the six expert teams who carried out seismic source characterization as part of the probabilistic seismic hazard analysis for Yucca Mountain (CRWMS M&O 1998, Table 4-1). Thus, because the point-source stress drop with a probability of exceedance of 10^{-8} decreases for larger moment magnitude earthquakes with smaller average annual occurrence frequencies, predicted water table rise, even for larger moment magnitudes, does not exceed about 115 m, which is still below the waste emplacement areas of the repository.

Table-1. Combined Impact of Change in Static Stress Drop and Change in Vertical Extent of Fault Rupture

Moment Magnitude	Annual Frequency	Point-Source Stress Drop with a Probability of Exceedance of 10^{-8} (bars)	Static Stress Drop with a Probability of Exceedance of 10^{-8} (bars)	Static Stress Drop Ratio[a]	Vertical Extent of Faulting (km)[b]	Vertical Extent of Faulting Ratio[c]	Water Table Rise Factor[d]
5.5	4.0×10^{-4}	460	230	2.3	5	0.5	1.15
6.0	1.3×10^{-4}	400	200	2.0	8	0.8	1.60
6.5	5.0×10^{-5}	350	175	1.8	12	1.2	2.16
6.75	2.0×10^{-5}	310	155	1.6	14	1.4	2.24

[a] Static Stress Drop Ratio is with respect to 100 bars assumed in *Ground Water at Yucca Mountain: How High Can It Rise*? (National Research Council 1992, p. 114.)

[b] Vertical Extent of Faulting is computed using the Wells and Coppersmith (1994, Table 2A) empirical relation between the logarithm of rupture width (RW) in kilometers and moment magnitude (**M**). The relation based on normal faulting events is used: log (RW) = −1.14 + 0.35 **M**. A fault dip of 60 degrees is used to compute vertical extent of faulting from down-dip rupture width.

[c] Vertical Extent of Faulting Ratio is with respect to 10 km assumed in *Ground Water at Yucca Mountain: How High Can It Rise*? (National Research Council 1992, p. 114.)

[d] Water Table Rise Factor equals Static Stress Drop Ratio times Vertical Extent of Faulting Ratio. In this approach, water table rise is determined by applying the Water Table Rise Factor to the 50 m value that the National Research Council concluded was unlikely to be exceeded in 10,000 years.

2. COMMITMENTS TO NRC

None.

3. DESCRIPTION OF PROPOSED LA CHANGE

None.

4. REFERENCES

CRWMS (Civilian Radioactive Waste Management System) M&O (Management and Operating Contractor) 1998. *Probabilistic Seismic Hazard Analyses for Fault Displacement and Vibratory Ground Motion at Yucca Mountain, Nevada*. Milestone SP32IM3, September 23, 1998. Three volumes. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19981207.0393.

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RAI Volume 3, Chapter 2.2.1.2.1, Second Set, Number 19, Supplemental Question 8:

> What is the technical basis for 0.01 (1%) porosity value given in paragraph 4 on p. 9 of the RAI response? Why is this conservative? If the effect is poroelastic wouldn't the change be relatively insensitive to the assumed porosity?

1. SUPPLEMENTAL RESPONSE

The total pore space within the volcanic rocks overlying the water table is comprised of fracture apertures and pores within the rock matrix surrounding the fractures. The pore space is filled with both water and air. The water-filled fraction of a volume of rock is referred to as the moisture content and the air-filled fraction of that volume of rock is referred to as the gas content. The water phase saturation represents the fraction of pore space filled by water, and the gas phase saturation (1 − water phase saturation) represents the remaining fraction of pore space filled with air. Within the zone where water table rise associated with seismicity is expected to occur, the fracture porosity (or fraction of the rock volume taken up by the fractures) is generally <0.001 (SNL 2008a, Table 6-13). Because the average rock matrix porosities for these rock units generally range between 0.175 and 0.346 (see Table 1), the matrix porosity dominates the total volume of pore space and associated gas content.

The value of 0.01 discussed in Section 1.2.3 of the response to RAI 3.2.2.1.2.1-2-019 refers to the unsaturated portion of the matrix pores or the gas content of the rock above the water table. The term "unsaturated porosity", which was used as a synonym for gas content above the water table in the original RAI response, will not be used herein due to the ambiguity of the term. The gas content is used to determine how high the water table will rise due to seismically induced poroelastic effects (i.e., earthquake stress drops at the fault rupture that are accompanied by compressive stress increases to adjacent crustal rocks and associated decreases in porosity below the water table). The lower the gas content above the water table, the higher the predicted water table rise in the regional stress change model because water table rise is inversely proportional to the gas content of the rock units above the water table (Kemeny and Cook 1992, Equation 6-15).

The extent of water table rise is a function of the air volume in the unsaturated zone which can be replaced by the water squeezed out of the saturated zone by compression. This air volume defined by the gas content is a function of porosity and water saturation, that is, the calculated water table rise will be sensitive to the assumed gas content and is limited by the assumed porosity (see Kemeny and Cook 1992, Equation 6-15).

The value of 0.01 for gas content in the unsaturated zone may be qualitatively evaluated based on the matrix porosity and saturation data for rock units at the water table. Figure 6.1-2 of *Mountain-Scale Coupled Processes (TH/THC/THM) Models* (BSC 2005) and Figure C3-2 of *Development of Numerical Grids for UZ Flow and Transport Modeling* (BSC 2004a) show that the main grid model units at the water table are the Calico Hills 4 (ch4) through the Calico Hills 6 (ch6), the Prow Pass (pp4) through the Prow Pass 1 (pp1), and the Bullfrog 3 (bf3). Note that the hydrogeologic units (HGUs) for ch1 as presented in Table 1 are BT1 and BT1a, the HGUs for ch2-ch5 are CHV or CHZ, and the HGUs for ch6 are BT1 and BT1a (altered). In addition, the HGUs above the Calico Hills units beneath the repository are the TLL, TM2 & TM1, PV3,

PV2a, and PV2v for grid-model units tsw35 through tsw39. Distributions for the matrix porosities of these units are presented in Table 6-6 of *Analysis of Hydrologic Properties Data* (BSC 2004b), and, except for the TLL, TM2 & TM1, and PV3, have mean values that range from 0.175 to 0.346 (see Table 1). The upper HGUs TLL, TM2 & TM1, and PV3, which are associated with grid-model units tsw35-tsw37, have lower porosities ranging from 0.048 to 0.131, but also tend to have observed saturations that average less than 0.95 as can be seen in (SNL 2008b), Figures D.1-1 through D.1-8. Observed saturation data presented in Appendix D of *UZ Flow Models and Submodels* (SNL 2008b), Figures D.1-1 through D.1-8 considered in conjunction with the mean matrix porosities presented in Table 1, show that the gas content above the water table is greater than 0.01. This is a conservative approach to evaluating the potential water table rise associated with poroelastic effects, that is, the actual gas content is likely greater than 0.01, so the water table would rise less than if the average gas content was 0.01. The figures also present the saturation results from the unsaturated zone flow model for the present day (pd), monsoonal (mo), and glacial transition (gt) 10th-, 30th-, 50th- and 90th-percentile flow fields (SAR Section 2.3.2.4.1.2.4.5). It can be seen by comparing the simulation results for the different climate states in *UZ Flow Models and Submodels* (SNL 2008b, Figures D.1-1 through D.1-8), that the simulated rock matrix saturations do not vary much from climate state to climate state. The observed saturation versus depth profiles presented in Figures D.1-1 through D.1-8 of *UZ Flow Models and Submodels* (SNL 2008b) suggest that the average water saturation in an 80-m zone above the water table is less than 0.95. If the average saturations are less than 0.95 and porosities are generally greater than 0.2, the average gas content of the rock above the water table exceeds 0.01 ($(1 - 0.95) \times 0.2 = 0.01$).

To show that the average water saturations below the repository footprint at the elevations of concern are less than 0.95, saturation profiles taken from *UZ Flow Models and Submodels* (SNL 2008b, Figures D.1-6, D.1-4, and D.1-5) are presented in Figures 1, 2, and 3. Figure 1 depicts the saturation data and glacial transition simulation results from wellbore UZ-14, which is representative of saturation profiles below the northern part of the repository. Figure 2 depicts saturation data and glacial transition simulation results from wellbore SD-9, which is representative of saturation profiles below the central (with respect to north and south) part of the repository. Figure 3 depicts saturation data and glacial transition simulation results from wellbore SD-12, which is representative of saturation profiles below the southern part of the repository. Because all but the first 550 years of the total system performance assessment (TSPA) model simulations considers the water table below the repository footprint to be at 850 m (SAR Section 2.3.8.5.3), the elevations of 850 to 930 m above mean sea level will be considered here. The 930-m upper bound elevation is based upon adding the 80 m water table rise discussed in RAI: 3.2.2.1.2.1-2-019, Section 1.2.3, to the 850 m future climates water table elevation below the repository footprint. Note that the 850 m water table elevation represents the elevation at which radionuclides enter the saturated zone under future climate conditions in the TSPA model. There are some areas north and northwest of the repository in the unsaturated zone transport model where the bottom elevation of the model is greater than 850 m, but flow directions dictate that radionuclides will never reach those areas.

Measured saturations from three different boreholes are presented in Figures 1 to 3. As can be seen in Figure 1, the observed saturations are fairly high between 850 m to 930 m above mean

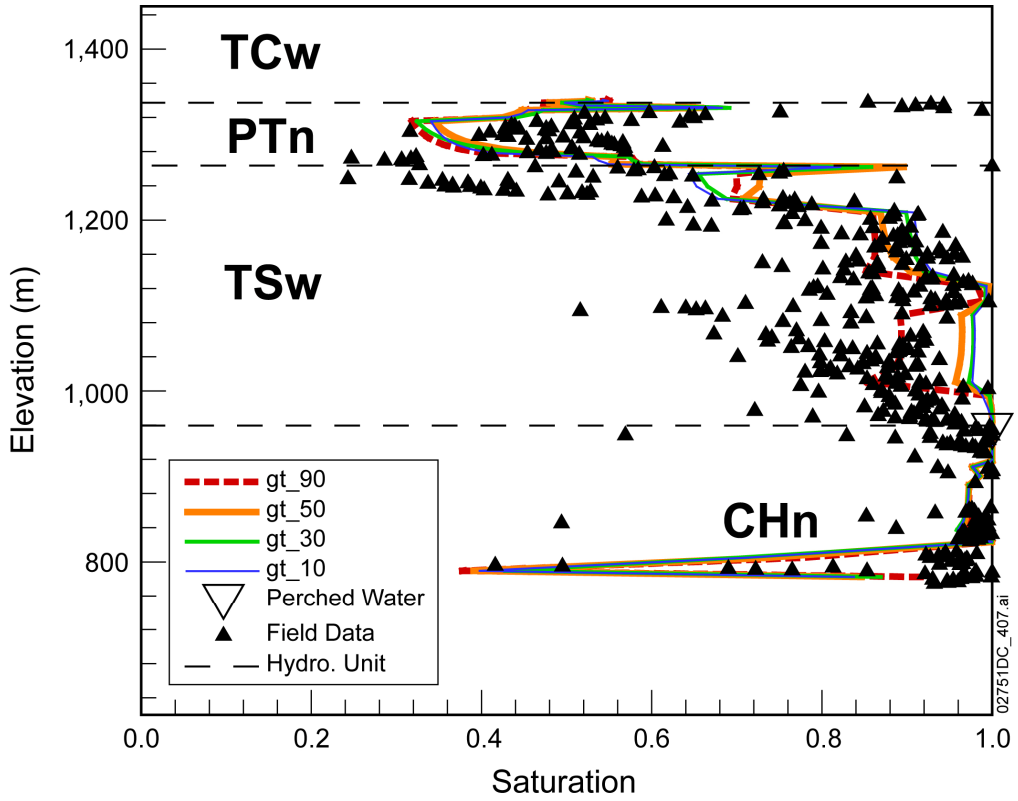
sea level and may average above 0.95. In Figure 2, it can be seen that the average saturation would be less than 0.95 between 850 to 930 m above mean sea level, and in Figure 3 it can be seen that the average saturation is well below 0.95 (approximately 0.6) between 850 to 930 m. This indicates that the average saturation below the repository footprint between the elevations of 850 and 930 m above mean sea level is less than 0.95, based on the data from the three boreholes. This justifies the choice of 0.01 for the gas content as a conservative assumption for the water table rise analyses. Note that the average saturation of less than 0.95 above the water table does include some perched zones where the water saturation is 1.0 and there is no gas that can be replaced. In addition, it can also be seen in Figure 1 that between 920 and 1,000 m elevation the saturation is below 0.95, indicating that it is highly unlikely that a seismically induced water table rise would reach the repository, which has a lower elevation of around 1,040 m above mean sea level (see RAI 3.2.2.1.2.1-2-019, Response to Question 9). Note that the choice of an 80-m zone is based on the calculated 80-m water-table rise discussed in the response to RAI 3.2.2.1.2.1-2-019, Section 1.2.3. An additional analysis presented in the response to supplemental Question 6 of RAI 3.2.2.1.2.1-2-019, indicates that water-table rises between 60 and 115 m are possible. An examination of Figures 1 through 3 in combination with the porosity values in Table 1 shows that in the zone between 930 to 965 m above mean sea level the choice of 0.01 is a conservative assumption for the water-table-rise analyses.

Table 1. Matrix Porosity Distributions Developed from Core Data

HGU	Mean Value	Standard Deviation	Number of Samples
TLL	0.131	0.031	502
TM1 & TM2	0.103	0.025	298
PV3	0.043	0.040	125
PV2a	0.275	0.096	13
PV2v	0.229	0.132	40
BT1a	0.285	0.051	46
BT1v	0.331	0.091	76
CHV[a]	0.346	0.049	130
CHZ[a]	0.322	0.048	520
BTa[b]	0.271	0.046	73
BTv[c,b]	0.331	0.091	76
PP4	0.321	0.047	52
PP3	0.318	0.032	168
PP2	0.221	0.058	127
PP1	0.297	0.043	280
BF 3	0.175	0.104	126

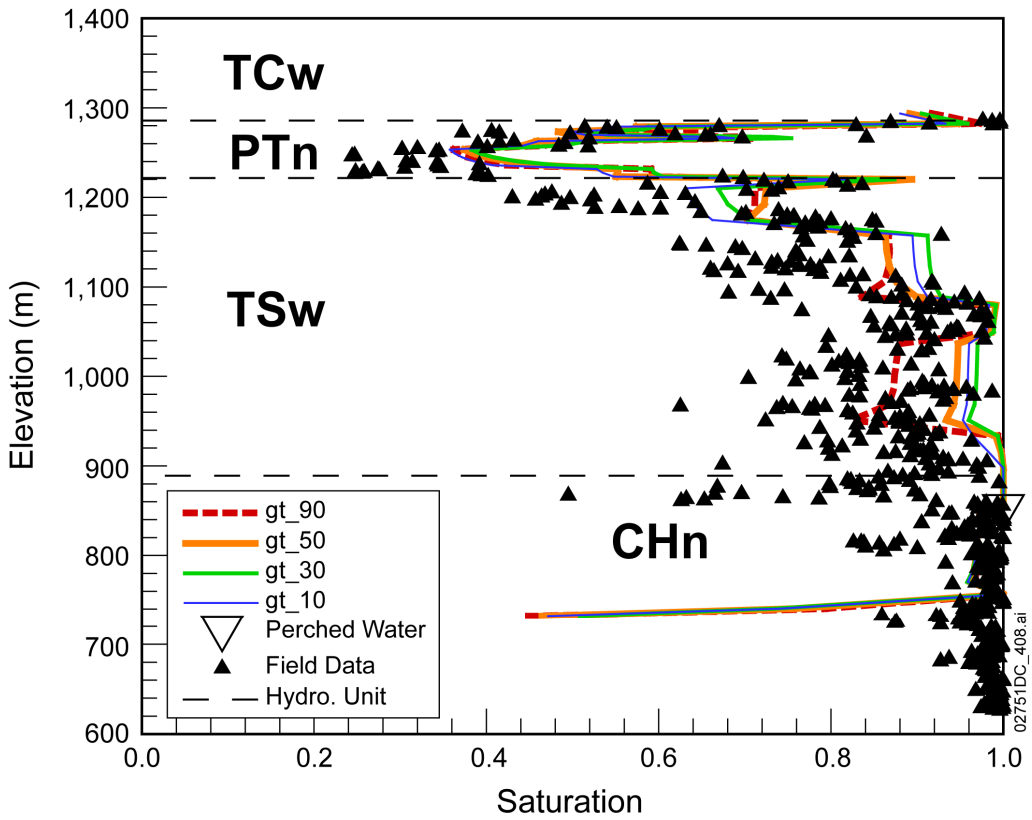
[a] CHV (vitric) and CHZ (zeolitic) include ch2 (vitric and zeolitic) – ch5 (vitric and zeolitic).
[b] BT includes ch6 (vitric and zeolitic).
[c] BT1v was used as an analogue for porosity because only one sample was available for BTv.

Source: BSC 2004b, Table 6-6.



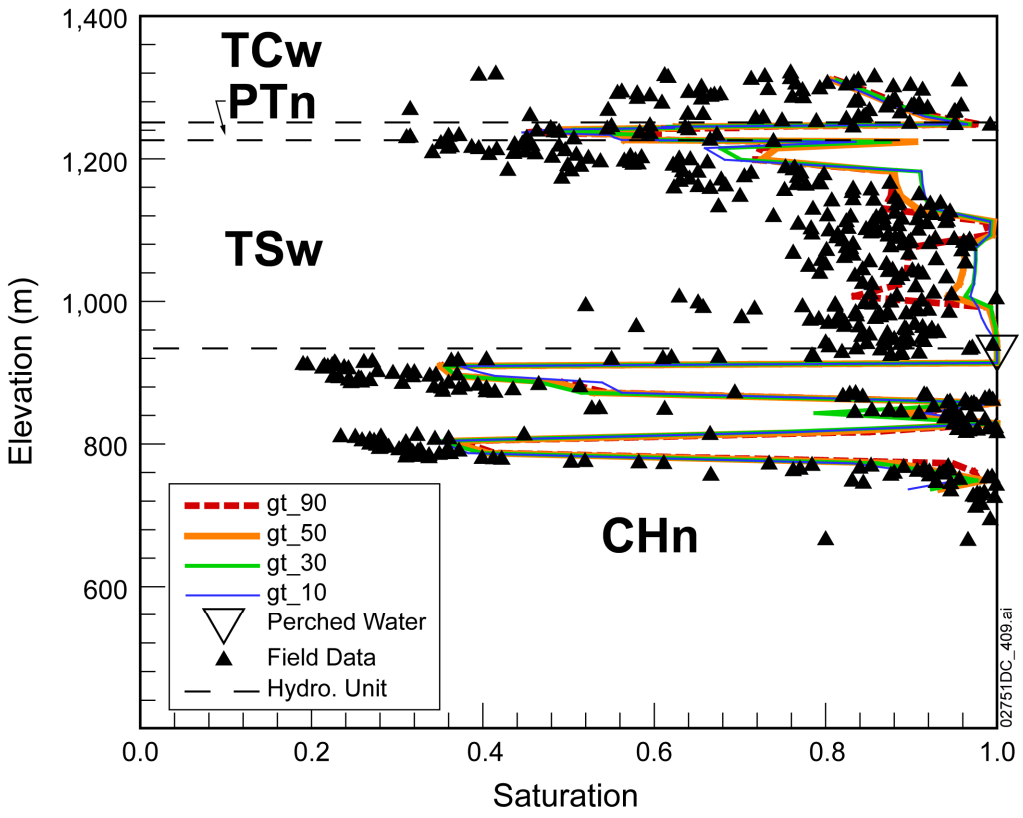
Source: SNL 2008b, Figure D.1-6.

Figure 1. Comparison of Observed Matrix Liquid Saturations at Borehole UZ-14 with Simulated Results for the Present-Day Infiltration Rates



Source: SNL 2008b, Figure D.1-4.

Figure 2. Comparison of Observed Matrix Liquid Saturations at Borehole SD-9 with Simulated Results for the Present-Day Infiltration Rates



Source: SNL 2008b, Figure D.1-5.

Figure 3. Comparison of Observed Matrix Liquid Saturations at Borehole SD-12 with Simulated Results for the Present-Day Infiltration Rates

2. COMMITMENTS TO NRC

None.

3. DESCRIPTION OF PROPOSED LA CHANGE

None.

4. REFERENCES

BSC (Bechtel SAIC Company) 2004a. *Development of Numerical Grids for UZ Flow and Transport Modeling.* ANL-NBS-HS-000015 REV 02. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20040901.0001[a]; LLR.20080522.0082[a].

BSC 2004b. *Analysis of Hydrologic Properties Data.* ANL-NBS-HS-000042 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20041005.0004.

BSC 2005. *Mountain-Scale Coupled Processes (TH/THC/THM) Models.* MDL-NBS-HS-000007 REV 03. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20050825.0007; LLR.20080522.0109.

Kemeny, J.M. and Cook, N.G.W. 1992. "Water Table Change Due to a Normal Faulting Earthquake." Section 6 of *Demonstration of a Risk-Based Approach to High-Level Waste Repository Evaluation: Phase 2.* EPRI TR-100384. Palo Alto, California: Electric Power Research Institute.

SNL (Sandia National Laboratories) 2008a. *Particle Tracking Model and Abstraction of Transport Processes.* MDL-NBS-HS-000020 REV 02 AD 02. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20080129.0008.

SNL 2008b. *UZ Flow Models and Submodels.* MDL-NBS-HS-000006 REV 03 AD 01. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20080108.0003.

NOTE: [a]Provided as an enclosure to letter from Williams to Sulima dtd 02/17/2009. "Yucca Mountain – Request for Additional Information Re: License Application (Safety Analysis Report Section 2.1), Safety Evaluation Report Volume 3 – Postclosure Chapters 2.2.1.1 and 2.2.1.3.7 – Submittal of Department of Energy Reference Citations."

RAI Volume 3, Chapter 2.2.1.2.1, Second Set, Number 19, Supplemental Question 9:

> If the present day water table depth ranges from 190 to 370 meters below the repository horizon and the future climate induced water table rise is expected to be a uniform 120 meters above its current position then the future water table under wetter conditions would range in depth from 70 to 250 meters below the repository horizon, not from 190 to 250 meters as stated in the RAI response on page 8, final paragraph in the subsection.

1. SUPPLEMENTAL RESPONSE

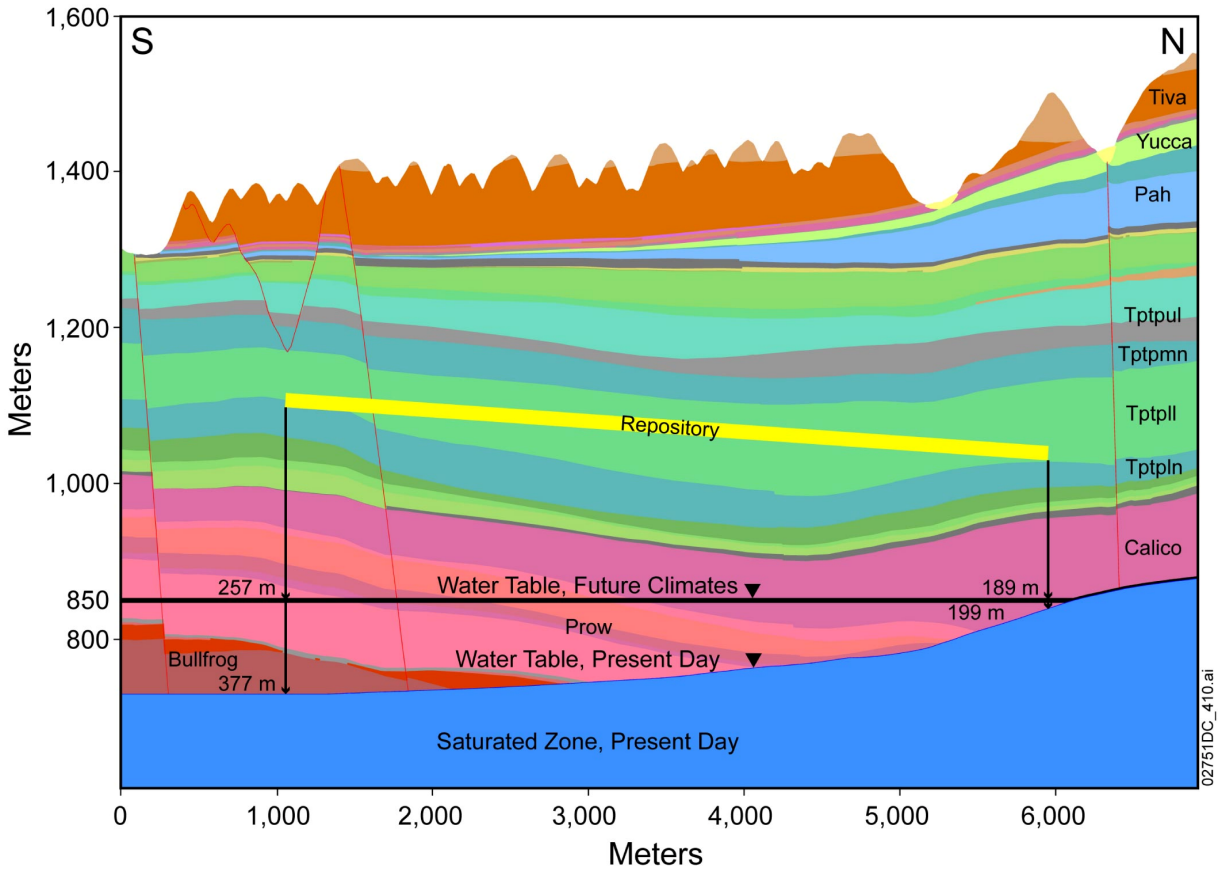
Within the repository footprint, the present-day water table varies from around 730 m above mean sea level in the south to less than 850 m above mean sea level in the north (BSC 2004, Figure 6-2). The repository elevation ranges between approximately 1,040 m above mean sea level in the north and 1,100 m above mean sea level in the south, indicating that the present-day water table depth below the repository horizon ranges from 190 m in the north, based on an approximate repository elevation of 1,040 m and water table elevation of 850 m, to 370 m in the south, based on an approximate repository elevation of 1,100 m and water table elevation of 730 m (see Figure 1). Figure 1 shows water table elevations for both present-day and future climate states; the bottom of the figure represents the current water table, while the dark black horizontal line represents the future water table. The depths to the present-day and future climate water tables from the northern and southern ends of the repository are also noted on Figure 1. Note that the depths to the water table discussed here are approximate and differ slightly from the more precise values presented in Figure 1 for a specific north-south cross-section.

To approximate the effects of future climates (monsoon, glacial-transition, and post-10,000-year) on radionuclide transport through the unsaturated zone, future climate flow fields used in the transport submodel have been post-processed to simulate the effects of a rising water table. Note that the bottom boundary for the flow models for all climate states is the present-day water table (SNL 2008, Section 6.11) as reflected in the flow field files prior to post-processing. In the post-processed files, the water table elevations for the future climate flow fields have been constrained to a minimum elevation of 850 m above sea level. This means that, for the future climate state flow fields: (1) any location where the present-day water table is below 850 m had its water table reset to 850 m, and (2) any location where the present-day water table is above 850 m did not have its water table elevation adjusted from the present-day elevation as shown in Figure 1.

These changes to the future climate flow fields represent a water table rise within the repository footprint that is a few meters (10 m in the cross section presented in Figure 1) in the north and is up to 120 m in the south (see Figure 1), effectively shortening the transport path through the unsaturated zone (see SAR Section 2.3.8.5.3). By constraining the water table to a minimum elevation of 850 m above sea level, the future climate water table depth ranges from 190 m (1,040 m – 850 m) to 250 m (1,100 m – 850 m) below the repository horizon.

Note: In the original response to RAI 3.2.2.1.2.1-2-019, in the last paragraph of Section 1.2.3, "(SNL 2008, Section 6.4.8)" is cited. The document that this citation refers to, however, was

inadvertently left out of the references section. In the original response, the only "SNL 2008" item included in the references section is *Features, Events, and Processes for the Total System Performance Assessment: Analyses* (ANL-WIS-MD-000027 REV 00). This is correct for all citations to "SNL 2008," except the one in the last paragraph of Section 1.2.3. For that one instance, "SNL 2008" refers to *Particle Tracking Model and Abstraction of Transport Processes* (MDL-NBS-HS-000020 REV 02 AD02, Las Vegas, Nevada: Sandia National Laboratories, ACC: DOC.20080129.0008; DOC.20070920.0003; LLR.20080325.0287; LLR.20080522.0170; LLR.20080603.0082; DOC.20090113.0002).



NOTE: The section is constructed looking S88.4°W (1.6 degrees south of straight west). The direction of view is perpendicular to a line the joins 1) the location where the emplacement horizon is closest to the saturated zone water table and 2) the location where the emplacement horizon is vertically most distant from the saturated zone water table. The vertical exaggeration in the section is 5:1.

Figure 1. Schematic Cross-Section Showing Location of Repository Relative to Present-Day and Potential Future Water Table Locations

2. COMMITMENTS TO NRC

None.

3. DESCRIPTION OF PROPOSED LA CHANGE

None.

4. REFERENCES

BSC (Bechtel SAIC Company) 2004. *Development of Numerical Grids for UZ Flow and Transport Modeling.* ANL-NBS-HS-000015 REV 02. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20040901.0001[a]; LLR.20080522.0082[a].

SNL (Sandia National Laboratories) 2008. *UZ Flow Models and Submodels.* MDL-NBS-HS-000006 REV 03 AD 01. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20080108.0003.

NOTE: [a]Provided as an enclosure to letter from Williams to Sulima dtd 02/17/2009. "Yucca Mountain – Request for Additional Information Re: License Application (Safety Analysis Report Section 2.1), Safety Evaluation Report Volume 3 – Postclosure Chapters 2.2.1.1 and 2.2.1.3.7 – Submittal of Department of Energy Reference Citations."