RAI Volume 3, Chapter 2.2.1.2.1, Fifth Set, Number 2:

For the FEPs listed below; clarify the rationale to exclude the FEP on the basis of low probability.

2.1.03.04.0A Hydride Cracking of Waste Packages

2.1.03.04.0B Hydride Cracking of Drip Shields

2.1.07.04.0A Hydrostatic Pressure on Waste Package

2.1.07.04.0B Hydrostatic Pressure on Drip Shield

2.1.09.28.0B Localized Corrosion on Drip Shield Surfaces Due to Deliquescence

2.1.11.06.0B Thermal Sensitization of Drip Shields

2.1.12.08.0A Gas explosions in EBS

This information is needed to verify compliance with 10 CFR 63.114 and 10 CFR 63.342.

Basis: The referred FEPs were excluded on the basis of low probability; however, there is no explicit reference to a probability value in the screening rationale in SNL (2008). A probability value (i.e., probability less than 10^{-4} of occurring within 10,000 years) is needed to exclude a FEP on the basis of probability, or an argument is needed to show that the FEP is of low consequence.

1. RESPONSE

The analyses performed in screening features, events, and processes (FEPs) used the criterion provided at 10 CFR 63.342(a) to justify excluding the seven listed FEPs, on the basis of low probability, from performance assessments conducted to demonstrate compliance with 10 CFR 63.311, 10 CFR 63.321, and 10 CFR 63.331. For five of the seven FEPs, the low probability justification is based on the conclusion that the FEP has a probability of occurrence within 10,000 years following disposal that is effectively (or qualitatively) equal to zero. This response will clarify the reasoning for those seven low probability determinations in *Features, Events, and Processes for the Total System Performance Assessment: Analyses* (SNL 2008), by explaining how the specific event or process will not occur and how the regulatory criterion is met.

In response to an observation by the NRC during the clarification teleconference on May 5, 2009, this response explains that, although SAR Section 2.2.1.2 (p. 2.2-16) states, "The low probability screening criterion has been applied in the FEP screening process to screen events that meet the quantitative threshold," DOE has used the probability criterion to screen all types of FEPs, rather than limiting its application to events. This application of the criterion is consistent with the requirements of 10 CFR 63.342(a), and is also consistent with language found elsewhere in SAR Section 2.2.1.2, which notes, for example, that "very unlikely FEPs can be excluded" consistent with regulatory requirements.

1.1 FEP 2.1.03.04.0A – HYDRIDE CRACKING OF WASTE PACKAGES

The screening justification provided in *Features, Events, and Processes for the Total System Performance Assessment: Analyses* (SNL 2008, Section 6.2) for this FEP concludes that "hydrogen embrittlement will not occur, and hydrogen-induced cracking (e.g., hydride cracking) of the waste package is excluded from the performance assessments conducted to demonstrate compliance with proposed 10 CFR 63.311, 10 CFR 63.321 (70 FR 53313), and with 10 CFR 63.331, on the basis of low probability." (There are no changes in the screening justification as a result of the issuance of the final 10 CFR 63 rule.) Hydrogen embrittlement refers to the deleterious impacts of hydrogen on the mechanical properties of a material, and therefore some degree of hydrogen embrittlement is, by definition, a required condition for hydrogen-induced cracking of materials. Fully annealed Ni-Cr-Mo alloys (including Alloy 22) are highly resistant to hydrogen-induced cracking even when heavily cold-worked or thermally aged to induce ordering or grain boundary segregation of sulfur or phosphorus, requiring hydrogen concentrations far in excess of what might be achieved within Yucca Mountain to cause embrittlement. The extremely low corrosion rates exhibited by Alloy 22 in repository environments will not generate sufficient hydrogen to cause hydrogen-induced cracking. If other materials from within the drift (e.g., drip shield, pallet, etc.) come into contact with the waste package, the resultant galvanic couples will not result in an increased rate of metal oxidation, and thus will not cause increased hydrogen production and uptake at the waste package surface. No credible mechanism has been found that would cause hydrogen embrittlement to the extent necessary to enable hydride cracking of the waste packages.

The conclusion that hydrogen embrittlement of waste packages will not occur, for the reasons stated in the screening justification as summarized here, is equivalent to concluding that the probability of hydrogen-induced cracking of the waste packages for 10,000 years following disposal is effectively equal to zero, which is below the probability criterion of one chance in 100,000,000 per year of occurring, as stated at 10 CFR 63.342(a).

1.2 FEP 2.1.03.04.0B – HYDRIDE CRACKING OF DRIP SHIELDS

The screening justification provided in *Features, Events, and Processes for the Total System Performance Assessment: Analyses* (SNL 2008, Section 6.2) for this FEP concludes that, although hydrogen absorption can occur in titanium alloys under some conditions, potentially leading to localized hydrogen embrittlement, bulk concentrations of hydrogen will remain well below the critical levels needed to induce cracking in the drip shield for 10,000 years. Support for this conclusion relative to the plate and support titanium alloys (but not the welded areas) is based upon a high general corrosion value at the 2.5×10^{-5} probability level (applied for 10,000 years), resulting in an amount of corrosion that produces a hydrogen content below the lower-bound critical hydrogen concentrations needed to observe hydride cracking. However, an overall probability is not assignable to this process since it also must consider potential hydride cracking in welded portions that does not rely primarily upon general corrosion. Therefore, the overall conclusion is equivalent to concluding that the probability of hydrogen-induced cracking of the drip shields (including welded areas) for 10,000 years following disposal is below one chance in 10,000, which is below the probability criterion of one chance in 100,000,000 per year of occurring, as stated at 10 CFR 63.342(a).

This FEP has been the subject of six previous Requests for Additional Information (RAIs), and the responses to these RAIs provide additional information relevant to the technical basis for the screening justification. Specifically:

- The response to RAI 3.2.2.1.2.1-2-003 provides additional discussion of the technical basis for the range of critical hydrogen concentration for fast fracture of Titanium Grade 29.

- The response to RAI 3.2.2.1.2.1-2-004 provides additional discussion of the technical basis for the beneficial role of Pd and Ru in increasing the critical hydrogen concentration values.

- The response to RAI 3.2.2.1.2.1-2-005 provides additional discussion of the technical basis for not considering potential enhancement of hydrogen absorption at cracks from stress corrosion cracking and delayed hydride cracking.

- The response to RAI 3.2.2.1.2.1-2-006 provides additional discussion of the rationale for basing the hydrogen absorption efficiency of Titanium Grade 29 on α-phase titanium alloys, given that Titanium Grade 29 is an (α+β)-phase titanium alloy.

- The response to RAI 3.2.2.1.2.1-2-007 provides additional discussion of the technical basis for not considering potential hydrogen redistribution in the drip shield induced by stress due to seismic events or rockfall and the hydrogen redistribution consequences on delayed-hydride cracking or fast fracture.

- The response to RAI 3.2.2.1.2.1-2-008 provides additional discussion of the technical basis for the conclusion that the Titanium Grade 28 weld filler metal will avoid the abrupt Al gradient that can lead to hydrogen redistribution and enhanced hydride formation.

In each case, the information provided in the responses to these referenced RAIs demonstrates the validity of DOE's previous conclusion that hydride-induced cracking of the drip shields will not occur for 10,000 years following disposal, and that the FEP has therefore been excluded from the performance assessments conducted to demonstrate compliance with 10 CFR 63.311, 10 CFR 63.321, and 10 CFR 63.331 on the basis of low probability.

1.3 FEP 2.1.07.04.0A – HYDROSTATIC PRESSURE ON WASTE PACKAGES

The screening justification provided in *Features, Events, and Processes for the Total System Performance Assessment: Analyses* (SNL 2008, Section 6.2) for this FEP concludes that "it is very unlikely that the water table will rise to the level of the repository." Although the phrase "very unlikely" is not quantified in the conclusion of the screening justification, it is intended to represent an event probability value much less than 1×10^{-8} per year. Additional information is provided in the FEP justification states that, "even under the extreme future climate conditions, the water table would not reach the repository horizon," and "even under the extreme wetter future climate conditions, the perched water bodies would not reach the repository horizon." The conclusions that neither the water table nor the perched water bodies are able to reach the repository level are equivalent to concluding that the probability of having hydrostatic water pressure affecting the waste packages for 10,000 years following disposal is effectively equal to zero. This effectively zero probability of encountering any hydrostatic pressure is much less than 1×10^{-8} per year, which is below the probability criterion of one chance in 100,000,000 per year of occurring, as stated at 10 CFR 63.342(a).

1.4 FEP 2.1.07.04.0B – HYDROSTATIC PRESSURE ON DRIP SHIELDS

The screening justification provided in *Features, Events, and Processes for the Total System Performance Assessment: Analyses* (SNL 2008, Section 6.2) for this FEP closely parallels that provided for FEP 2.1.07.04.0A, Hydrostatic Pressure on Waste Packages, and also concludes that "it is very unlikely that the water table will rise to the level of the repository." Although the phrase "very unlikely" is not quantified in the conclusion of the screening justification, it is intended to represent an event probability value much less than 1×10^{-8} per year. Additional information is provided in the FEP justification states that "even under the extreme future climate conditions, the water table would not reach the repository horizon," and "even under the extreme wetter future climate conditions, the perched water bodies would not reach the repository horizon." The conclusions that neither the water table nor the perched water bodies are able to reach the repository level are equivalent to concluding that the probability of having hydrostatic water pressure affecting the drip shields for 10,000 years following disposal is effectively equal to zero. This effectively zero probability of encountering any hydrostatic pressure is much less than 1×10^{-8} per year, which is below the probability criterion of one chance in 100,000,000 per year of occurring, as stated at 10 CFR 63.342(a).

1.5 FEP 2.1.09.28.0B – LOCALIZED CORROSION ON DRIP SHIELD SURFACES DUE TO DELIQUESCENCE

The screening justification provided in *Features, Events, and Processes for the Total System Performance Assessment: Analyses* (SNL 2008, Section 6.2) for this FEP concludes, "Therefore, significant localized corrosion of the drip shields due to dust deliquescence is not anticipated to occur, and FEP 2.1.09.28.0B (Localized Corrosion on Drip Shield Surfaces Due to Deliquescence) is excluded from the performance assessments conducted to demonstrate compliance with proposed 10 CFR 63.311 and 63.321 (70 FR 53313), and with 10 CFR 63.331 on the basis of low probability." The phrase "is not anticipated to occur" is not quantified in this statement, but information is provided elsewhere in the screening justification that supports the conclusion that localized corrosion on drip shield surfaces due to deliquescence will not occur (i.e., with a probability of occurrence much less than 1×10^{-8} per year). Specifically from the FEP analysis, point (3) of the screening discussion discusses how even the most potentially corrosive repository-relevant deliquescent brines are unable to cause localized corrosion on the drip shields, and point (4) of the discussion further describes how, even if potentially corrosive brines could form on the drip shields, they would not initiate localized corrosion due to physical limitations (e.g., brine volume, dust capillarity, and brine chemistry evolution). Both of those very unlikely phenomena would have to occur in order for there to be localized corrosion of the drip shield material.

The conclusions from the FEP analysis, that corrosive brines would not form on drip shields due to deliquescence and could not initiate localized corrosion, together are equivalent to concluding that the probability of localized corrosion on drip shield surfaces due to deliquescence for 10,000 years following disposal is effectively equal to zero, which is below the probability criterion of one chance in 100,000,000 per year of occurring, as stated at 10 CFR 63.342(a).

1.6 FEP 2.1.11.06.0B – THERMAL SENSITIZATION OF DRIP SHIELDS

The screening justification provided in *Features, Events, and Processes for the Total System Performance Assessment: Analyses* (SNL 2008, Section 6.2) for this FEP concludes that thermal sensitization of the drip shields can be excluded from performance assessments on the basis of low probability "based on the experimental evidence," but does not provide a specific probability value. The experimental evidence indicates that the titanium alloys used for drip shield fabrication are thermally stable under repository exposure conditions. Therefore, enhanced stress corrosion cracking, intergranular corrosion, or mechanical degradation of the drip shield will not occur in the repository. The justification also makes a comparison of the likelihood of thermal sensitization of the relevant titanium alloys (Titanium Grade 7 and Titanium Grade 29) to the likelihood of thermal sensitization of Alloy 22, which is discussed in FEP 2.1.11.06.0A, Thermal Sensitization of Waste Packages (SNL 2008, Section 6.2). In that FEP, the probability of conditions in excess of 300°C that could lead to thermal sensitization of Alloy 22 is shown to be "about one in 10,000 for 10,000 years after closure." The conditions that could lead to thermal sensitization of the drip shield titanium alloys are significantly less likely than those identified for the waste packages, both because the drip shield sensitization process requires higher temperatures (exceeding 315°C), and because the drip shield surfaces are at all times cooler than the waste packages. The stated value of "about one in 10,000 within the first 10,000 years after closure" for the sensitization of Alloy 22 therefore provides an overestimate for the probability of thermal sensitization of drip shields. Because the probability of reaching in excess of 315°C is less than 1×10^{-8} per year, the probability of thermal sensitization of drip shields for 10,000 years following disposal also must be below the probability criterion of one chance in 100,000,000 per year of occurring, as stated at 10 CFR 63.342(a).

Therefore, thermal sensitization of drip shields has been excluded from the performance assessments conducted to demonstrate compliance with 10 CFR 63.311, 10 CFR 63.321, and 10 CFR 63.331 on the basis of low probability.

1.7 FEP 2.1.12.08.0A – GAS EXPLOSIONS IN EBS

The screening justification provided in *Features, Events, and Processes for the Total System Performance Assessment: Analyses* (SNL 2008, Section 6.2) for this FEP concludes that "the probability of an explosion occurring is zero." As described in *Features, Events, and Processes for the Total System Performance Assessment: Analyses* (SNL 2008, Section 6.2), this conclusion is based on the prevalence of aerobic conditions in the drifts that will effectively preclude generation of hydrogen and methane from anaerobic processes, on the large volume of atmospheric gas available in the drifts and surrounding rock with which any flammable gases will mix, and on the relatively open nature of the fractured unsaturated rock that will further disperse any flammable gasses, thereby keeping concentrations below flammable levels. Additional information is provided in *Features, Events, and Processes for the Total System Performance Assessment: Analyses* (SNL 2008, Section 6.2) for the related excluded FEPs 2.1.02.08.0A (Pyrophoricity from DSNF), 2.1.13.01.0A (Radiolysis), and 2.1.02.29.0A (Flammable Gas Generation from DSNF).

With an insignificant likelihood of reaching explosive gas concentrations, the probability of an explosion within the emplacement drifts for 10,000 years following disposal is qualitatively zero, which is below the probability criterion of one chance in 100,000,000 per year of occurring, as stated at 10 CFR 63.342(a). Gas explosions in the EBS have therefore been excluded from the performance assessments conducted to demonstrate compliance with 10 CFR 63.311, 10 CFR 63.321, and 10 CFR 63.331 on the basis of low probability.

1.8 SUMMARY

For each of the seven FEPs identified in this RAI, the screening justification provided in *Features, Events, and Processes for the Total System Performance Assessment: Analyses* (SNL 2008, Section 6.2) supports a conclusion that the FEP has been appropriately excluded from the performance assessments conducted to demonstrate compliance with 10 CFR 63.311, 10 CFR 63.321, and 10 CFR 63.331 on the basis of low probability. For five of the seven FEPs, this response clarifies that screening is based on a conclusion that the event or process will not occur for 10,000 years following disposal, which is equivalent to a conclusion that the probability of occurrence is effectively equal to zero, which is below the probability criterion of one chance in 100,000,000 per year of occurring, as stated at 10 CFR 63.342(a). For FEP 2.1.03.04.0B (Hydride Cracking of Drip Shields), this response clarifies that the low probability justification has two parts, one a quantitative demonstration and the other qualitatively equal to zero; considered either separately or together, they both demonstrate a probability below one chance in 100,000,000 per year of this process FEP occurring, as stated at 10 CFR 63.342(a). For FEP 2.1.11.06.0B (Thermal Sensitization of Drip Shields), this response clarifies that the low probability justification is based on the demonstration that an existing analysis (in SNL 2008 for FEP 2.2.11.06.0A, Thermal Sensitization of the Waste Packages) provides an overestimate for the probability of this FEP, and that when considering the less thermally sensitive titanium alloys the probability is below the regulatory criterion.

2. COMMITMENTS TO NRC

None.

3. DESCRIPTION OF PROPOSED LA CHANGE

None.

4. REFERENCES

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; DOC.20080407.0009; DOC.20080722.0002.

RAI Volume 3, Chapter 2.2.1.2.1, Fifth Set, Number 4:

In light of observations and interpretations of the presence of liquid water in the Passive Test in the Enhance Characterization of the Repository Block (ECRB) drift, provide a technical basis for exclusion of FEP 1.1.01.01.0B and FEP 2.1.06.04A which addresses vapor migration into drifts and subsequent condensation. This information is needed to verify compliance with 10 CFR 63.114.

Basis: Salve and Kneafsey (2005) describe how observations of liquid water in the Passive Test (BSC, 2004, Section 6.10.2.2) of the ECRB drift can be explained using a conceptual model of vapor migration through the fracture network and into the drift. They describe three models for vapor flux into the drift, and the degree to which each model appears to best fit the observations of hydrologic conditions and liquid water in the drift.

Observations in the Passive Test consistent with water dripping into the drift (seepage per the DOE definition) are said to be lacking (SAR Section 2.3.3.2.2.2). The distribution of water in the drift of the Passive Test is qualitatively explained by condensation after redistribution of moisture driven by small temperature and relative humidity variations (SAR Section 2.3.3.2.2.2.5). Similar variations of temperature and relative humidity would be expected to occur after the thermal perturbation period in emplacement drifts.

Influx through holes drilled in the drift wall (FEP 1.1.01.01.0B) and flow through rock reinforcement materials (FEP 2.1.06.04.0A) are currently excluded FEPs due to low consequence. Boreholes, however, would facilitate the exchange of vapor from within the host rock to locations in the drift. As per the current design (SAR, Section 1.3.4.4.1), several tens of rock bolts will be installed around the drift periphery over the length of a waste package. In the design, rock bolts will be ungrouted (installed using pressure), and are assumed by DOE to corrode at the start of post-closure period. Regardless of the extent of corrosion, open vapor air pathways will be present.

1. RESPONSE

Two features, events, and processes (FEPs), 1.1.01.01.0B, Influx through Holes Drilled in Drift Wall, and 2.1.6.04.0A, Flow through Rock Reinforcement Materials in EBS address flow in open rockbolt boreholes and other rock reinforcement components, and how this flow could possibly promote seepage of water into drifts. Although there could be small amounts of vapor influx through open rockbolt boreholes, the increase in the available moisture within emplacement drifts and thus increase condensation in the emplacement areas will be negligible.

The technical bases for the exclusion of FEPs 1.1.01.01.0B and 2.1.6.04.0A (SNL 2008a) focus on the long-term post-thermal aspects of seepage (i.e., ambient seepage) when thermal effects are negligible. In the exclusion justifications for these FEPs, the effects of vapor influx through open rockbolt holes drilled in drift walls and vapor flow through rock reinforcement materials are not directly evaluated as potential contributions to the availability of moisture in the emplacement drifts. This response provides further justification that takes these effects into account. Also, the exclusion justification for FEPs 1.1.01.01.0B and 2.1.6.04.0A does not directly evaluate the effects of vapor/water reflux through open rockbolt boreholes in the drift wall on seepage during the thermal period. That justification is provided in the response to RAI 3.2.2.1.2.1-5-003.

1.1 COMPARISON OF THE IN-DRIFT CONDENSATION MODEL WITH ECRB OBSERVATIONS

Thermal gradients in the repository may lead to condensation of moisture in cooler parts of the emplacement drifts. Such effects are included in the TSPA using the condensation model (SAR Section 2.3.5.4.2). The condensation model describes the phenomena of evaporation of water from the drift wall and invert, transport of water along the drift, and condensation at cooler locations. There are two outcomes of these processes that bound the possibilities for condensation. If axial transport of the water vapor is sufficiently strong, condensation will occur only in unheated parts of the emplacement drifts, and relative humidity in the emplacement areas will be decreased. Alternatively, if axial transport is limited, relative humidity will be higher and local condensation in the emplacement area may occur (SNL 2007, Sections 6.3.7.2 and 6.1[a]).

As discussed in SAR Section 2.3.5.4.2, observations from the passive test in the ECRB showed that evaporation and condensation occur in response to small thermal gradients. The parts of the ECRB that were in the vicinity of heat sources (heat from the tunnel boring machine transformer) remained dry, while adjacent unheated regions were wet. Condensate was observed on thermally conductive surfaces after the ECRB bulkhead doors had been closed for periods ranging from a few weeks to several months (BSC 2004, Section 6.10.2.2; Figure 6-113). The observations are consistent with the condensation model representation that moisture can: (1) evaporate from warmer areas; (2) migrate along the drift as vapor, driven by natural convection processes; and (3) condense at cooler locations. In the repository, water from the rock will evaporate from the drift walls at warmer locations and condense at colder locations. For certain conditions, condensation may occur at cooler waste package locations. The rates of evaporation and condensation, and the rate of water vapor transport in the drift, will determine the humidity in the drift and the extent of condensation.

The condensation model as implemented for TSPA (SNL 2008b, Section 6.3.3.2) uses a 100% relative humidity (saturated water vapor pressure for local temperature) condition at the drift wall, to maximize the availability of moisture for evaporation. This approach causes the rate of vapor influx into the drift (and condensation in cooler areas) to be overestimated, because it does not account for: (1) capillary vapor pressure lowering in the rock near the drift; (2) flow resistance that vapor transport would encounter through a zone of relatively dry rock around the opening; or (3) the lower temperature, and thus lower saturation vapor pressure, a short distance into the rock. The latter effect means that if evaporation occurs within the rock away from the opening, the relative humidity will decrease as that vapor migrates to the drift. Even with this bounding condition applied at the drift wall, the resulting condensation is predicted to occur mostly outside the heated area (SNL 2007, Section 6.3.3.1). Direct evaporation from water films at the drift wall was considered and rejected by Salve and Kneafsey (2005) because the mechanism acted too quickly, not because it could not provide the observed moisture flux. Hence, the condensation model boundary condition (which assumes 100% relative humidity at the drift wall and, therefore, provides moisture at a faster rate than observed in the ECRB test) is conservative with respect to the availability of water to enter the emplacement drifts as vapor. A detailed discussion of how the models evaluated by Salve and Kneafsey (2005) apply to the modeling approach implemented in the condensation model is presented in the response to RAI 3.2.2.1.3.6-002.

1.2 VAPOR INFLUX THROUGH OPEN ROCKBOLT BOREHOLES IN THE DRIFT WALL

Salve and Kneafsey (2005) proposed that vapor influx through fractures caused rehydration of the closed section of the ECRB after the isolating bulkheads were closed. The RAI suggests that open boreholes such as those used for rock bolts (after the bolts have corroded) may similarly act as open pathways that increase vapor influx into repository drifts, and therefore increase the rate of condensation.

Open rockbolt boreholes may contribute to the availability of moisture for evaporation during the hottest part of the thermal period (within approximately 2,000 years after repository closure), but in later time the rate of evaporation decreases substantially, in such a way that additional availability of moisture would have no influence. Simulation of evaporation and condensation using the condensation model (SAR Section 2.3.5.4.2) shows that there is limited potential for open rockbolt boreholes to increase condensation. The primary reasons are that: (1) water vapor migrates away from the heated parts of the drift and condenses in the unheated parts, regardless of the percolation flux, which represents the availability of moisture; and (2) the rate of evaporation from the rock approaches zero because the vapor mass fraction of the gas in the drift approaches the equilibrium vapor mass fraction for the prevailing temperature at the drift wall.

Drift wall condensation occurs only for the 1,000-year case used for TSPA (SAR Section 2.3.5.4.2.4), which is applied during the final cooling stage, but only when the drift wall cools below boiling until 2,000 years after closure. During this period, evaporation occurs near the center of each emplacement drift, and condensation occurs closer to the ends. For the 1,000-year case, when drift wall condensation can occur, the rate of evaporation from the drift wall exceeds the incident percolation flux by a factor of up to three because of capillary pumping (SNL 2007, Section 6.3.5.1.4). This behavior is further explained in the response to RAI 3.2.2.1.3.6-002. In addition, open rockbolt boreholes will access rock that is at a lower temperature than the drift wall, and would therefore tend to decrease humidity at the drift wall during the thermal period, which may lead to liquid/vapor reflux in these open rockbolt boreholes. However, as discussed in the response to RAI 3.2.2.1.3.6-003, vapor/liquid reflux during the thermal period has little effect on seepage.

Thus, while the condensation model does not explicitly account for open rockbolt boreholes, it captures percolation from a distance comparable to the reach of rockbolt boreholes, during the thermal period when evaporation is active near the center of each drift. The occurrence of drift wall condensation during this period, as predicted by the condensation model for the 1,000-year case, is included in the TSPA and treated as seepage (SNL 2008b, Section 6.3.3.2). Seepage during this period has little effect on repository performance (see the response to RAI 3.2.2.1.3.6-003).

For the balance of the 10,000-year period, the rate of evaporation will approach zero throughout much of the drift, although near the ends of the heated region (where waste packages are emplaced) the evaporation rate will remain higher because proximity to the unheated regions allows the vapor to migrate away. This means that locally, the partial pressure of water is less than the equilibrium vapor pressure for the local temperature of the drift wall, driving evaporation. Note that this effect does not lead to condensation in the emplacement area. This occurs even though the condensation model uses a bounding 100% relative humidity condition at the drift wall throughout the heated area to represent the availability of moisture for evaporation. Therefore, the presence of open rockbolt boreholes would not substantially change the rate of evaporation or vapor production into the drift, nor increase the rate of condensation. Note that the results described here are obtained even with the lower-bound dispersivity parameter representing low axial mobility of vapor, and that barometric pumping would tend to increase the axial vapor mobility (SAR Section 2.3.5.4.2.3.1).

In summary, the potential effect of vapor influx through open rockbolt boreholes on the amount of water vapor entering drifts and potentially condensing in the waste emplacement area will be negligible, and the low consequence exclusion of influx processes for FEP 1.1.01.01.0B and FEP 2.1.06.04A is justified.

2. COMMITMENTS TO NRC

None.

3. DESCRIPTION OF PROPOSED LA CHANGE

None.

4. REFERENCES

BSC (Bechtel SAIC Company) 2004. *In Situ Field Testing of Processes.* ANL-NBS-HS-000005 REV 03. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20041109.0001; DOC.20051010.0001; DOC.20060508.0001; DOC.20080724.0006.

Salve, R. and Kneafsey, T.J. 2005. "Vapor-Phase Transport in the Near-Drift Environment at Yucca Mountain." *Water Resources Research*, *41*, (1). Washington, D.C.; American Geophysical Union.

SNL (Sandia National Laboratories) 2007. *In-Drift Natural Convection and Condensation.* MDL-EBS-MD-000001 REV 00 AD 01. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20050330.0001; DOC.20051122.0005; DOC.20070907.0004; LLR.20080324.0007.

SNL 2008a. *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; DOC.20080407.0009; LLR.20080522.0166; DOC.20080722.0002.

SNL 2008b. *Total System Performance Assessment Model /Analysis for the License Application.* MDL-WIS-PA-000005 REV 00 AD 01. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20080312.0001; LLR.20080414.0037; LLR.20080507.0002; LLR.20080522.0113; DOC.20080724.0005; DOC.20090106.0001[a].

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, Fifth Set, Number 6:

> In light of SAR Section 2.2.1.4.1.1.1, Figure 2.2-4, and the description provided in SNL (2008b, Section 1), provide the justification, including the ranges of parameters, used to determine that the two sequences of events [i.e., (1) improper manufacturing, resulting in the absence and/or loss of efficacy of the neutron absorber material, and (2) improper loading of fuel assemblies] are the dominant event sequences, and the bases for screening the other event sequences. This information is needed to assess compliance with 10 CFR 63.114.
>
> Basis: SAR Section 2.2.1.4.1.1.1 states that the criticality potential evaluation begins with the identification of applicable configuration classes and describes how configuration classes are used for this evaluation. SAR Figure 2.2-4 and the information used to screen out the individual feature, event, and process (SNL, 2008a) appear to be inconsistent. SAR Section 2.2.1.4.1.1.1 and Figure 2.2-4, which describe the disposal criticality analysis methodology approach, seem to indicate that quantification is to be used in waste form configuration class evaluations yet SNL (2008a), and references cited therein (SNL, 2008b and BSC, 2004), only discuss qualitative analyses.

1. RESPONSE

This response supplements the information already provided in the responses to RAIs 3.2.2.1.2.1-4-020 and 3.2.2.2.1-4-034.

1.1. JUSTIFICATION FOR USE OF DOMINANT EVENTS IN PROBABILITY CALCULATIONS

The waste packages and associated engineered barriers have been designed to function within the geologic repository to preclude criticality for the waste that meets the Yucca Mountain Project waste acceptance criteria under credible waste form and package conditions that can occur over the initial 10,000 years after repository closure. Criticality control within the commercial and DOE spent nuclear fuel (SNF) disposal canisters is achieved by controlling the following parameters during canister loading operations: neutron absorber loading, geometry at time of loading, and waste form loading requirements. A deviation in either the as-designed properties/specifications or the waste loading that would result in an increase in reactivity must occur in order to achieve criticality. Potential defects or deviations related to the neutron absorber efficacy or errors in waste loading are the only credible means to increase reactivity, thereby resulting in the potential for criticality, and hence were identified as the dominant events in sequences with the potential for criticality. No credit is taken for the fact that a significant number of waste packages will be loaded with fuel sufficiently burned so as to not need neutron absorber to maintain criticality control.

A comprehensive series of postclosure criticality evaluations have been performed to determine the configurations and parameters of influence that yield the highest system k_{eff} values over the first 10,000 years after waste emplacement. Models were developed (i.e., design basis configurations) to bound potential relevant variations in materials, geometry, and neutron spectrum that occur as the internals of the SNF canisters change over long periods of time. The most reactive configurations (design basis configurations) were developed considering processes that result in maximizing k_{eff} while accounting for repository characteristics, material characteristics of the waste forms and basket structures, and chemical and physical mechanisms for internal reconfiguration. These evaluations were performed to determine the neutron absorbing material requirements, waste form loading requirements, and/or basket configurations/requirements necessary to maintain subcriticality over the postclosure period for the design basis configuration. Therefore, the loading specifications for standard fuel (as defined in 10 CFR 961.11, Appendix E) have been engineered to account for internal component degradation and reconfiguration.

An event sequence for consideration of criticality potential is characterized by an initiating event that results in breach of the waste package outer barrier and several other events (e.g., material degradation and reconfiguration, design nonconformance) that must occur, as illustrated in the representative event tree provided in Figure 1. The formation of different configurations is dependent upon other parameters affecting the repository that are temporally and spatially dependent upon one another. Sensitivity evaluations have been performed to evaluate the different parameter effects over broad distribution ranges during the development of the design basis configurations, with relevant ranges of parameters provided in the response to RAI 3.2.2.1.2.1-4-034. Discussions of how other events have been considered in the event sequences are provided in the response to RAI 3.2.2.1.2.1-4-20. Therefore, using the design basis configuration as always forming with a probability of one, bounds the configuration probability in the event sequence and obviates the need to include additional probabilities for other events within the sequence that may affect the different configurations. Including these other events can only result in decreasing the probability calculation because probabilities less than one can only result in a monotonically decreasing event sequence probability. Because the probability of occurrence of the design basis configuration is set to one, and the criticality controls are designed to accommodate this configuration, the only mechanism that could increase k_{eff} above the design critical limit is design nonconformance (i.e., basket manufacturing error which results in removal or the absence of the neutron absorber, or the waste form loading being out of specification).

1.2. SAR FIGURE 2.2-4 IMPLEMENTATION IN FEATURES, EVENTS, AND PROCESSES SCREENING

The process outlined in SAR Figure 2.2-4 represents an iterative process for evaluating Engineered Barrier System and SNF packaging design features in order to develop an acceptable design. The RAI Basis states that the features, events, and processes (FEPs) screening process and SAR Figure 2.2-4 appear to be inconsistent. This apparent inconsistency is because they were developed for different purposes. However, the criticality event class, which is the aggregate of the individual criticality FEPs, is what is screened for inclusion in the performance assessment consistent with the FEPs screening process. SAR Figure 2.2-4 depicts the process to screen the entire criticality event class for exclusion from the performance assessment considering all events and processes which could lead to the occurrence of a criticality. In contrast, the FEPs screening discussion presented in *Features, Events, and Processes for the*

Total System Performance Assessment: Analyses (SNL 2008a) provides a screening justification for the individual FEPs to be considered in screening the criticality event class and compares the probability estimate from box 3 in SAR Figure 2.2-4 with the box 7 decision point. Both analyses are performed to ensure that the individual criticality scenarios have not been defined too narrowly, thereby resulting in premature exclusion of the individual criticality FEPs. Individual criticality FEPs were evaluated to determine which scenarios would need consequence analyses performed if the criticality event class probability was not below the criterion for event inclusion in the total system performance assessment for the license application (TSPA-LA).

NUREG-1804 indicates that criticality is to be screened by location; the locations are in-package, near-field, and far-field. Of the 16 criticality FEPs, eight are for the in-package location. Because the criticality FEPs are screened by location, only one probability value is required for the in-package location for either the intact or degraded configuration. Because the design basis configuration is used, the probability of criticality for the in-package location for either the intact or degraded configuration is the same. Near-field and far-field criticality is discussed in Section 1.2.5.

The process used as described in SAR Figure 2.2-4 does not require full quantification of the probability of criticality to be calculated for screening out FEPs. The first decision point identified as diamond 1 in SAR Figure 2.2-4 represents a predetermined probability screening criterion defined to be well below (a minimum of two orders of magnitude) the 10 CFR 63.114(d) regulatory criterion. The wording for this screening criterion has been modified for clarity in *Screening Analysis of Criticality Features, Events, and Processes for License Application* (SNL 2008b) to the *a priori* screening criterion. This criterion is used to screen from further consideration configuration classes that have an insignificant contribution to the total probability of a criticality occurring in the repository during the 10,000-year period following closure of the repository, where "insignificant" means an evaluation that included the configuration class would not change the overall result.

In order to simplify and bound the probability of criticality evaluations, all events that cause waste package breach are considered to result in formation of the design basis configuration (see representative event tree in Figure 1). Thus, the probability of forming the design basis configuration given a breach of the waste package is set to a probability of one, which is bounding for the event sequence calculation and makes the configuration class probability equal the waste package breach probability. Therefore, when considering the criticality FEPs, the initiating event (i.e., rockfall, early-failure, seismic, and igneous) probabilities that result in breaching one or more packages in the repository are compared against the *a priori* screening criterion (box 1).

1.2.1. Rockfall Initiating Event Features, Events, and Processes

The rockfall initiating event does not result in failure of the drip shield or breach of the waste package outer barrier; therefore, the probability of criticality resulting from rockfall is effectively equal to zero. *Features, Events, and Processes for the Total System Performance Assessment: Analyses* (SNL 2008a, FEP 2.1.07.01.0A) provides the basis of the consequences associated with rockfall events. Thus, decision point 1 in SAR Figure 2.2-4 is satisfied and the probability carried forth to the criticality FEPs associated with rockfall (2.1.14.21.0A, 2.1.14.22.0A, 2.1.14.23.0A, and 2.2.14.11.0A) is considered an insignificant contributor to the criticality event class, and thus can be screened from consideration with no probability calculation.

1.2.2. Early Failure Initiating Event Features, Events, and Processes

The early-failure initiating event has several mechanisms that can lead to breach of the waste package outer barrier as discussed in *Screening Analysis of Criticality Features, Events, and Processes for License Application* (SNL 2008b, Section 6.3). The mean probability of breach per waste package is 1.13×10^{-4} (SNL 2008b, p. 6-15). Inherent in this value is the bounding assumption that if a drip shield is misaligned such that a gap is present over the waste package, the probability of localized corrosion of the underlying waste package is one. This probability value (1.13×10^{-4}) is used in the first decision point for comparison against the *a priori* screening criterion. This probability is not sufficiently below the *a priori* screening criterion and thus, scenario development from this initiating event warrants further evaluation. The design basis configuration is conservatively assumed to form from this breach mechanism; therefore, the configurations that violate the criticality acceptance criterion (box 2 in SAR Figure 2.2-4) are those in which there is also an absorber error or waste form loading error as illustrated in the representative event tree in Figure 1. The probability of criticality for the in-package location (FEPs 2.1.14.15.0A and 2.1.14.16.0A) resulting from this sequence of events is calculated by completing box 3 of SAR Figure 2.2-4. These calculations are provided in *Screening Analysis of Criticality Features, Events, and Processes for License Application* (SNL 2008b, p. 6-15)

1.2.3. Seismic Initiating Event Features, Events, and Processes

The seismic initiating event has several mechanisms that can lead to breach of the waste package outer barrier as discussed in *Screening Analysis of Criticality Features, Events, and Processes for License Application* (SNL 2008b, Section 6.4). The mechanisms for consideration include: vibratory ground motion; faulting; and rockfall induced by seismic event(s) for potential waste package breach or drip shield failure that can result in localized corrosion breach of the waste package outer barrier. The seismic fragility for the waste packages is dependent upon the waste package type—commercial SNF waste package or DOE codisposal waste package. The probabilities of breach from seismic initiating events are summarized in Table 1. These probability values are not sufficiently below the *a priori* screening criterion, and hence warrant further evaluation. The design basis configuration is conservatively assumed to form from this breach mechanism; therefore, the configurations that violate the criticality acceptance criterion (box 2 in SAR Figure 2.2-4) are those in which there is also an absorber error or waste form loading error as illustrated in the representative event tree in Figure 1. The probability of criticality for the in-package location (FEPs 2.1.14.09.0A and 2.14.17.0A) resulting from this sequence of events is calculated by completing box 3 of SAR Figure 2.2-4. These calculations are provided in *Screening Analysis of Criticality Features, Events, and Processes for License Application* (SNL 2008b, pp. 6-28, 6-35, and 6-36, and Table 6.4-7).

Table 1. Waste Package Breach Probabilities from Seismic Initiating Events for 10,000 Years After Repository Closure

Seismic Breach Mechanism	Waste Package Variant		Reference Source
	Commercial SNF	DOE Codisposal	
Vibratory damage results in stress corrosion cracking (SCC)	2.6×10^{-4}	0.24	SNL 2008b, p. 6-27
Fault displacement	1.2×10^{-4} to 4.3×10^{-4}	3.0×10^{-5} to 1.0×10^{-4}	SNL 2008b, Table 6.4-9
Seismic-induced rockfall rupture of drip shield leading to localized corrosion	1.04×10^{-3}	7.2×10^{-4}	SNL 2008d, Table 7-4

1.2.4. Igneous Initiating Event Features, Events, and Processes

The screening for the igneous initiating event criticality FEPs did not follow the process outlined in SAR Figure 2.2-4. The annual frequency of igneous disruptive events is characterized with a mean frequency of occurrence of 1.7×10^{-8} per year, which translates into a mean probability of one or more igneous events of 1.7×10^{-4} over 10,000 years. This is not sufficiently below the *a priori* screening criterion (a minimum of two orders of magnitude below the 10 CFR 63.114(d) regulatory criterion of one chance in 10,000 of occurring over 10,000 years); however, a probability calculation was not completed as depicted in SAR Figure 2.2-4. The basis for not performing detailed probability calculations for the in-package igneous initiating event criticality FEPs (2.1.14.24.0A and 2.1.14.25.0A) is that the probability of breach is sufficiently below (by a factor of 1,400) the seismic vibratory probability of breach for the DOE codisposal waste package to conclude that the igneous initiating event contribution to the total probability of a criticality is insignificant. Waste form evaluations for igneous intrusive scenarios have been performed for DOE SNF and commercial SNF confirming that the design basis configurations are applicable for the igneous initiating event FEPs. This means that the same design nonconformance (i.e., basket manufacturing error which results in removal or the absence of the neutron absorber or the waste form loading being out of specification) is required to achieve criticality. Therefore, any further quantification of the probability of criticality will be orders of magnitude below the DOE codisposal waste package probability of criticality so as to not affect the sum for the criticality event class (i.e., an insignificant contribution). Additionally, as discussed in *Screening Analysis of Criticality Features, Events, and Processes for License Application* (SNL 2008b, Section 6.6.1), the probability of an extrusive igneous event is 4.8×10^{-5} over 10,000 years, which is not sufficiently below the *a priori* screening criterion. However, given the violent nature of an extrusive event, it is expected that the fuel materials would be sufficiently dispersed so as not to form a critical configuration, and hence the probability of criticality from such an event is insignificant.

As discussed in *Screening Analysis of Criticality Features, Events, and Processes for License Application* (SNL 2008b, Section 6.6), the conditions associated with an igneous intrusive event are deleterious to the integrity of the drip shields and waste packages, and are expected to result in waste package outer barrier breach. Using the same calculation process described in

Screening Analysis of Criticality Features, Events, and Processes for License Application (SNL 2008b, Equation 6.3-2), the probability of criticality over 10,000 years for the in-package location for the igneous criticality event scenario can be determined as follows:

- Pressurized water reactor (PWR) transportation, aging, and disposal (TAD) canister absorber misload:
  - $1.7 \times 10^{-4} \times \{1 - P_B\,(0; 1.25 \times 10^{-7}), 4568\} = 9.7 \times 10^{-8}$
- PWR TAD canister loading curve error:
  - $1.7 \times 10^{-4} \times \{1 - P_B\,(0; 1.65 \times 10^{-7}), 4568\} = 1.3 \times 10^{-7}$
- Boiling water reactor (BWR) TAD canister absorber misload:
  - $1.7 \times 10^{-4} \times \{1 - P_B\,(0; 1.25 \times 10^{-7}), 2915\} = 6.2 \times 10^{-8}$
- DOE SNF canister absorber misload:
  - $1.7 \times 10^{-4} \times \{1 - P_B\,(0; 1.25 \times 10^{-7}), 1223\} = 2.6 \times 10^{-8}$.

Probability of one or more criticalities from an igneous initiating event = 3.2×10^{-7}.

As demonstrated above, the probability of criticality from igneous events is over two orders of magnitude below that associated with seismic vibratory ground motion and codisposal waste packages (i.e., 3.7×10^{-5} (SNL 2008b, p. 6-28)). Thus, including the probability of criticality from igneous events in the total criticality event class probability would not change the screening decision.

1.2.5. External Criticality Features, Events and Processes

In addition to a breach of the waste package outer barrier, several other processes must also be considered, as discussed in SAR Sections 2.2.1.4.1.3.3 and 2.2.1.4.1.3.4, when evaluating for external criticality. The process outlined in SAR Figure 2.2-4 was followed for screening the external criticality FEPs (2.1.14.17.0A, 2.2.14.09.0A, 2.1.14.20.0A, 2.2.14.10.0A, 2.1.14.26.0A, and 2.2.14.12.0A). Rockfall FEPs (2.1.14.23.0A and 2.2.12.11.0A) were discussed in Section 1.2.1.

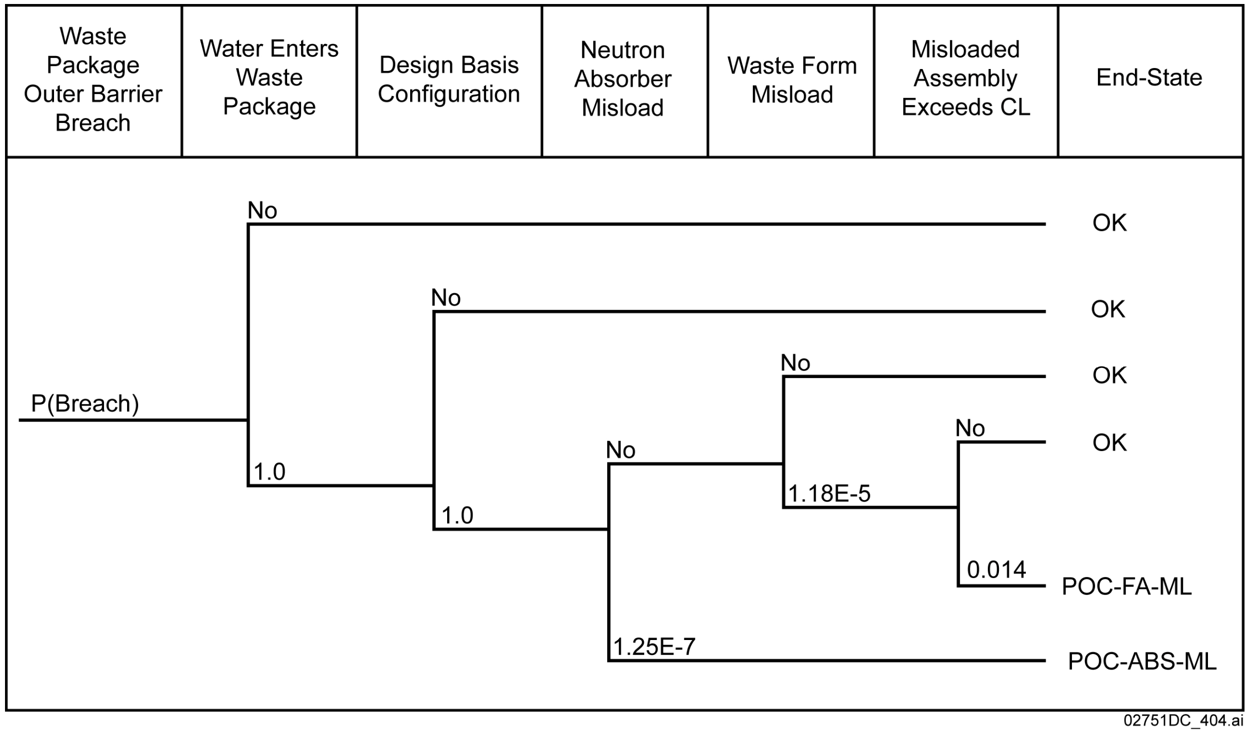
Considering all of the characteristics identified in SAR Figure 2.2-4 (e.g., the geochemical material characteristics, waste form characteristics, repository site characteristics), two geochemistry model reports were generated: *Geochemistry Model Validation Report: Material Degradation and Release Model* (SNL 2007a) and *Geochemistry Model Validation Report: External Accumulation Model* (SNL 2007b). These geochemistry model reports evaluated how much fissile material could be transported out of the waste package and accumulate in the external environment, forming the bases for configuration class development. The accumulation sites considered are the near-field environment, which contains crushed tuff, and the far-field within fractures of the host rock and within larger void spaces (lithophysae) distributed throughout the host rock. Since the exact location of the breach(es) and the focalization of the effluent can significantly alter the fissile material precipitation rates, the model used optimum mixing ratios to maximize the fissile material accumulation. In other words, there was no volume displacement considered which would alter the mixing ratio after a certain amount of material had precipitated in a given location, which would have prevented additional accumulation within that location.

Any breach of a waste package can ultimately lead to transport of fissile material outside the waste package; therefore, the probability of achieving the configuration classes conditional on waste package breach is conservatively set to one (as discussed in Sections 1.2.2 to 1.2.4). The waste package breach probabilities are used in the first decision point (box 1 of SAR Figure 2.2-4), and are all above the *a priori* screening criterion. Therefore, further criticality analyses are warranted.

Design basis configurations for the external environment were developed in *Geochemistry Model Validation Report: External Accumulation Model* (SNL 2007b, Section 6.9[a]) based on a search for the minimum critical mass under optimized conditions considering the repository host rock characteristics and potential accumulation sites. Based on the geochemistry model results, an insufficient amount of fissile material accumulates to form a critical mass under idealized conditions. Therefore, decision point 2 in SAR Figure 2.2-4 is satisfied and no probability of criticality needs to be calculated. Not all DOE SNF waste forms were evaluated explicitly, as discussed in SAR Section 2.2.1.4.1.3.3, but justification for not needing an evaluation was provided.

1.3. SUMMARY

The probability of occurrence for a configuration class is used as an upper bound for the probability of criticality for that configuration class if the *a priori* screening criterion is satisfied and thus, excluded from further consideration. If the *a priori* screening criterion is not satisfied, then a probability evaluation for configurations that exceed the design critical limit is performed. Design basis configurations are used in the criticality calculations to engineer criticality control parameter design specifications. The use of design basis configurations bounds and obviates the need for intermediate probability values associated with variations of waste package internal component and waste form degradation. Therefore, design nonconformance associated with basket manufacturing error, which results in removal or absence of the neutron absorber, or the waste form loading being out of specification, are the dominant (only) events within a sequence that can result in criticality.



NOTE: ABS = absorber; CL = Critical Limit; FA = fuel assembly; ML = misload; POC = probability of criticality.

Figure 1. Representative Event Tree

2. COMMITMENTS TO NRC

None.

3. DESCRIPTION OF PROPOSED LA CHANGE

None.

4. REFERENCES

SNL (Sandia National Laboratories) 2007a. *Geochemistry Model Validation Report: Material Degradation and Release Model.* ANL-EBS-GS-000001 REV 02. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20070928.0010

SNL 2007b. *Geochemistry Model Validation Report: External Accumulation Model.* ANL-EBS-GS-000002 REV 01 AD 01. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20071106.0015.

SNL 2008a. *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; DOC.20080407.0009; LLR.20080522.0166; DOC.20080722.0002 .

SNL 2008b. *Screening Analysis of Criticality Features, Events, and Processes for License Application.* ANL-DS0-NU-000001 REV 00. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20080208.0001; DOC.20080317.0008; LLR.20080401.0255; LLR.20080423.0161; DOC.20090302.0002[a].

SNL 2008d. *Waste Package Flooding Probability Evaluation.* CAL-DN0-NU-000002 REV 00C AD 01. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20080424.0001[b]; LLR.20080401.0269[a]; DOC.20090210.0002[a].

NOTES: [a] Provided as an enclosure to letter from Williams to Sulima dtd 03/31/2009. “Yucca Mountain – Request for Additional Information – Volume 3, Chapter 2.2.1.2.1 (Scenario Analysis), 4th Set (U.S. Department of Energy’s Safety Analysis Report Section 2.2.1.2) – Submittal of Department of Energy Reference Citations”

[b] Provided as an enclosure to letter from Williams to Sulima dtd 03/03/2009. “Yucca Mountain – Request for Additional Information Re: License Application, Safety Evaluation Report Volume 3, Chapters 2.2.1.2.1, Second Set – Submittal of U.S. Department of Energy Reference Citations.”

RAI Volume 3, Chapter 2.2.1.2.1, Fifth Set, Number 7:

Clarify how the FEPs associated with criticality were identified. This information is needed to assess compliance with 10 CFR 63.114.

Basis: SAR Section 2.2.1.1.1 describes the process used to identify FEPs. However, SAR Section 2.2.1.4.1.1.1 implies that the Disposal Criticality Analysis Methodology Topical Report (CRWMS M&O, 2003) was the method used to identify criticality related FEPs. The SAR states that the configuration classes cover the criticality related FEPs. This implies that the probability of criticality calculated based on configuration classes will be conservative with respect to the criticality FEPs. SAR Section 2.2.1.4.1.1.1 also states that the configuration classes are grouped according to their corresponding FEPs and that the probability estimates are made for each class, not for each FEP.

1. RESPONSE

The development of a comprehensive list of features, events, and processes (FEPs) potentially relevant to postclosure performance of the Yucca Mountain repository was an iterative process based on site-specific information and design evolution. The process described in SAR Section 2.2.1.1.1 was used to identify all FEPs, including those associated with criticality. A detailed discussion with supporting information that can be used to trace the overall evolution of the FEP identification methodology is provided in *Features, Events, and Processes for the Total System Performance Assessment: Methods* (SNL 2008a, Section 6.1.1) and its supporting references.

Disposal Criticality Analysis Methodology Topical Report (YMP 2003) provides a master scenario list that consists of a standard set of degradation scenarios that must be considered part of the criticality analysis of any waste form disposed of in the repository. The development of degradation scenarios is based on a combination of FEPs that affect the repository and that result in degraded configurations to be evaluated for criticality. As discussed in SAR Section 2.2.1.4.1.1.2.1, design basis configurations were used for the waste forms for both in-package and out-of-package configurations that bound the range of potential critical configurations to facilitate a simplified and bounding event tree sequence analysis to determine which events must occur to achieve criticality. The criticality FEPs link the initiating events that can cause a breach of the waste package with the event tree sequences.

The following discussion summarizes the FEP identification process, and provides specific information regarding criticality FEP identification, and describes how *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003) is used in the FEP screening process.

1.1 CRITICALITY FEP IDENTIFICATION

Scenarios for postclosure nuclear criticality were developed based on the Criticality Workshop on March 18-20, 1997 (CRWMS M&O 1997). At that workshop, experts in nuclear physics and nuclear engineering met with geotechnical experts to identify the areas of concern for criticality.

The workshop identified three physical regions where criticality events should be considered: (l) inside the waste package, (2) in the near-field immediately surrounding the waste package (considered for these analyses to be the emplacement drift), and (3) in the far-field (defined as the host rock surrounding the emplacement drift). This scenario definition process produced a set of degradation scenarios that might occur in the repository and affect the probability of criticality. These scenarios were termed the "Master Scenarios List" (MSL) and were included in Revision 0 of *Disposal Criticality Analysis Methodology Topical Report*, and subsequently accepted by the NRC in *Safety Evaluation Report for Disposal Criticality Analysis Methodology Topical Report, Revision 0* (Reamer 2000).

The approach for developing an initial list of FEPs in support of the total system performance assessment for the license application (TSPA-LA) was documented by Freeze et al. (2001). The criticality FEPs were initially developed using the MSL as the starting basis for those conditions that must occur to achieve criticality. There were twenty-two FEPs from the total system performance assessment for the site recommendation (TSPA-SR) in the Yucca Mountain Project FEPs database (Freeze et al. 2001) identified as criticality-related, two of which were redundant and subsequently deleted (TSPA-SR FEPs 2.1.14.01.00 and 2.2.14.01.00), and one of which (TSPA-SR FEP 2.1.14.14.00) was expanded to address multiple disruptive initiating events (seismic, igneous, and rockfall). For TSPA-SR, this FEP (2.1.14.14.00) only addressed an igneous initiating event.

Based on the deletion and expansion of FEPs as discussed above, an initial criticality FEPs list for TSPA-LA was developed. The initial TSPA-LA criticality FEPs are listed in Table 1.

Table 1. Listing of Initial TSPA-LA Criticality Features, Events, and Processes

FEP Number	FEP Name	FEP Description
2.1.14.02.0A	Criticality in situ, nominal configuration, top breach	The waste package internal structures and the waste form remain intact (nominal configuration). There is a breach near the top of the waste package, which allows water to collect in the waste package. Criticality then occurs in situ.
2.1.14.03.0A	Criticality in situ, WP internal structures degrade faster than waste form, top breach	The waste package internal structures degrade, but not the waste form. There is a breach near the top of the waste package, which allows standing water to collect in the waste package. Significant amounts of the neutron absorber are flushed out the top of the waste package and criticality occurs in situ.
2.1.14.04.0A	Criticality in situ, WP internal structures degrade at same rate as waste form, top breach	The waste package internal structures degrade at the same rate as the waste form. There is a breach near the top of the waste package, which allows water to collect in the waste package. Significant amounts of the neutron absorber are flushed out the top of the waste package. A slurry with insufficient neutron absorbing material forms at the waste package bottom and criticality occurs in situ.
2.1.14.05.0A	Criticality in situ, WP internal structures degrade slower than waste form, top breach	The waste package internal structures degrade slower than waste form. There is a breach near the top of the waste package, which allows water to collect in the waste package. The waste form degrades, separating from the neutron absorbers. A slurry forms at the waste package bottom and criticality occurs in situ.

Table 1. Listing of Initial TSPA-LA Criticality Features, Events, and Processes (Continued)

FEP Number	FEP Name	FEP Description
2.1.14.06.0A	Criticality in situ, waste form degrades in place and swells, top breach	The waste package internal structures remain intact while the waste form degrades. There is a breach near the top of the waste package, which allows water to collect in the waste package. The waste form degrades in place, but swells into a more reactive configuration, which may overwhelm the in-place neutron absorbing material. Criticality occurs in situ.
2.1.14.07.0A	Criticality in situ, bottom breach allows flow through WP, fissile material collects at bottom of WP	There is a breach at the bottom of the waste package, which does not allow water to collect in the waste package. Moderation is provided by water retained in clay or hydrated metal corrosion products accumulating in the bottom of the waste package with the fissile material. Significant amounts of the neutron absorber are either flushed from the waste package or remain distributed throughout the waste package, while fissile material collects at bottom of the waste package. Criticality occurs in situ.
2.1.14.08.0A	Criticality in situ, bottom breach allows flow through WP, waste form degrades in place	There is a breach at the bottom of the waste package, which does not allow water to collect in the waste package. Moderation is provided by water trapped in the clay or oxides. The waste form degrades in place and the neutron absorbing material mobilizes away from the waste form. Criticality occurs in situ.
2.1.14.09.0A	Near-field criticality, fissile material deposited in near-field pond	Fissile material-bearing solution or intact fissile material is deposited in a near-field pond. Fissile material may migrate due to bottom-only breach of cask or due to massive structural failure of waste package. Near-field criticality can result if fissile material geometry represents critical configuration and sufficient water is present in pond.
2.1.14.10.0A	Near-field criticality, fissile solution flows into drift low point	Near-field criticality results when fissile material-bearing solution flows into a drift low point. The poison has already been separated from the solution carrying the fissile material, either due to retention in intact components within the waste package or prior removal by flow-through leaching within the waste package.
2.1.14.11.0A	Near-field criticality, fissile solution is adsorbed or reduced in invert	Near-field criticality results from fissile solution adsorbed or reduced in invert (concrete and crushed tuff). The geometry of the invert allows zonal precipitation (under the influence of gravity) wherein the fissile and non fissile species may precipitate at different places within the invert.
2.1.14.12.0A	Near-field criticality, filtered slurry or colloidal stream collects on invert surface	Near-field criticality results when slurry or colloidal stream is filtered (i.e., neutron absorbers are removed) by waste package corrosion products and collect on top of invert surface.
2.1.14.13.0A	Near-field criticality associated with colloidal deposits	Near-field criticality could result from colloids deposited in fractured or degraded concrete, from colloids filtered in the invert, or from colloids deposited in dead-ends of stress-relief cracks in the surrounding tunnel.

Table 1. Listing of Initial TSPA-LA Criticality Features, Events, and Processes (Continued)

FEP Number	FEP Name	FEP Description
2.1.14.14.0A	Criticality resulting from disruptive events	Nuclear criticality refers to a self-sustaining fission chain reaction that requires sufficient concentration and localized (critical) mass of isotopes (e.g., U-235, Pu-239). This can include thermal criticality, which requires the additional presence of neutron-moderating materials (e.g., water) in a suitable geometry. Fast criticality can occur without moderator, but generally requires a much larger critical mass than thermal criticality. The repository will house a variety of nuclear waste types and configurations (e.g., CSNF and DSNF). A disruptive event such as seismic ground motion, rockfall, or igneous intrusion could lead to damaged packages and allow water (a moderator) to enter the packages. They could also lead to destruction of the internal configuration of the packages; release and distribution of the waste exterior to package; or in the case of an igneous intrusion drastically change the chemical environment and/or mix with the waste. Thereby, disruptive events could be a criticality initiating event.
2.2.14.02.0A	Far-field criticality, precipitation in organic reducing zone in or near water table	Fissile material is transported to an organic reducing zone and precipitates in a geometrically favorable configuration in or near water table.
2.2.14.03.0A	Far-field criticality, sorption on clay/zeolite in TSbv	Fissile material is transported to Topopah Spring unit where it sorbs onto the clays and zeolites of the basal vitrophyre in a geometrically favorable configuration.
2.2.14.04.0A	Far-field criticality, precipitation caused by hydrothermal upwell or redox front in the saturated zone	Fissile material is transported to the saturated zone where it encounters hydrothermal upwelling or a redox front and precipitates in a geometrically favorable configuration in the saturated zone.
2.2.14.05.0A	Far-field criticality, precipitation in perched water above TSbv	Fissile material is transported to the perched water above the Topopah Spring basal vitrophyre, where chemical change causes it to precipitate in a geometrically favorable configuration.
2.2.14.06.0A	Far-field criticality, precipitation in fractures of TSw rock	Fissile material is transported to Topopah Spring welded unit where it precipitates in a geometrically favorable configuration within the fractures.
2.2.14.07.0A	Far-field criticality, dryout produces fissile salt in a perched water basin	Fissile material is transported to a perched water basin. Dryout (evaporation exceeds infiltration) of the basin and the solution containing fissile material results in a fissile salt in a geometrically favorable configuration in the basin.
2.2.14.08.0A	Far-field criticality associated with colloidal deposits	Far-field criticality could result from colloids deposited in clays/zeolites in TSbv or deposited in perched water above the relatively impermeable TSbv.

NOTES: FEP names and descriptions presented verbatim.

CSNF = commercial spent nuclear fuel; DSNF = DOE spent nuclear fuel; WP = waste package; TSbv = Topopah Spring basal vitrophyre; TSw = Topopah Spring welded.

Prior to their documentation in the licensing basis, the initial criticality FEPs for TSPA-LA were updated to improve clarity and transparency. Because the potential for criticality at a minimum requires a breach of the waste package, the event scenarios for criticality were modified from the four scenario classes identified in SAR Section 2.2.1.3.1 (i.e., nominal, early-failure, seismic, and igneous). As discussed in SAR Section 2.2.1.4.1, the criticality event scenarios focus on initiating events that either result in, or provide conditions (e.g., loss of function of drip shield) that can result in, a breach of the waste package over the first 10,000 years after repository closure. Therefore, the criticality event scenarios are nominal/early-failure, igneous, seismic, and rockfall. The nominal scenario class was combined with the early-failure scenario class because both reflect nominal repository conditions in the absence of other initiating events. Igneous and seismic scenario classes were retained, as these are disruptive events that can have the most influence on the repository. Rockfall is screened from consideration for the performance assessment on the basis of low consequence and continued functionality of the drip shield (SNL 2008b, FEP 2.1.07.01.0A). However, the potential for rockfall to initiate criticality is considered explicitly with the criticality initiating events for evaluation in case of maximum drip shield deflection resulting in contact with and subsequent breach of the waste package outer barrier.

To facilitate the screening analysis, the criticality FEPs classification was organized to connect initiating events with specific locations of concern for criticality (in-package, near-field, or far-field). This classification scheme is consistent with the review criteria provided in *Yucca Mountain Review Plan, Final Report* (NRC 2003, Section 2.2.1.2.2, Review Method (1): "Confirm that criticality events, for the purpose of the initial screening of the features, events, and processes list, are calculated separately, only by location of the criticality event (e.g., in-package, near-field, and far-field)." As the canister components degrade and reconfigure, different states for different waste forms represent the most reactive credible condition. Some waste forms are more reactive when the canister internal components are degraded, but the waste form remains intact, and some waste forms are more reactive when both the waste form and internal components have degraded. Therefore, the in-package location was delineated into separate FEPs for both intact and degraded configurations, resulting in a total of 16 criticality FEPs. Table 2 presents the revised list of 16 criticality FEPs for TSPA-LA that resulted from the reclassification.

The "Internal to the Waste Package" degraded configuration FEPs encompass the configuration classes identified in Figures 3-2a and 3-2b of *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003). Figure 3-2a defines in-package bathtub configuration classes (hole at top of waste package and waste package flooded). Figure 3-2b defines in-package flow-through configuration classes (hole at top and bottom of waste package and water flowing through and over waste package internals and waste form).

The "External to the Waste Package" near-field configuration FEPs encompass the degraded configuration classes identified in Figure 3-3a of *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003), and the far-field configuration FEPs encompass the configuration classes of Figure 3-3b. The near-field environment is defined as external to the waste package and inside the drift wall (including any drift liner and the invert). The far-field environment is defined as the area beyond the drift wall (i.e., in the host rock of the repository). Because the revised list (Table 2) of 16 criticality FEPs and the initial list of 20 criticality FEPs (see Table 1) were derived from the scenarios identified in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Figures 3.2a, 3.2b, 3.3a, and 3.3b), the revised list (Table 2) completely replaced and superseded the initial list (Table 1). Table 2 also provides a cross-reference to confirm that all of the initial criticality FEPs have been incorporated into the revised list of criticality FEPs for the TSPA-LA.

Table 2. Listing of Revised TSPA-LA Criticality Features, Events, and Processes

FEP Number	FEP Name	FEP Description	Cross-Reference to Initial LA FEP List
FEPs Associated with Nominal (Early Failure) Event Sequence Initiators			
2.1.14.15.0A	In-package criticality (intact configuration)	The waste package internal structures and the waste form remain intact. If there is a breach (or are breaches) in the waste package that allows water to either accumulate or flow-through the waste package, then criticality could occur in-situ.	2.1.14.02.0A
2.1.14.16.0A	In-package criticality (degraded configurations)	The waste package internal structures and the waste form may degrade. If a critical configuration (sufficient fissile material, and neutron moderator, lack of neutron absorbers) develops, a criticality event could occur in-situ. Potential in-situ critical configurations are defined in Figures 3.2a and 3.2b of *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003).	2.1.14.03.0A 2.1.14.04.0A 2.1.14.05.0A 2.1.14.06.0A 2.1.14.07.0A 2.1.14.08.0A
2.1.14.17.0A	Near-field criticality	Near-field criticality could occur if a fissile material-bearing solution from the waste package is transported into the drift and the fissile material is precipitated into a critical configuration. Potential near-field critical configurations are defined in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Figure 3-3a).	2.1.14.09.0A 2.1.14.10.0A 2.1.14.11.0A 2.1.14.12.0A 2.1.14.13.0A
2.2.14.09.0A	Far-field criticality	Far-field criticality could occur if a fissile material-bearing solution from the waste package is transported beyond the drift and the fissile material is precipitated into a critical configuration. Potential far-field critical configurations are defined in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Figure 3-3b).	2.2.14.02.0A 2.2.14.03.0A 2.2.14.04.0A 2.2.14.05.0A 2.2.14.06.0A 2.2.14.07.0A 2.2.14.08.0A

Table 2. Listing of Revised TSPA-LA Criticality Features, Events, and Processes (continued)

FEP Number	FEP Name	FEP Description	Cross-Reference to Initial LA FEP List
FEPs Associated with Seismic Event Sequence Initiators			
2.1.14.18.0A	In-package criticality resulting from a seismic event (intact configuration)	The waste package internal structures and the waste form remain intact either during or after a seismic disruptive event. If there is a breach (or are breaches) in the waste package that allow(s) water to either accumulate or flow-through the waste package, then criticality could occur in-situ.	2.1.14.14.0A
2.1.14.19.0A	In-package criticality resulting from a seismic event (degraded configurations)	Either during or as a result of a seismic disruptive event, the waste package internal structures and the waste form may degrade. If a critical configuration develops, criticality could occur in-situ. Potential in-situ critical configurations are defined in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Figures 3-2a and 3-2b).	
2.1.14.20.0A	Near-field criticality resulting from a seismic event	Either during or as a result of a seismic disruptive event, near-field criticality could occur if fissile material-bearing solution from the waste package is transported into the drift and the fissile material is precipitated into a critical configuration. Potential near-field critical configurations are defined in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Figure 3-3a).	
2.2.14.10.0A	Far-field criticality resulting from a seismic event	Either during, or as a result of, a seismic disruptive event, far-field criticality could occur if fissile material-bearing solution from the waste package is transported beyond the drift and the fissile material is precipitated into a critical configuration. Potential far-field critical configurations are defined in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Figure 3-3b).	

Table 2. Listing of Revised TSPA-LA Criticality Features, Events, and Processes (continued)

FEP Number	FEP Name	FEP Description	Cross-Reference to Initial LA FEP List
FEPs Associated with Rockfall Event Sequence Initiators			
2.1.14.21.0A	In-package criticality resulting from rockfall (intact configuration)	The waste package internal structures and the waste form remain intact either during or after a rockfall event. If there is a breach (or are breaches) in the waste package that allow(s) water to either accumulate or flow-through the waste package then criticality could occur in situ.	2.1.14.14.0A
2.1.14.22.0A	In-package criticality resulting from rockfall (degraded configurations)	Either during or as a result of a rockfall event, the waste package internal structures and the waste form may degrade. If a critical configuration develops, criticality could occur in-situ. Potential in-situ critical configurations are defined in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Figures 3-2a and 3-2b).	
2.1.14.23.0A	Near-field criticality resulting from rockfall	Either during or as a result of a rockfall event, near-field criticality could occur if fissile material-bearing solution from the waste package is transported into the drift and the fissile material is precipitated into a critical configuration. Potential near-field critical configurations are defined in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Figure 3-3a).	
2.2.14.11.0A	Far-field criticality resulting from rockfall	Either during or as a result of a rockfall event, far-field criticality could occur if fissile material-bearing solution from the waste package is transported beyond the drift and the fissile material is precipitated into a critical configuration. Potential far-field critical configurations are defined in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Figure 3-3b).	
FEPs Associated with Igneous Event Sequence Initiators			
2.1.14.24.0A	In-package criticality resulting from an igneous event (intact configuration)	The waste package internal structures and the waste form remain intact either during or after an igneous disruptive event. If there is a breach (or are breaches) in the waste package that allow(s) water to either accumulate or flow-through the waste package then criticality could occur in-situ.	2.1.14.14.0A
2.1.14.25.0A	In-package criticality resulting from an igneous event (degraded configurations)	Either during or as a result of an igneous disruptive event, the waste package internal structures and the waste form may degrade. If a critical configuration develops, criticality could occur in-situ. Potential in-situ critical configurations are defined in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Figures 3-2a and 3-2b).	

Table 2. Listing of Revised TSPA-LA Criticality Features, Events, and Processes (continued)

FEP Number	FEP Name	FEP Description	Cross-Reference to Initial LA FEP List
2.1.14.26.0A	Near-field criticality resulting from an igneous event	Either during or as a result of an igneous disruptive event, near-field criticality could occur if fissile material-bearing solution from the waste package is transported into the drift and the fissile material is precipitated into a critical configuration. Potential near-field critical configurations are defined in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Figure 3-3a).	
2.2.14.12.0A	Far-field criticality resulting from an igneous event	Either during or as a result of an igneous disruptive event, far-field criticality could occur if fissile material-bearing solution from the waste package is transported beyond the drift and the fissile material is precipitated into a critical configuration. Potential far-field critical configurations are defined in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Figure 3-3b).	

NOTE: FEP names and descriptions from SNL 2008b.

1.2 CRITICALITY FEP PROBABILITY EVALUATION

A configuration is defined by a set of parameters characterizing the amount and physical arrangement of the materials that have a significant effect on criticality (e.g., fissionable materials, neutron absorbing materials, reflecting materials, and moderators) at a specific location. A configuration class is a set of similar configurations whose composition and geometry is defined by specific parameters that distinguish one class from another (e.g., physical location, waste form). The MSL from *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003) is used for developing these configuration classes. Design basis configurations have been developed with respect to the MSL to bound the relevant variations in materials, geometry, and neutron spectrum that occur as the waste packages and internals change over long periods of time. This results in each configuration class being bounded by a single, most reactive configuration (i.e., design basis) for that waste form for each location (i.e., in-package, near-field, or far-field). Each criticality FEP represents a potential repository future with an end-state(s) resulting in conditions able to support criticality, but does not necessarily mean that criticality can or does occur. Only configuration classes that can actually achieve criticality require a probability evaluation. Therefore, since the design basis configuration is used, the calculation of the probability of criticality for the configuration class is conservative for the criticality FEP, as the calculation depends on the series of events occurring which can result in formation of that configuration. This methodology is consistent with *Safety Evaluation Report for Disposal Criticality Analysis Methodology Topical Report, Revision 0* (Reamer 2000): "The NRC staff found that grouping sets of similar configurations into configuration classes is a reasonable way to reduce the calculational burden but still provide reasonable assurance that the probability of criticality will not be significantly underestimated."

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) 1997. *Criticality Abstraction/Testing Workshop Results*. B00000000-01717-2200-00187. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980528.0040.

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Reamer, C.W. 2000. "Safety Evaluation Report for Disposal Criticality Analysis Methodology Topical Report, Revision 0." Letter from C.W. Reamer (NRC) to S.J. Brocoum (DOE/YMSCO), June 26, 2000, with enclosure. ACC: MOL.20000919.0157.

NRC (U.S. Nuclear Regulatory Commission) 2003. *Yucca Mountain Review Plan, Final Report*. NUREG-1804, Rev. 2. Washington, D.C.: U.S. Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguards.

SNL (Sandia National Laboratories) 2008a. *Features, Events, and Processes for the Total System Performance Assessment: Method*s. ANL-WIS-MD-000026 REV 00. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20080211.0010.

SNL 2008b. *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; DOC.20080407.0009; LLR.20080522.0166; DOC.20080722.0002.

YMP (Yucca Mountain Site Characterization Project) 2003. *Disposal Criticality Analysis Methodology Topical Report*. YMP/TR-004Q, Rev. 02. Las Vegas, Nevada: Yucca Mountain Site Characterization Office. ACC: DOC.20031110.0005.

RAI Volume 3, Chapter 2.2.1.2.1, Fifth Set, Number 8:

> Justify performance of neutron absorber shot used in DOE5 and DOE8 waste forms calculations and its impact on the calculation of the probability of criticality. This information is needed to assess compliance with 10 CFR 63.114.
>
> Basis: SNL (2008a) states that the fuel types other than DOE1, 2, and 7, do not rely on neutron absorber plates for criticality control. SNL (2008b) states, however, that absorber material for the DOE5 and DOE8 SNF waste forms consists of a combination of both plates and shot and, thus, the absorber misload probability is considered insignificant. No justification was provided for the shot performance in presence of water flow during first 10,000 years of postclosure period. The arguments did not address the number of DOE5 and DOE8 CDSP waste packages in the screening calculation in SNL (2008a).

1. RESPONSE

For the DOE spent nuclear fuel (SNF) postclosure criticality analysis, the intact flooded canisters are subcritical even without the neutron absorber. The shot containing gadolinium is used as a mechanism to install a measurable quantity of gadolinium needed for postulated, degraded conditions. Poisoned beads (i.e., shot) contribute to criticality safety by displacing moderator and by inserting poison in a form that can move with fuel debris as the canister and waste package degrade. Although the exact shot material has not been fully specified at this time, it will be either an iron- or aluminum-based shot with a gadolinium neutron absorber. Due to its high corrosion resistance, $GdPO_4$ represents the most likely material to be integrated with the shot. The $GdPO_4$ is insoluble based on experimental studies and manufacturer's data (BSC 2004, Section 6.3.3). In addition, natural analogue data for monazite (lanthanide phosphate) indicates solubility rates comparable to quartz, since both quartz and monazite have been found to accumulate in beach sands due to weathering of host rocks containing more soluble minerals. Baseline analysis configurations for the nine DOE fuel groups demonstrate that k_{eff} below the critical limit is realized under the most reactive credible configurations. Final loading configurations (i.e., fuel quantity, basket, and poison form) for each DOE SNF will be specified prior to packaging for repository acceptance.

The shot's ability to perform its intended functions in the presence of water flow (i.e., displace moderator and distribute poison) is not sensitive to the shot material's corrosion performance. Shot materials under consideration would increase in volume as they corrode, and the remaining corrosion products are insoluble. Thus, the gadolinium neutron absorber will remain in close proximity to the SNF and perform as intended, independent of the shot corrosion performance over the first 10,000 years of the postclosure period.

As described in SAR Section 5.10.2.4.2 and Table 5.10-3, the specific constraints on loading operations will be compiled in a *Technical Requirements Manual* and controlled by DOE in accordance with the requirements of the license specifications. The *Technical Requirements Manual* will contain information necessary to support and implement programs listed in the administrative controls section of the license specifications that are unique to the geologic repository, such as the Waste Form and Waste Package Qualification Program and the Waste Package Loading, Handling, and Emplacement Program, including controls needed to ensure reliability of manufacturing, procedural compliance, documentation, and inspection. These programs will delineate the waste receipt inspection and verification at the repository to confirm that the incoming waste form meets the waste acceptance criteria for criticality safety. SAR Section 2.2.1.4.1 presents the methodology and analyses required to confirm that waste forms are acceptable from a postclosure criticality perspective. The administrative controls described in SAR Section 5.10.2 and SAR Table 5.10-3 require that similar analyses be completed prior to receiving individual waste forms, or waste package design configurations that are not explicitly analyzed in the license application.

1.1 SHOT PERFORMANCE

The corrosion performance of shot material and evaluations of gadolinium retention under different water flow scenarios have been evaluated in *Geochemistry Model Validation Report: Material Degradation and Release Model* (SNL 2007), in *EQ6 Calculation for Chemical Degradation of Enrico Fermi Codisposal Waste Packages: Effects of Updated Design and Rates* (BSC 2001), and in *EQ6 Calculation for Chemical Degradation of Shippingport LWBR (Th/U Oxide) Spent Nuclear Fuel Waste Packages* (CRWMS M&O 2000). A recent evaluation of the performance of the aluminum-gadolinium shot was documented in *Geochemistry Model Validation Report: Material Degradation and Release Model* (SNL 2007) with the Fast Flux Test Facility (FFTF) (identified as DOE1) waste form. Both Light Water Breeder Reactor (LWBR) and FFTF waste packages consist of a DOE standardized canister loaded with DOE SNF, five defense high-level waste glass canisters, a carbon steel waste package basket, stainless steel inner barrier, and nickel alloy outer barrier. Within the DOE SNF canister, both SNF compositions are oxides (uranium/plutonium oxide for FFTF and thorium/uranium oxide for LWBR) and all the basket and cladding materials within these DOE canisters are stainless steel and corrosion resistant nickel- or zirconium-based alloys. Therefore, due to the similarity of the contents of waste packages containing LWBR (identified as DOE5) and FFTF SNF, the chemistry of the aqueous solutions within the waste packages during degradation would produce geochemical environments resulting in similar performance of the aluminum-gadolinium shot. In *Geochemistry Model Validation Report: Material Degradation and Release Model* (SNL 2007), degradation calculations with waste packages containing FFTF SNF show that >99% of the gadolinium is retained within the waste package (SNL 2007, Figure F-2) after 10,000 years of seepage infiltration. Results show that after about 600 years of seepage exposure, the aluminum-gadolinium shot has fully degraded and the gadolinium from the shot has precipitated into gadolinium phosphate ($GdPO_4{:}xH_2O$) and gadolinium carbonate ($Gd(CO_3)_3$) minerals (SNL 2007, Figures E-12 and E-13).

For waste packages loaded with Enrico Fermi (identified as DOE8) SNF, degradation calculations were performed using a mixture of iron shot and $GdPO_4$ shot for criticality control, rather than aluminum gadolinium shot in *EQ6 Calculation for Chemical Degradation of Enrico Fermi Codisposal Waste Packages: Effects of Updated Design and Rates* (BSC 2001). Rather than using a zero dissolution rate for $GdPO_4$ as recommended in *Aqueous Corrosion Rates for Waste Package Materials* (BSC 2004, Section 6.3.3), a higher dissolution rate, equivalent to the quartz dissolution rate, was used in a series of calculations varying seepage rates, steel and alloy degradation rates, and waste form degradation rates. The retention of gadolinium in the waste package was greater than 97% in all cases after 250,000 years (BSC 2001, Table 10) of seepage exposure.

1.2 PERFORMANCE AFTER RECONFIGURATION

A set of sensitivity evaluations was performed representing various degraded internal component and waste form configurations to identify the most reactive configurations. A summary of the various configurations analyzed (Radulescu et al. 2004, Sections 10.4 and 10.5) shows that the most reactive configuration for the DOE5 and DOE8 fuels occurs when the fuel rods are intact and reconfigured with radial expansion in pitch. This is the bounding configuration used to set the amount of gadolinium required to maintain k_{eff} below the k_{eff} design limit. The physical and chemical processes required for this geometric configuration to form are associated with the shot and absorber corrosion products expanding to force the fuel rods apart, which can occur only if shot corrosion product and $GdPO_4$ remains distributed within the interstices of the fuel rods.

1.3 INCLUSION OF DOE5 AND DOE8 PACKAGES IN SCREENING CALCULATION

The codisposal waste package for DOE5 and DOE8 SNF consists of a single DOE 18-in. outer diameter standardized canister per package. Therefore, numbers of DOE5 and DOE8 canisters, as well as codisposal waste packages, are 53 and 18, respectively, as listed in SAR Table 2.2-12. Although *Screening Analysis of Criticality Features, Events, and Processes for License Application* (SNL 2008) indicates that a combination of absorber plate and shot would be used, the specific packaging strategies have not been finalized. The most reactive configurations for DOE5 and DOE8 fuel do not credit any neutron absorber in the plates, and rely on the shot absorber for criticality control. The rationale for the DOE5 and DOE8 canisters not being considered with the number of DOE SNF waste packages that could have neutron absorber misload is because the absorber will be added to the system using a shot carrier. In addition to the standard quality checks, a number of redundant and independent processes, involving confirmation of the shot material and loading, are expected to be available, making the absorber shot misload probability insignificant (i.e., reduce human error rates: e.g., single facility loading of canisters, low total number of canisters requiring shot, processes regarding hot cell operations, and a weight measurement that would readily detect errors (i.e., shot not loaded)).

If credit were not taken for the redundant and independent processes discussed above, the impact of including the neutron absorber shot loading error (analogous with neutron absorber plate loading error) in the probability of criticality calculations could be conservatively estimated by using the information provided in *Screening Analysis of Criticality Features, Events, and Processes for License Application* (SNL 2008, Section 6) and following the same methodology. The total number of waste packages would be 214 (71 DOE5 and DOE8 waste packages and 143 DOE1 waste packages). DOE1 fuel uses both shot and plate absorber for criticality control; therefore the DOE1 waste packages would also need to be included in the absorber shot error probability evaluations. Inclusion of shot absorber misload in the probability evaluations would result in an increase to the total probability of criticality for the commercial SNF and DOE SNF waste forms from 3.7×10^{-5} to 4.4×10^{-5} over the initial 10,000 years after waste disposal. Note that the probability calculation was already conservative as the damage probability for the codisposal waste package is based on a bounding value for residual stress threshold (RST) versus a distribution range for RST as discussed in SAR Section 2.2.1.4.1.3.2.2, resulting in a factor of 3 greater probability of damage for the codisposal waste package. Inclusion of the RST distribution in addition to the number of waste packages containing shot to the probability calculation would result in a net decrease to the total probability of criticality. Therefore the probability increase from conservatively neglecting the redundant and independent checks associated with loading shot, is subsumed by the conservatism already present in the probability calculation from using the bounding RST value, and would not change the conclusion that the criticality event class can be screened from inclusion in the performance assessment on the basis of low probability.

2. COMMITMENTS TO NRC

None.

3. DESCRIPTION OF PROPOSED LA CHANGE

None.

4. REFERENCES

BSC (Bechtel SAIC Company) 2001. *EQ6 Calculation for Chemical Degradation of Enrico Fermi Codisposal Waste Packages: Effects of Updated Design and Rates.* CAL-EDC-MD-000015 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20020102.0190.

BSC 2004. *Aqueous Corrosion Rates for Waste Package Materials.* ANL-DSD-MD-000001 REV 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20041012.0003.

CRWMS (Civilian Radioactive Waste Management System) M&O (Management and Operating Contractor) 2000. *EQ6 Calculation for Chemical Degradation of Shippingport LWBR (Th/U Oxide) Spent Nuclear Fuel Waste Packages.* CAL-EDC-MD-000008 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000926.0295.

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RAI Volume 3, Chapter 2.2.1.2.1, Fifth Set, Number 1:

10 CFR Part 63 (NRC, 2009) was recently codified. Address compliance with the updates to the Final Rule requirements. In particular:

1. Demonstrate that the information available in the safety analysis report (SAR) is in conformance with the final rule, or provide the information necessary to demonstrate compliance based on the arithmetic mean of the projected doses from the performance assessment evaluation during the period within 1 million years after disposal (10 CFR 63.303).

2. Address compliance with the water table rise requirement due to seismic activity beyond the 10,000-year post-disposal period through the period of geologic stability [10 CFR 63.342(c)(1)(i)].

3. Address the impact of changes to the range of deep percolation rates to assess the effects of climate change [10 CFR 63.342(c)(2)] on compliance with the postclosure performance objectives (10 CFR 63.113).

Basis:

1. Most of the dose estimates reported in the SAR show confidence bands including median and mean doses. Clarification is needed on whether the safety analysis report conforms with10 CFR 63.303 regarding the use of the arithmetic mean of projected doses beyond 10,000 years.

2. The applicant addressed water table rise as part of the screening argument for FEP 1.2.10.01.0A Hydrological Response to Seismic Activity (SNL, 2008). However, the FEP screening argument (SNL, 2008) focused on the first 10,000 years, while 10 CFR 63.342(c)(1)(i) requires consideration of water table rise past 10,000 years.

3. 10 CFR 63.342 (c)(2) (NRC, 2009) requires consideration of deep percolation rates to assess the effects of climate change based on a lognormal distribution with arithmetic mean of 41 mm/yr and a standard deviation of 33 mm/yr, but truncated to range from 10 to 100 mm/yr. The effects of these changes on the performance assessment results and the demonstration of compliance with postclosure performance objectives (10 CFR 63.113) have not been addressed.

1. RESPONSE

DOE has performed a detailed comparison between the proposed 10 CFR Part 63 published for comment on September 8, 2005, and the final 10 CFR Part 63 that became effective on April 13, 2009, and has identified material changes in the final rule and how those changes may materially impact the license application (LA). DOE has evaluated the potential impacts of all material changes and concluded that none of the conclusions in the LA require modification as a result of the new rule. The following discussion provides more information regarding the three specific areas addressed in the NRC's RAI and additional areas of the LA that were reviewed for impact.

1.1. POST-10,000-YEAR COMPLIANCE STANDARD – 350 MREM VS. 100 MREM

The final rule specifies that DOE must demonstrate, using performance assessment, that there is a reasonable expectation that the reasonably maximally exposed individual (RMEI) receives an annual dose of no more than 1.0 mSv (100 mrem) after 10,000 years, but within the period of geologic stability, at 10 CFR 63.311. In the proposed rule, this dose limit was 3.5 mSv (350 mrem). This change will have no impact on the conclusions presented in SAR Section 2.4, because the means of the projected doses from DOE performance assessments are well below 100 mrem.

1.2. ARITHMETIC MEAN OF PROJECTED DOSES

The proposed rule specified, at 63.303, that DOE must demonstrate compliance "based upon the median of the projected doses from DOE's performance assessment for the period after 10,000 years of disposal and through the period of geologic stability." The final rule changes this requirement to "compliance is based on the arithmetic mean of the projected doses from DOE's performance assessments for the period within 1 million years after disposal."

SAR Section 2.4.2.1.2 provides the methodology for computing the mean annual dose. The total system performance assessment (TSPA) model computes mean annual dose by integrating over both aleatory and epistemic uncertainty (SAR Section 2.4.2.1.2). A variety of statistical measures are derived from the results of the TSPA model calculations, including the mean, median, and the 5th and 95th percentile curves. SAR Section 2.4 discusses compliance, for the period after 10,000 years, in terms of the median of the projected doses. However, the figures in SAR Section 2.4 that display results for the period after 10,000 years include the arithmetic mean of the projected doses.

SAR Figure 2.4-10(b) shows the distribution of total expected annual dose, combining all modeling cases, for 1,000,000 years after repository closure. Note that the value of the Individual Protection Standard shown on SAR Figure 2.4-10(b) is from the proposed rule (350 mrem), not the final rule (100 mrem). The red curve on this figure is the arithmetic mean specified at 10 CFR 63.303. The peak value of the mean occurs at 1,000,000 years and the peak value is 2.0 mrem (SNL 2008a, Table 8.1-1[a]).

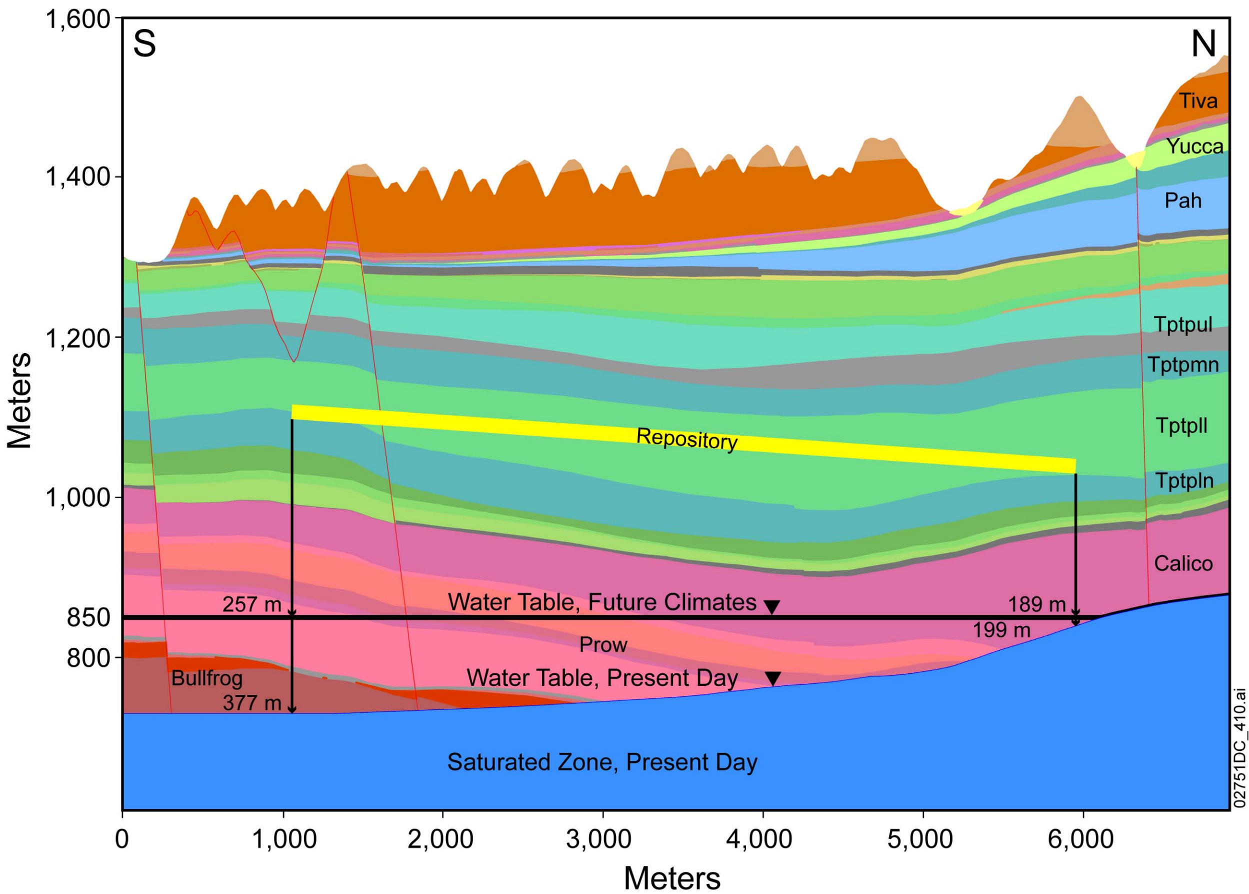
SAR Figure 2.4-11 shows the distribution of expected annual dose for the human intrusion modeling case. The value of the Human Intrusion Standard shown on SAR Figure 2.4-11 is also from the proposed rule (350 mrem). The red curve on this figure is the arithmetic mean specified at 10 CFR 63.303. The peak value of the mean occurs within a few thousand years after the intrusion and the peak value is 0.013 mrem (SNL 2008a, Section 8.1.3.2[a]).

1.3. WATER TABLE RISE DUE TO SEISMIC ACTIVITY

The screening justification for excluded feature, event, and process (FEP) 1.2.10.01.0A, Hydrologic Response to Seismic Activity, addresses effects on water table elevation and groundwater geochemistry from seismic activity (SNL 2008b). The discussion focuses on the first 10,000 years after closure of the repository, consistent with 10 CFR 63.342. However, information presented in the response to RAI 3.2.2.1.2.1-2-019, including the response to supplemental question 6, is used to update the screening justification for excluding the FEP so it is also applicable to the 1,000,000-year time frame addressed by the final 10 CFR Part 63 rule.

The direct effects of seismic activity on the water table are transient and of low consequence considering the height of the repository above the water table. Direct effects include the dynamic stress changes associated with vibratory ground motion and static changes in the stress state of the rock resulting from the dynamic fault rupture and permanent fault displacement of the fault on which the earthquake occurred. *Features, Events, and Processes for the Total System Performance Assessment: Analyses* (SNL 2008b) concludes that the maximum projected water table rise due to seismic activity is no more than 50 m. This result was based on work by the National Research Council (1992), whose report discusses several different analyses of earthquake-induced water table rise. The analysis that produced the greatest effect was based on a poroelastic response to a static stress change resulting from movement on a normal fault. The National Research Council considered reasonably conservative parameter values (e.g., static stress drop of 100 bars) and took into account the sensitivity of model results to parameter variation. They concluded that, for the 10,000 years after closure of the repository, earthquake-induced water table rise was unlikely to exceed 50 m.

The results of the National Research Council investigation were extrapolated by estimating the combined effect on water table rise of changes, as a function of moment magnitude, in the point-source stress drop with an annual probability of exceedance of 10^{-8} and vertical extent of faulting (see response to RAI 3.2.2.1.2.1-2-019, supplemental question 6). For an earthquake with a moment magnitude of 6.75, the associated static stress drop is 155 bars and the estimated water table rise is 115 m. This is still significantly less than the minimum distance (190 m) between the repository horizon and the present-day water table. Under future climate conditions, for which the water table may rise as high as a constant elevation of 850 m, the minimum distance between the repository horizon and the water table remains at approximately 190 m (Figure 1; see response to RAI 3.2.2.1.2.1-2-019, supplemental question 9). Furthermore, the earthquake-induced water table rise is expected to be transient (National Research Council 1992, p. 115; Neuzil 2003, p. 59). The assessment of the static stress drop with a 10^{-8} mean annual probability of exceedance is not dependent on the 10,000-year time period after closure because the assessment is process based and the processes are expected to continue throughout the 1,000,000-year time frame. The screening justification for FEP 1.2.10.01.0A (Hydrologic Response to Seismic Activity) is equally applicable to 10,000 years or 1,000,000 years.



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 that 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

Effects of seismic activity that could lead to permanent changes in hydrologic properties are evaluated in the screening justifications for excluded FEPs 2.2.06.01.0A (Seismic Activity Changes Porosity and Permeability of Rock), 2.2.06.02.0A (Seismic Activity Changes Porosity and Permeability of Faults), and 2.2.06.02.0B (Seismic Activity Changes Porosity and Permeability of Fractures) (SNL 2008b). These evaluations are also based on earthquake effects with mean annual-exceedance probabilities of 10^{-8}. For instance, changes in fracture aperture, which could result from seismic activity, are evaluated in Appendix I of *Features, Events, and Processes for the Total System Performance Assessment: Analyses* (SNL 2008b). Appendix I reports the results of a sensitivity analysis conducted to evaluate the potential for changes to the hydrogeologic system caused by fault displacement. The parameter values used in the sensitivity analysis were determined by using changes resulting from fault displacements near Yucca Mountain that have a mean annual exceedance probability of 10^{-8}. On this basis, the arguments presented in the screening justifications for excluding these FEPs (SNL 2008b, pp. 6-897 to 6-913) are equally applicable to the 10,000-year or the 1,000,000-year timeframe.

1.4. CHANGES TO THE RANGE OF DEEP PERCOLATION RATES

In its final rule, NRC specifies that the DOE may represent the effects of climate change after 10,000 years after disposal by means of a distribution for deep percolation rates. The constant-in-time deep percolation rates are to be the spatial average of the deep percolation rate within the area bounded by the repository footprint, and shall be based on lognormal distribution with arithmetic mean of 41 mm/yr and a standard deviation of 33 mm/yr, truncated to vary between 10 and 100 mm/yr (10 CFR 63.342(c)(2)). Truncation of the lognormal distribution leads to an arithmetic mean of the truncated distribution of 37 mm/yr. In the LA, DOE represented the effect of climate change after 10,000 years after disposal by means of a log-uniform distribution for deep percolation rates, ranging between 13 and 64 mm/yr, with an arithmetic mean of 32 mm/yr (SAR Section 2.3.2.3.5.1).

Implementation of the new, NRC-specified distribution would require replacing the log-uniform distribution with the truncated lognormal distribution in the TSPA analyses. This change would result in a greater likelihood of larger volumes of water flowing through the unsaturated zone. In particular, mean rates of deep percolation would increase by 16%.

The response to RAI 3.2.2.1.3.6-007 describes the results of a sensitivity study that was conducted to evaluate the effect of the generalized likelihood uncertainty estimate (GLUE) weighting procedure on TSPA results. The analysis is relevant to this RAI response because it has quantified the effect on repository performance of higher probabilities of larger water volume in the unsaturated zone. The analysis compares seepage and percolation rates, mean annual dose to the RMEI for the seismic ground motion and igneous intrusion modeling cases, and total annual dose to the RMEI, for the 10,000-year time frame, resulting from GLUE-weighted and unweighted cases. The analysis illustrates that increasing the repository average percolation rate by at least 80% (as shown in Table 1) results in a relatively small increase (9%) in the contribution to mean annual dose at 10,000 years from the seismic ground motion modeling case, and in a roughly proportional increase (81%) in the contribution to mean annual dose at 10,000 years from the igneous intrusion modeling case. As explained in the response to RAI 3.2.2.1.3.6-007, the minimal effect on the mean annual dose from the seismic ground motion modeling case results from the near absence of advective flux through waste packages, whereas in the igneous intrusion modeling case, the higher likelihood of greater advective flux through waste packages resulted in higher likelihood of greater mobilized masses of radionuclides.

Table 1. Mean Percolation Rates (mm/yr) for Each Climate State Considered in Sensitivity Study of Infiltration Scenario Weighting

Climate State	Mean Percolation Rate (mm/yr)		Increase (%)
	GLUE-Weighted Case	Unweighted Case	
Present-Day	8.6	17.5	104
Monsoon	16.1	38.4	139
Glacial-Transition	21.8	39.5	81

Although the sensitivity study considered only 10,000 years after closure, it is reasonable to extrapolate the conclusions of the sensitivity study beyond 10,000 years. Specifically, the study demonstrates that increasing the mean percolation flux has a minimal effect on contributions to mean annual dose from modeling cases with minimal advective flux through waste packages, and that the contributions to mean annual dose from modeling cases with advective flux through all waste packages are expected to increase in proportion with the increased mean percolation flux.

During the 1,000,000-year period after closure, the total mean annual dose is largely composed of contributions from the igneous intrusion modeling case and the seismic ground motion modeling case (SAR Figure 2.4-18(b)). The seismic ground motion modeling case accounts for the combined effects of seismic ground motions and nominal corrosion processes. In the igneous intrusion modeling case, after an igneous intrusion, all drip shields and waste packages are assumed to be destroyed and the waste is exposed for advective transport. In the seismic ground motion modeling case, seismic events infrequently result in advective flux through waste packages, when either punctures or ruptures occur (SAR Figures 2.1-16 and 2.1-17). In addition, general corrosion processes infrequently result in patch failures on waste packages, which would permit advection through the failed waste packages (SAR Figure 2.1-10). Thus, advection through waste packages is possible in both modeling cases which largely comprise the total mean annual dose, but in the seismic ground motion modeling case, advective transport of radionuclides does not frequently occur.

These observations lead to a bounding estimate of total mean annual dose to the RMEI for the time period from 10,000 years after closure through the period of geologic stability that could result from the distribution for deep percolation flux specified in the final rule. The bounding estimate is obtained by scaling the results reported in SAR Section 2.4 by the increase in the arithmetic mean (16%) of the distribution of deep percolation rates specified by the rule. The estimate is bounding because the scaling factor is derived from the effect of increased likelihood of larger water volumes on the igneous intrusion modeling case where all of the waste is exposed to advective flux. Advection is possible in the seismic ground motion modeling case, but does not frequently occur, so the scaling overestimates the effect on the contribution to total mean annual dose from this modeling case.

Using a scaling approximation, increasing the mean deep percolation rate by 16% could increase the total mean annual dose for 1,000,000 years postclosure by not more than 16%. The estimated maximum of the total mean annual dose for 1,000,000 years postclosure is 2.0 mrem (SNL 2008a, Table 8.1-1[a]). An increase in this quantity of 16% (to 2.32 mrem) is insignificant compared to the difference between the total mean annual dose and the individual protection standard limit of 100 mrem (10 CFR 63.311(2)). Thus, the results of the performance assessment presented in SAR Section 2.4, supplemented by the sensitivity analysis reported in this response, demonstrate compliance with the individual protection standard as updated in the final rule.

1.5. DOSIMETRY

10 CFR 63.102(o) of the final rule adopts the EPA specification of the weighting factors to be used for estimating potential radiation doses for members of the public. With respect to the individual protection standard after permanent closure specified in 10 CFR 63.311, the requirements for calculation of radiation exposure to the RMEI are unchanged in the final rule as compared to the proposed rule. As described in SAR Section 2.4.2.3.2.1.11, calculations of annual doses to the RMEI were performed using dose coefficients from Federal Guidance Report 13 and weighting factors consistent with the requirements of the final rule.

Preclosure analyses, demonstrating compliance with the dose standards of 10 CFR 63.111 and 63.204, were also performed using weighting factors consistent with the final rule or have been shown to be conservative relative to the weighting factors specified in the final rule. NRC's final rule requires that the specified weighting factors for members of the public also be used for dose calculations for workers. Preclosure dose estimates reported in the license application are consistent with the final rule, with the exception of direct radiation from contained sources (e.g., shielding calculations) and worker doses from inhalation and submersion. Because 10 CFR 63.111 specifies that the geologic repository operations area (GROA) meet the requirements of 10 CFR 20, worker doses were calculated in accordance with the requirements of 10 CFR 20 in effect at the time of submittal of the license application; this included the use of weighting factors and fluence rate to dose equivalent factors based on 10 CFR 20 requirements.

The resulting direct radiation and worker inhalation and submersion doses included in the SAR meet the intent of the NRC final rule, in that the reported results are based on a more conservative method of calculating regulatory dose, notwithstanding the fact that specific weighting factors referenced in the final rule were not utilized. In particular, offsite doses resulting from event sequences used weighting factors consistent with those specified in the final rule. The resulting projected radiation exposures reported in SAR Table 1.8-36 are well below the exposure limits contained in 10 CFR 63.111 and 63.204. DOE believes that its calculation methodology is appropriate to this circumstance regarding the use of weighting factors.

- Shielding calculations described in SAR Section 1.10 were performed using weighting factors and fluence rate to dose equivalent factors consistent with 10 CFR Part 20 in effect at the time of submittal of the license application. However, as described in SAR Section 1.10.3.2, a calculation has been performed to demonstrate that the direct radiation doses from the shielding calculations, for the specific radiation sources and shielding materials anticipated in the repository, are conservative relative to those based on the weighting factors specified in the final rule.

- Calculation of worker doses from inhalation and submersion were performed using two sets of weighting factors: one set consistent with 10 CFR 20 in effect at the time of submittal of the license application, and a set of weighting factors consistent with those specified in the final rule. The larger of the two results was subsequently incorporated into the dose estimates reported in SAR Section 1.8.

Therefore, radiation dose estimates to the public and to workers during the preclosure period presented in the license application are either based explicitly on weighting factors consistent with the final rule or, for the two discrete areas of shielding and doses due to inhalation and submersion, meet the intent of the rule by use of more conservative methodology.

1.6. ADDITIONAL CHANGES

The changes discussed above focus on the material impacts on the LA by the differences between the proposed and final rules. For reader convenience, Table A-1 in Appendix A provides the text from the proposed rule and the text from the final rule. DOE has evaluated all of these changes and determined that none of them will have a significant impact on the LA. The largest impact from most of the changes is that there are a large number of places in the LA where the wording in the LA text does not conform to the text of the final rule. These include items such as direct quotes from the regulation, discussion of the median as the post-10,000 years compliance metric, use of the word 'proposed' in front of 10 CFR Part 63, and other similar modifications. DOE is not making these changes to the LA at this time because none of the potential changes would have a significant impact on the technical basis or the conclusions in the LA.

1.7. SUMMARY

DOE has evaluated all changes between the proposed 10 CFR Part 63 published for comment on September 8, 2005, and the final 10 CFR Part 63 that became effective on April 13, 2009. None of the conclusions presented in the LA changed as a result of the changes in the rule.

SAR Section 2.4.1.3 presents the methodology for the computation of mean annual dose. The peak value of the arithmetic mean of the projected doses from the performance assessment is approximately 2.0 mrem and it occurs at 1,000,000 years.

The screening justifications for FEPs related to effects of seismic activity on water table rise are based on evaluation of earthquake effects of low probabilities and are equally applicable to a 10,000-year and a 1,000,000-year time frame. Consequently, those FEPs should continue to be excluded from the performance assessment.

Implementing the new distribution of deep percolation rates will result in a greater likelihood of larger volumes of water flowing through the unsaturated zone. A bounding analysis shows that the impact of this change is likely to be small and any increase in dose to the RMEI is likely to be insignificant in magnitude relative to the compliance standard.

2. COMMITMENTS TO NRC

None.

3. DESCRIPTION OF PROPOSED LA CHANGE

None.

4. REFERENCES

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.

Neuzil, C.E. 2003. "Hydromechanical Coupling in Geologic Processes." *Hydrogeology Journal*, *11*, (1), 41-83. New York, New York: Springer-Verlag.

SNL (Sandia National Laboratories) 2008a. *Total System Performance Assessment Model /Analysis for the License Application*. MDL-WIS-PA-000005 REV 00 AD 01. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20080312.0001; LLR.20080414.0037; LLR.20080507.0002; LLR.20080522.0113; DOC.20080724.0005; DOC.20090106.0001[a].

SNL 2008b. *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; DOC.20080407.0009; DOC.20080722.0002.

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."

APPENDIX A

COMPARISON OF PROPOSED AND FINAL 10 CFR PART 63

Table A-1. Comparison of Proposed and Final 10 CFR Part 63

Issue No.	Issue Description	Proposed 10 CFR Part 63 (2005)	Final 10 CFR Part 63 (2009)
1	"Total effective dose equivalent (TEDE)" has replaced "weighting factor".	§ 63.2 *Weighting factor for an organ or tissue is the proportion of the risk of stochastic effects resulting from irradiation of that organ or tissue to the total risk of stochastic effects when the whole body is irradiated uniformly. For calculating the effective dose equivalent, the values in Appendix A of 40 CFR part 197 are to be used.* § 63.111(a)(1) *The geologic repository operations area must meet the requirements of part 20 of this chapter. Calculation of doses to meet the requirements of part 20 of this chapter shall use the definition for ''weighting factor'' in § 63.2.*	§ 63.2 *Total effective dose equivalent (TEDE) means the sum of the effective dose equivalent (for external exposures) and the committed effective dose equivalent (for internal exposures).* § 63.102(o) *Implementation of TEDE. When external exposure is determined by measurement with an external personal monitoring device, the deep-dose equivalent must be used in place of the effective dose equivalent, unless the effective dose equivalent is determined by a dosimetry method approved by the NRC. The assigned deep-dose equivalent must be for the part of the body receiving the highest exposure. The assigned shallow-dose equivalent must be the dose averaged over the contiguous 10 square centimeters of skin receiving the highest exposure. The radiation and organ or tissue weighting factors in Appendix A of 40 CFR part 197 are to be used to calculate TEDE. After the effective date of this regulation, the Commission may allow DOE to use updated factors, which have been issued by consensus scientific organizations and incorporated by EPA into Federal radiation guidance. Additionally, as scientific models and methodologies for estimating doses are updated, DOE may use the most current and appropriate (e.g., those accepted by the International Commission on Radiological Protection) scientific models and methodologies to calculate the TEDE. The weighting factors used in the calculation of TEDE must be consistent with the methodology used to perform the calculation.* § 63.111(a)(1) describing the GROA is now unchanged from the 2001 rule.

Table A-1. Comparison of Proposed and Final 10 CFR Part 63 (continued)

Issue No.	Issue Description	Proposed 10 CFR Part 63 (2005)	Final 10 CFR Part 63 (2009)
2	§ 63.114(b) has been reworded to support new structure of § 63.114.	§ 63.114(b) *Any performance assessment used to demonstrate compliance with § 63.113 for the period of time after 10,000 years through the period of geologic stability must be based on the performance assessment specified in paragraph (a) of this section.*	§ 63.114(b) *The performance assessment methods used to satisfy the requirements of paragraph (a) of this section are considered sufficient for the performance assessment for the period of time after 10,000 years and through the period of geologic stability.*
3	"Mean" has replaced "median" for the 1,000,000-year case.	§ 63.303 *(a) Compliance is based upon the arithmetic mean of the projected doses from DOE's performance assessments for the period within 10,000 years after disposal for:* *(1) § 63.311(a)(1); and* *(2) §§ 63.321(b)(1) and 63.331, if performance assessment is used to demonstrate compliance with either or both of these sections.* *(b) Compliance is based upon the median of the projected doses from DOE's performance assessments for the period after 10,000 years of disposal and through the period of geologic stability for:* *(1) § 63.311(a)(2); and* *(2) § 63.321(b)(2), if performance assessment is used to demonstrate compliance.*	§ 63.303 *(a) Compliance is based upon the arithmetic mean of the projected doses from DOE's performance assessments for the period within 1 million years after disposal, with:* *(1) Sections 63.311(a)(1) and 63.311(a)(2); and* *(2) Sections 63.321(b)(1), 63.321(b)(2), and 63.331, if performance assessment is used to demonstrate compliance with either or both of these sections.*

Table A-1. Comparison of Proposed and Final 10 CFR Part 63 (continued)

Issue No.	Issue Description	Proposed 10 CFR Part 63 (2005)	Final 10 CFR Part 63 (2009)
4	§ 63.305(c) has been reworded slightly.	§ 63.305(c) *DOE must vary factors related to the geology, hydrology, and climate based upon cautious, but reasonable assumptions consistent with present knowledge of factors that could affect the Yucca Mountain disposal system during the period of geologic stability and consistent with the requirements for performance assessments specified at § 63.342.*	§ 63.305(c) *DOE must vary factors related to the geology, hydrology, and climate based upon cautious, but reasonable assumptions of the changes in these factors that could affect the Yucca Mountain disposal system during the period of geologic stability, consistent with the requirements for performance assessments specified at § 63.342.*
5	"100 mrem" has replaced "350 mrem" for the 1,000,000-year case.	§ 63.311(a)(2) *3.5 mSv (350 mrem) after 10,000 years, but within the period of geologic stability.* § 63.321(b)(2) *3.5 mSv (350 mrem) after 10,000 years, but within the period of geologic stability.*	§ 63.311(a)(2) *1.0 mSv (100 mrem) after 10,000 years, but within the period of geologic stability.* § 63.321(b)(2) *1.0 mSv (100 mrem) after 10,000 years, but within the period of geologic stability.*
6	"Environmental" has been removed from description of pathways.	§ 63.311(b) *DOE's performance assessment must include all potential environmental pathways of radionuclide transport and exposure.*	§ 63.311(b) *DOE's performance assessment must include all potential pathways of radionuclide transport and exposure.*

Table A-1. Comparison of Proposed and Final 10 CFR Part 63 (continued)

Issue No.	Issue Description	Proposed 10 CFR Part 63 (2005)	Final 10 CFR Part 63 (2009)
7	Specific words for probability of unlikely events have changed. Also, a pointer to §§ 63.321(b) changed.	§ 63.342(a) and (b) *(a) DOE's performance assessments conducted to show compliance with §§ 63.311(a)(1), 63.321(b)(1), and 63.331 shall not include consideration of very unlikely features, events, or processes, i.e., those that are estimated to have less than one chance in 10,000 of occurring within 10,000 years of disposal (less than one chance in 100,000,000 per year). In addition, DOE's performance assessments need not evaluate the impacts resulting from any features, events, and processes or sequences of events and processes with a higher chance of occurrence if the results of the performance assessments would not be changed significantly in the initial 10,000 year period after disposal.* *(b) For performance assessments conducted to show compliance with §§ 63.321(b) and 63.331, DOE's performance assessments shall exclude the unlikely features, events, and processes, or sequences of events and processes, i.e., those that are estimated to have less than one chance in 10 and at least one chance in 10,000 of occurring within 10,000 years of disposal (less than one chance in 100,000 per year and at least one chance in 100,000,000 per year).*	§ 63.342(a) and (b) *(a) DOE's performance assessments conducted to show compliance with §§ 63.311(a)(1), 63.321(b)(1), and 63.331 shall not include consideration of very unlikely features, events, or processes, i.e., those that are estimated to have less than one chance in 100,000,000 per year of occurring. In addition, DOE's performance assessments need not evaluate the impacts resulting from any features, events, and processes or sequences of events and processes with a higher chance of occurring if the results of the performance assessments would not be changed significantly in the initial 10,000-year period after disposal.* *(b) For performance assessments conducted to show compliance with §§ 63.321(b)(1) and 63.331, DOE's performance assessments shall exclude the unlikely features, events, and processes, or sequences of events and processes, i.e., those that are estimated to have less than one chance in 100,000 per year of occurring and at least one chance in 100,000,000 per year of occurring.*
8	Sequences of events and processes have been added to consideration of probability limits for unlikely FEPs for seismic and igneous scenarios.	§ 63.342(c)(1) *DOE must assess the effects of seismic and igneous scenarios subject to the probability limits in paragraph (a) of this section for very unlikely features, events, and processes. Performance assessments conducted to show compliance with § 63.321(b)(2) are also subject to the probability limits in paragraph (b) of this section for unlikely features, events, and processes.*	§ 63.342(c)(1) *DOE must assess the effects of seismic and igneous activity scenarios, subject to the probability limits in paragraph (a) of this section for very unlikely features, events, and processes, or sequences of events and processes. Performance assessments conducted to show compliance with § 63.321(b)(2) are also subject to the probability limits in paragraph (b) of this section for unlikely features, events, and processes, or sequences of events and processes.*

Table A-1. Comparison of Proposed and Final 10 CFR Part 63 (continued)

Issue No.	Issue Description	Proposed 10 CFR Part 63 (2005)	Final 10 CFR Part 63 (2009)
9	Water table rise is now included in seismic analysis for 1,000,000-year case.	§ 63.342(c)(1)(i) *The seismic analysis may be limited to the effects caused by damage to the drifts in the repository and failure of the waste package.*	§ 63.342(c)(1)(i) *The seismic analysis may be limited to the effects caused by damage to the drifts in the repository, failure of the waste packages, and changes in the elevation of the water table under Yucca Mountain (i.e., the magnitude of the water table rise under Yucca Mountain).*
10	Instructions for percolation rates for 1,000,000-year case have changed.	§ 63.342(c)(2) *DOE must assess the effects of climate change. The climate change analysis may be limited to the effects of increased water flow through the repository as a result of climate change, and the resulting transport and release of radionuclides to the accessible environment. The nature and degree of climate change may be represented by constant climate conditions. The analysis may commence at 10,000 years after disposal and shall extend to the period of geologic stability. The constant value to be used to represent climate change is to be based on a log-uniform probability distribution for deep percolation rates from 13 to 64 mm/year (0.5 to 2.5 inches/year).*	§ 63.342(c)(2) *DOE must assess the effects of climate change. The climate change analysis may be limited to the effects of increased water flow through the repository as a result of climate change, and the resulting transport and release of radionuclides to the accessible environment. The nature and degree of climate change may be represented by constant-in-time climate conditions. The analysis may commence at 10,000 years after disposal and shall extend through the period of geologic stability. The constant-in-time values to be used to represent climate change are to be the spatial average of the deep percolation rate within the area bounded by the repository footprint. The constant-in-time deep percolation rates to be used to represent climate change shall be based on a lognormal distribution with an arithmetic mean of 41 mm/year (1.6 in./year) and a standard deviation of 33 mm/year (1.3 in./year). The lognormal distribution is to be truncated so that the deep percolation rates vary between 10 and 100 mm/year (0.39 and 3.9 in./ year).*

NOTES: Blue text calls attention to text that has changed between the proposed and final versions of 10 CFR Part 63. However, in some cases, the changes are too extensive to show in this manner. Also, text changes that are clearly editorial and nonmaterial are not shown as blue. If such changes are the only changes in a paragraph, they are not shown in this table at all. Accordingly, this table shows selected differences between the proposed and final rule, rather than all of the differences.

LA changes can result from any differences between the proposed and the final 10 CFR Part 63, even if those differences are editorial and/or nonmaterial. For example, all direct quotes of 10 CFR Part 63 will need to be checked for accuracy with the final rule.

RAI Volume 3, Chapter 2.2.1.2.1, Fifth Set, Number 3:

In light of observations, related to temperature fluctuations recorded by sensors in boreholes of the Drift-Scale Heater Test, provide the technical basis for exclusion of FEP 1.1.01.01.0B and FEP 2.1.06.04A. These FEPs address flow in boreholes and rock reinforcement components. This information is needed to assess compliance with 10 CFR 63.114.

Basis: Analysis of several heater tests suggests that observations of temperature fluctuations could be explained by the occurrence of heat pipes in boreholes (Green, et al., 2008). Refluxing water associated with the heat pipes in the boreholes may lead to pulses of water preferentially breaching the dryout zone and possibly reaching the drift ceiling when the average drift wall rock temperatures are above 100 °C. These observations occurred in ungrouted MPBX boreholes in the Drift Scale Heater Test.

DOE has not clearly addressed how the three arguments presented as the basis for exclusion of FEPs 1.1.01.01.0B and 2.1.06.04A in SNL (2008) account for observations in the dryout zone of the Drift-Scale Heater Test of apparent refluxing within MPBX boreholes, and consequently, the possibility of liquid water reaching the drift. For the current design (SAR, Section 1.3.4.4.1), there will be approximately 26 rock bolts in the seepage area for a typical waste package that could act as pathways for refluxing water.

1. RESPONSE

Two features, events, and processes (FEPs), 1.1.01.01.0B, Influx through Holes Drilled in Drift Wall, and 2.1.6.04.0A, Flow through Rock Reinforcement Materials in EBS, address flow in boreholes and other rock reinforcement components, and how these processes could possibly promote seepage of water into drifts. The RAI suggests that refluxing of water associated with vapor migration and condensation in ungrouted boreholes may lead to pulses of water reaching the drift wall above the drip shields and waste packages, at average rock temperatures above 100°C, thus implying that thermal seepage could be possible at temperatures higher than the temperature threshold chosen in the thermal seepage abstraction.

The technical bases for the exclusion of FEPs 1.1.01.01.0B and 2.1.6.04.0A focus on the long-term postclosure period of ambient seepage, when thermal effects are negligible, which is appropriate because these FEPs have no significant effect during the brief thermal period when drip shields are intact. The presence of open boreholes does not impact ambient seepage, since a capillary barrier reduces flow of pore water into the boreholes, just as a capillary barrier reduces flow of water from the fractured rock into the drifts. This technical information was also discussed in the response to RAI 3.2.2.1.3.6-003. Possible thermal reflux in open rock bolt boreholes can be influenced by: (1) the initial and final ground support systems for waste emplacement drifts; (2) the flow processes expected in boreholes initially equipped with rock bolts; and (3) the longevity of rock bolts in the preclosure and postclosure environments. Based on the function of the drip shield, seepage caused by thermal reflux in open boreholes during the thermal period, if it does occur, is not significant to repository performance.

1.1 THERMAL REFLUX IN OPEN ROCK BOLT BOREHOLES

For this RAI response, boreholes refer to the drift ground support boreholes and not surface drilling boreholes. The RAI attributes the concern about thermal reflux in open boreholes to observations of temperature oscillations from sensors emplaced in ungrouted boreholes. There there may be open, ungrouted boreholes in the drift wall, such as those used for initial ground support. Green et al. (2008) reviewed several heater tests conducted within the Yucca Mountain program and described in detail the temperature excursions that occurred in ungrouted boreholes in the Drift Scale Test. These boreholes contained multi-point borehole extensometer (MPBX) assemblies, extending from the drift wall into the fractured rock. Except for the MPBX assemblies, these boreholes were essentially open for axial flow of vapor or liquid. Thermal refluxing can occur in such vertical or subvertical boreholes when the borehole collar is in an above-boiling environment and the distal end extends past the bulk rock boiling isotherm. The borehole initially provides a conduit for upward movement of vapor that has been evaporated from pore water at the hot end. As vapor condenses at the cooler, distal end, the condensed water can flow back toward the borehole collar.

The emplacement drift ground support is described in SAR Section 1.3.4.4 as well as in *Ground Control for Emplacement Drifts for LA* (BSC 2007 Section 6.6). An initial ground support system provides worker safety until the final ground support system is installed. The initial ground support is installed using carbon-steel frictional rock bolts of 1.5-m length. The initial rock bolts remain in place after final ground support installation. The final ground support is installed with radially oriented Swellex-type rock bolts with approximately 240° coverage around the tunnel above the invert. The Swellex-type rock bolts are 3 m long and made of Stainless Steel Type 316.

Swellex-type rock bolts are a friction-type system placed into a drilled hole and expanded by high-pressure water such that the bolts compact the material surrounding the hole and deform to fit the irregularities of the borehole, providing a frictional and mechanical interlock (SAR Section 1.3.4.4; BSC 2007, Section 6.6.1.1, p. 82). The major portion of the interface between the rock bolt and the rock wall resembles a natural small-aperture rock fracture with many asperity contacts providing the frictional and mechanical interlock. In order to expand the bolt by high-pressure water, the inside of the bolt is sealed at both ends, with a domed face plate at the collar end of the rock bolt. Once the rock bolt has expanded, the water is allowed to drain via a small hole in the domed face plate. Thus, boreholes equipped with Swellex-type rock bolts do not act like completely open boreholes (or like the MPBX boreholes in the Drift Scale Test). There is resistance to vapor-liquid flow processes in the contact between the rock bolt and the rock surface, similar to the resistance in natural rock fractures at Yucca Mountain. There is also resistance to vapor entry into the inner portion of the rock bolt, as the metal body of the Swellex bolt excludes pore water and vapor, except for the small hole in the domed faced plate. Thus, the processes leading to thermal reflux are different from those occurring in completely open boreholes, and the potential for—as well as the intensity of—thermal reflux within the boreholes used for repository ground support is much smaller.

Another kind of friction-type rock bolt is the Split-Set system, which will potentially be used for the initial ground support system (SAR Section 1.3.4.4.1). The Split-Set bolt is a slotted tube (like a large roll pin) that is driven into an undersized hole, and exerts radial pressure against the rock. With respect to the potential for thermal reflux, the two systems are similar; both have a tight contact between the rock bolt and the rock wall and both have a metal tube that impedes the movement of pore water and vapor. The Split-Set tube, however, is open along its length and at the collar, such that vapor can more readily enter and refluxing liquid can more readily escape.

Swellex-type rock bolts have been used for ground support in the heated drift of the Drift Scale Test. As reported in *Thermal Testing Measurements Report* (SNL 2007a, Section 6.3.4.3.4) and by Green et al. (2008), observations were made after the conclusion of the test that may indicate that water entered the drift through the bolts. These observations include a few corroding cables on the floor of the tunnel, one instance of staining along the roof emanating from a rock bolt, and a few stains on floor canisters, with the location of the stains correlated to borehole collars at the roof. With the exception of the red stains on the floor canisters, the observations were made when the test was being dismantled, so that the timing could not be determined. The red stains were first observed during a video camera run in August 2002. Since these stains had not been observed in an earlier run conducted in April 2002, the material had been deposited between April and August 2002, during the period of rapid cooling after the heaters were turned off (SNL 2007a, Section 6.3.4.3.4). The same reference suggests that the red stains on the floor canisters are mostly iron oxides, most likely derived from corrosion of the carbon-steel rock bolts. It is not clear whether the materials were deposited with dripping water or fell as particulate matter from the roof.

The Drift Scale Test observations thus provide no direct evidence that thermal reflux in boreholes equipped with Swellex-type rock bolts led to water seeping into the tunnel during the heating period of the test. In other words, there is no verifiable direct evidence of thermal seepage for the time period when large volumes of water were mobilized by boiling, and vigorous vapor-liquid flow processes occurred that increase the potential for thermal reflux. Although the exact timing is uncertain, the red spots on the floor canisters were apparently deposited a few months after the heaters were turned off while the test block was rapidly cooling. Rapid cooling is not representative of repository conditions, where the thermal output of the radioactive waste decreases slowly and cooling of the repository is a long-term gradual process. The other indications of water entry, such as the stain on the ceiling, may also have occurred after the heaters were turned off. The observations of possible water entry made in the Drift Scale Test are not inconsistent with the thermal seepage abstraction.

For the conditions expected in the emplacement drifts, the permanent ground support system is designed to last at least 100 years with minimal maintenance. While no credit for ground support function is taken in the license application beyond a 100-year lifetime, the longevity of the stainless-steel rock bolts is probably orders of magnitude greater (BSC 2004a, Table 4-5). Thus, these rock bolts are likely to persist throughout the thermal period. The temporary rock bolts, on the other hand, are made of carbon steel and are expected to corrode faster. Boreholes associated with temporary ground support may therefore provide open conduits for thermal reflux, and as a result, may cause some dripping of water into the drifts when the drift wall temperature is >100°C. These boreholes are not represented in the predictive model for thermal seepage (BSC 2005). However, significant thermal reflux can only occur in vertical or sub-vertical boreholes when vapor is produced in the rock near the collar while the end of the borehole is at below-boiling temperatures such that the migrating vapor condenses. The postclosure time period during which these conditions are met is relatively short for boreholes of 1.5-m length. At later stages, after the thermal pulse, all open boreholes act as capillary barriers to the unsaturated flow in the fractured rock. Simulations conducted in *Seepage Model for PA Including Drift Collapse* (BSC 2004b, Section 6.5, pp. 6 to 13ff) demonstrate the effective capillary-barrier behavior of an open borehole in the fractured rock surrounding an emplacement drift and show that their presence does not lead to enhanced seepage.

1.2 DISCUSSION OF DRIP SHIELD FUNCTION DURING THE THERMAL PERIOD

Boreholes used for temporary rock bolts may provide pathways for thermal reflux, which could lead to some dripping of water. Thus, the extent and quantity of seepage may be greater than is represented explicitly in the TSPA. Such dripping of water is not significant to repository performance. Based on this discussion, the exclusion of FEPs 1.1.01.01.0B and 2.1.06.04.0A does not result in a significant change in the magnitude or time of radiological exposures to the reasonably maximally exposed individual (RMEI) or radionuclide releases to the accessible environment. Therefore, the exclusion (low consequence) of these FEPs is warranted.

Significant thermal reflux may occur only until the rock temperature near the drifts cools below boiling, which occurs by approximately 1,400 years after closure (SAR Figure 2.3.5-32(a)). With the drip shields functioning as barriers to seepage, the occurrence of seepage does not affect the waste packages. In the unlikely event of seismic damage to waste packages under intact drip shields, radionuclide releases are relatively insensitive to the occurrence of seepage (see DOE response to RAI 3.2.2.1.3.6-7). The effects on seepage chemistry from degrading ground support (including corrosion of steels) are addressed in the screening justification for excluded FEP 2.1.06.01.0A, Chemical Effects of Rock Reinforcement and Cementitious Materials in EBS (SNL 2008a), where it is concluded that corrosion of steels in ground support does not significantly impact aqueous chemistry of seepage waters. Accordingly, thermal reflux does not significantly affect performance of the drip shield. Thus, the effects of thermal reflux are limited to those TSPA-LA modeling cases where events may cause drip shield failure prior to 1,400 years and which use the seepage abstraction.

The TSPA model considers three cases which use the seepage abstraction and in which drip shield failure may occur within 10,000 years: the drip shield early failure modeling case; the seismic fault displacement modeling case; and the seismic ground motion modeling case. The analysis for the human intrusion standard (10 CFR 63.321) does not use the seepage abstraction.

1.2.1 Individual Protection Standard (10 CFR 63.311)

The total mean annual dose (summed over all modeling cases) is compared to the limit specified in the individual protection standard. The contribution of each modeling case to the total mean annual dose is shown on SAR Figure 2.4-18(a). The mean annual dose from the drip shield early failure modeling case is more than two orders of magnitude below the total mean annual dose. The magnitude of the mean annual dose from the drip shield early failure modeling case is primarily determined by the low expected number of early-failed drip shields (SAR Section 2.4.2.2.1.2.4.1); increasing either the occurrence or extent of seepage in the drip shield early failure modeling case would have a negligible effect on the total mean annual dose. Similarly, the fault displacement modeling case contributes only a minor amount of the total mean annual dose, due to the low frequency of fault displacement events and the expected number of waste packages affected by fault displacement (SAR Section 2.4.2.2.1.2.2.2). Also, full collapse of the drift is generally associated with fault displacement (SNL 2008b, Sections 6.6.1.3.9 and 6.6.2.1), which would lead to borehole collapse as well. Therefore, thermal reflux in open boreholes has a negligible effect on the mean annual dose from seismic fault displacement.

The mean annual dose for 10,000 years from the seismic ground motion modeling case is estimated by considering only seismically induced stress-corrosion cracking of codisposal waste packages (SAR Section 2.4.2.2.1.1.2, p. 2.4-57). The potential contributions to mean annual dose from other consequences of vibratory ground motion are analyzed in *Total System Performance Assessment Model/Analysis for the License Application* (SNL 2008b, Section 7.3.2.6.1.3) and are determined to be minor compared to the contribution from seismically induced stress-corrosion cracking of codisposal waste packages. In particular, the potential contribution to mean annual dose from seismic events that cause drip shield failure is shown (SNL 2008b, Section 7.3.2.6.1.3.2) to be negligible. Seismic events sufficient to cause drip shield failure within 10,000 years (before significant drip shield plate thinning; SNL 2007b, Table 6-36) are also of sufficient magnitude to cause significant rockfall (SNL 2007b, Tables 6-29 and 6-30). Significant rockfall with partial or full collapse of the drifts would lead to borehole collapse as well. Therefore, thermal reflux in such boreholes has a negligible effect on the mean annual dose from seismic ground motion.

In summary, the potential effect of thermal reflux on total mean annual dose to the RMEI is negligible.

1.2.2 Standards for Protection of Groundwater (10 CFR 63.331)

Compliance with the separate standards for protection of groundwater is demonstrated in SAR Section 2.4.4. The models used to demonstrate compliance with the separate standards for protection of groundwater are the same as those used to demonstrate compliance with the individual protection standard. However, because unlikely FEPs are excluded from the analysis for the separate standards for protection of groundwater, the seismic fault displacement modeling case does not contribute to the estimates of performance (SAR Section 2.4, p. 2.4-326).

Figure 8.1-10[a] of *Total System Performance Assessment Model/Analysis for the License Application* (SNL 2008b) shows that most (more than 90%) of the estimated mean concentration of radium in groundwater results from the seismic ground motion modeling case, and that the sum of contributions from all cases is approximately six orders of magnitude less than the background radium activity concentration. Also, thermal reflux has a negligible effect on the seismic ground motion modeling case. Accordingly, the potential effect of thermal reflux on the radium concentration in groundwater is negligible.

Figure 8.1-12[a] of *Total System Performance Assessment Model/Analysis for the License Application* (SNL 2008b) shows that the largest contribution to the maximum of the estimated mean gross alpha concentration in groundwater results from the seismic ground motion modeling case. The drip shield early failure modeling case contributes modestly to the overall mean concentration. The maximum of the estimated mean gross alpha concentration in groundwater is nearly four orders of magnitude below the limit specified in 10 CFR 63.331. An increase in the occurrence and volume of seepage resulting from thermal reflux may increase the mass of alpha-emitting radionuclides transported to the groundwater in the drip shield early failure modeling case. However, any potential contribution to seepage from thermal reflux would not be sufficiently large (i.e., orders of magnitude larger in volume) to alter the demonstration of compliance. Thus, the potential effect of thermal reflux on the radium concentration in groundwater is negligible.

Figure 8.1-15[a] of *Total System Performance Assessment Model/Analysis for the License Application* (SNL 2008b) shows that essentially all of the maximum whole body and organ dose from beta- and photon-emitting radionuclides results from the seismic ground motion modeling case. Because thermal reflux has a negligible effect on this modeling case, the potential effect of thermal reflux on whole body and organ doses is negligible.

1.3 SUMMARY

Boreholes used for temporary rock bolts may provide pathways for thermal reflux, which could lead to some dripping of water for a limited time period after closure of the repository. Although the extent and quantity of seepage may be greater than that represented explicitly in the TSPA, it has been demonstrated that it is not significant to repository performance. The exclusion of FEPs 1.1.01.01.0B and 2.1.06.04.0A does not result in a significant change in the magnitude or time of radiological exposures to the RMEI or radionuclide releases to the accessible environment. Therefore, as documented in the screening justifications for these two FEPs and considering the additional technical information presented in this response, the exclusion of these FEPs is warranted.

2. COMMITMENTS TO NRC

None.

3. DESCRIPTION OF PROPOSED LA CHANGE

None.

4. REFERENCES

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BSC 2005. *Drift-Scale Coupled Processes (DST and TH Seepage) Models.* MDL-NBS-HS-000015 REV 02. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20050114.0004; DOC.20051115.0002.

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SNL (Sandia National Laboratories) 2007a. *Thermal Testing Measurements Report.* TDR-MGR-HS-000002 REV 01. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20070307.0010.

SNL 2007b. *Seismic Consequence Abstraction.* MDL-WIS-PA-000003 REV 03. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20070928.0011; LLR.20080414.0012.

SNL 2008a. *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; DOC.20080407.0009; LLR.20080522.0166; DOC.20080722.0002.

SNL 2008b. *Total System Performance Assessment Model /Analysis for the License Application.* MDL-WIS-PA-000005 REV 00 AD 01. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20080312.0001; LLR.20080414.0037; LLR.20080507.0002; LLR.20080522.0113; DOC.20080724.0005; DOC.20090106.0001[a].

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, Fifth Set, Number 5:

Provide a technical basis for exclusion of FEP 2.2.07.05.0A that addresses: (1) the observation that temporally varying percolation fluxes may induce time-averaged seepage that is larger than would occur with the same average flux applied at a steady rate; (2) temperature and tritium field observations that suggest episodic flow may be prevalent at Yucca Mountain, at least in scattered locations; and (3) why multi-decadal climate fluctuations necessarily have a negligible effect on performance when percolation fluctuations demonstrably may result in a systematic increase in seepage. This information is needed to evaluate compliance with 10 CFR 63.114.

Basis: Depending on the timing of the fluctuations, temporally varying percolation fluxes may induce time-averaged seepage that is larger than would occur with the same average flux applied at a steady rate. For example, DOE (2009, RAI 3.2.2.1.1-002, Figure 1-1) provides an illustrative example with mean seepage 50 percent larger under variable percolation fluxes than under the equivalent steady percolation flux.

The screening argument for excluding FEP 2.2.07.05.0A relies on numerical modeling to demonstrate that the porous matrix of the PTn imbibes wetting pulses. The screening argument uses a numerical model to explain observations of chlorine-36 in the ESF as a result of fast pathways from approximately 1 percent of infiltration. However, the screening argument does not address temperature and tritium field observations that suggest episodic flow may be prevalent at Yucca Mountain, at least in scattered locations.

1. RESPONSE

This RAI response provides additional information to support exclusion of the feature, event, or process (FEP) described under FEP 2.2.07.05.0A, *Flow in the UZ from Episodic Infiltration*, addressing: (1) temporally varying percolation fluxes; (2) temperature and tritium data relevant to episodic flow; and (3) climate and seepage fluctuations relevant to performance. This response shows that DOE relied on field tests, site data, and modeling to demonstrate that the porous matrix of the Paintbrush nonwelded (PTn) hydrogeologic unit imbibes wetting pulses. Therefore, excluding episodic flow from the performance assessment on the basis of low consequence is justified.

Analyses are provided in Section 1.1 to respond to: (1) the observation that temporally varying percolation fluxes may induce time-averaged seepage that is larger than would occur with the same average flux applied at a steady rate, and (3) why multi-decadal climate fluctuations necessarily have a negligible effect on performance when percolation fluctuations demonstrably may result in a systematic increase in seepage. This is an extension of an existing analysis presented in the response to RAI 3.2.2.1.1-002.

An evaluation of the tritium data and pertinent temperature data are provided in Sections 1.2 and 1.3, respectively, to respond to (2) concerning the consistency of these data relative to the exclusion of episodic flow.

Sections 1.4 and 1.5 present evaluations of field observations of transient flow behavior in the PTn hydrogeologic unit and measurements of ^{14}C in the unsaturated zone. These data provide additional evidence supporting the exclusion of episodic flow.

Throughout this response, reference is made to three different classifications of unsaturated zone stratigraphy, lithostratigraphic nomenclature, unsaturated zone flow model layers, and major hydrogeologic units. A cross-walk between these different classifications is given in Table 1. There is a general correspondence between unsaturated zone flow model layers and major hydrogeologic units.

Table 1. Unsaturated Zone Stratigraphic Cross-Walk

Lithostratigraphic Nomenclature	Unsaturated Zone Flow Model Layer	Major Hydrogeologic Units
Tpcr	tcw11	Tiva Canyon welded (TCw)
Tpcp	tcw12	
TpcLD		
Tpcpv3	tcw13	
Tpcpv2		
Tpcpv1	ptn21	Paintbrush nonwelded (PTn)
Tpbt4	ptn22	
Tpy (Yucca)		
	ptn23	
	ptn24	
Tpbt3		
Tpp (Pah)	ptn25	
Tpbt2	ptn26	
Tptrv3		
Tptrv2		
Tptrv1	tsw31	Topopah Spring Welded (TSw)
Tptrn		
	tsw32	
Tptrl, Tptf	tsw33	
Tptpul, RHHtop		
Tptpmn	tsw34	
Tptpll	tsw35	
Tptpln	tsw36	
	tsw37	
Tptpv3	tsw38	

Table 1. Unsaturated Zone Stratigraphic Cross-Walk (Continued)

Lithostratigraphic Nomenclature	Unsaturated Zone Flow Model Layer	Major Hydrogeologic Units
Tptpv2	tsw39 (vit, zeo)	Calico Hills nonwelded (CHn)
Tptpv1	ch1 (vit, zeo)	
Tpbt1		
Tac (Calico)	ch2 (vit, zeo)	
	ch3 (vit, zeo)	
	ch4 (vit, zeo)	
	ch5 (vit, zeo)	
Tacbt (Calicobt)	ch6 (vit, zeo)	
Tcpuv (Prowuv)	pp4	
Tcpuc (Prowuc)	pp3	
Tcpmd (Prowmd)	pp2	
Tcplc (Prowlc)		
Tcplv (Prowlv)	pp1	
Tcpbt (Prowbt)		
Tcbuv (Bullfroguv)		
Tcbuc (Bullfroguc)	bf3	Crater Flat undifferentiated (CFu)
Tcbmd (Bullfrogmd)		
Tcblc (Bullfroglc)		
Tcblv (Bullfroglv)	bf2	
Tcbbt (Bullfrogbt)		
Tctuv (Tramuv)		
Tctuc (Tramuc)	tr3	
Tctmd (Trammd)		
Tctlc (Tramlc)		
Tctlv (Tramlv)	tr2	
Tctbt (Trambt) and below		

Source: SAR Table 2.3.2-2.

1.1 INFILTRATION VARIABILITY, TRANSIENT FLOW, AND EFFECTS ON SEEPAGE INTO DRIFTS

1.1.1 Exclusion of Episodic Flow

FEP 2.2.07.05.0A, *Flow in the UZ from Episodic Infiltration*, provides information to justify exclusion of episodic flow in the unsaturated zone from the total system performance assessment (TSPA). Infiltration refers to water movement from the ground surface or, if present, unconsolidated surficial materials, into one of the unsaturated zone strata shown in Table 1; percolation refers to water movement within the unsaturated zone domain. The analysis focuses on episodic infiltration events characteristic of desert climates where infiltration occurs over a few days during a typical year (SNL 2008a, Figure 6.5.7.7-6[a]). The unsaturated zone above the repository is divided into three main hydrogeologic units: the Tiva Canyon welded (TCw) hydrogeologic unit, the PTn hydrogeologic unit, and the Topopah Spring welded (TSw) hydrogeologic unit. The TCw and TSw hydrogeologic units have low rock matrix porosity and permeability along with high fracture permeability that tends to transmit episodic flow with relatively little damping. By contrast, the PTn hydrogeologic unit, which is between the TCw and the TSw hydrogeologic units, has much greater rock matrix porosity and permeability, along with high capillary strength relative to the fractures. These characteristics of the PTn hydrogeologic unit rock matrix lead to strong imbibition from the fracture system and significant damping of episodic flow (SAR Section 2.3.2.2.1).

Simulations of extreme events were performed using an episodic infiltration pattern consisting of a week-long infiltration episode every 50 years (SNL 2007a, Section 6.9). During the week-long episode, the infiltration is raised by a factor of about 360 above the prevailing rate during the remainder of the 50-year cycle. The simulations were conducted for a representative "thin" PTn hydrogeologic unit with a thickness of 21 m and a representative "thick" PTn hydrogeologic unit with a thickness of 81 m. The simulations show that percolation fluxes resulting from episodic infiltration are substantially damped by the PTn hydrogeologic unit. The maximum percolation flux variation below the PTn is about 50% of the mean for the case with a thin PTn and only a few percent for the case with a thick PTn hydrogeologic unit. These variations in flux are small in comparison with other uncertainties in percolation flux included in the TSPA model, and support exclusion of episodic flow below the PTn hydrogeologic unit on the basis of low consequence.

1.1.2 Infiltration Variability and Transient Flow Phenomena

Longer-term changes in climate in the TSPA are represented through discrete climate states that are explicitly included in the infiltration model and downstream models, including drift seepage. Climate states are defined for specific durations into the future and last from hundreds to thousands of years. Uncertainty in climate and infiltration is represented by discrete, temporally uniform scenarios for each climate state. However, as pointed out in the Center for Nuclear Waste Regulatory Analyses (CNWRA) report, "The Nature of Flow in the Faulted and Fractured Paintbrush Nonwelded Hydrogeologic Unit" (Manepally et al. 2007), temporal variations in infiltration can deviate from the longer-term climate state mean, and these deviations may persist for decades to centuries.

The main focus of Manepally et al. (2007) was to evaluate the effects of these longer-term temporal variations in infiltration on flow in and below the PTn hydrogeologic unit. The study found that temporal variations in percolation flux fall within ±20% of the long-term average 80% of the time, and that the range in percolation flux falls within 50% of the long-term average. The effect of longer-term transient flow as presented by CNWRA (Manepally et al. 2007) was discussed in SAR Section 2.3.2.4.2.1.2. Variations in percolation flux induced by longer-term transient flow are similar in magnitude to those found in the investigation of shorter-term transient flow. These are excluded because of larger variations in percolation flux associated with infiltration uncertainty. The range in percolation flux for short- and long-term transient flow processes is used to provide a more specific evaluation of effects of episodic flow on drift seepage.

1.1.3 Effects of Infiltration Variability on Longer-Term Transient Flow and Drift Seepage

The question of barrier performance relative to damping of episodic flow is described in the response to RAI 3.2.2.1.1-002. That RAI response demonstrates drift seepage is smaller for a steady flow process than for an episodic flow process with the same average percolation flux. The question here is similar: what is the impact on drift seepage of an assumed steady flow for each climate state given that some level of transient flow behavior may penetrate the PTn hydrogeologic unit and affect percolation flux at waste emplacement drifts. Therefore, the analysis of mean seepage rate as a function of percolation flux for transient and equivalent steady flow processes is presented in the response to RAI 3.2.2.1.1-002 is also applicable to this question.

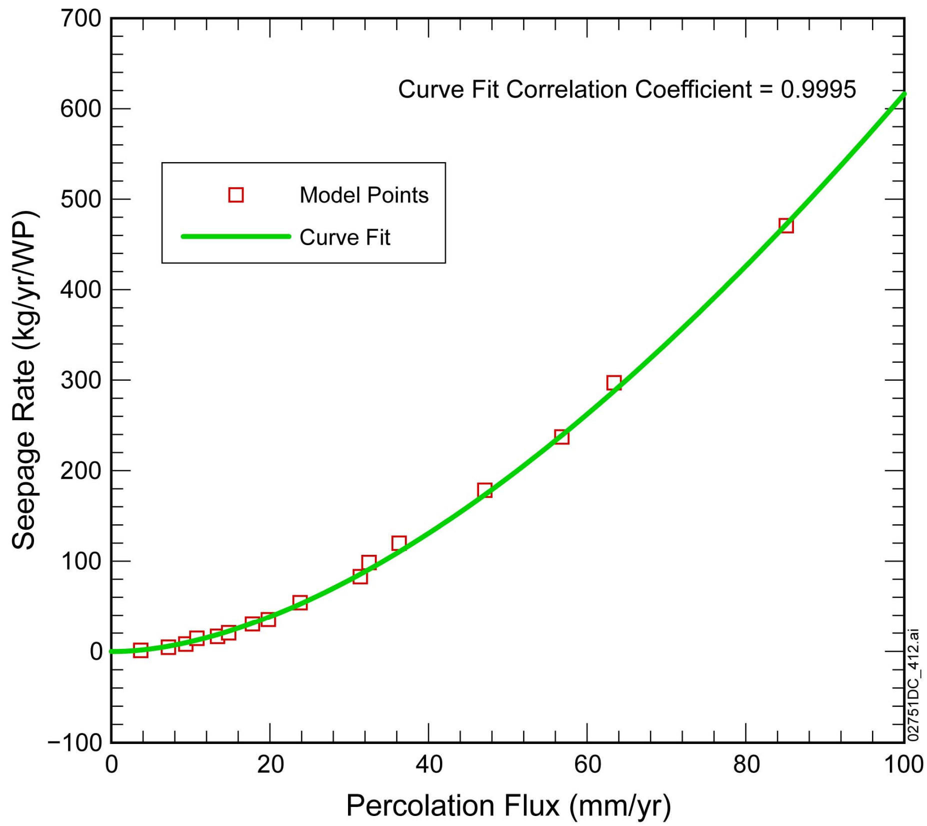
If seepage into drifts is assumed to be a quasi-steady process under transient percolation flux conditions, the variation in seepage behavior for different steady percolation fluxes may be used to evaluate differences in seepage rate into drifts for episodic percolation flux conditions as compared with the equivalent steady percolation flux. "Equivalent steady percolation flux" is defined as the time-weighted average of the series of spatially averaged percolation fluxes defining the episodic flow process. In this response, spatially averaged percolation flux over the repository footprint is referred to as "percolation flux."

The mean seepage rate as computed in the seepage abstraction model is the total amount of water entering drifts divided by the total number of waste packages (SNL 2007b, p. 6-29[a]). In this response, only mean seepage rates will be discussed. (To simplify the description, "mean seepage rate" will be termed "seepage rate.") Because the total number of waste packages is constant, only the seepage rate per waste package needs to be considered as a function of percolation flux. The relationship between seepage rate and percolation flux is shown in Figure 1. The model points (red squares on Figure 1) have been fit using an empirical function (green line on Figure 1) that is constrained to be zero for a percolation flux less than 1 mm/yr and is asymptotically proportional to the percolation flux for large values. The seepage rate curve fit is given by:

$$S_{rm} = H(P_a - 1)\left[0.2\exp(-0.003P_a)(P_a - 1)^{1.69} + 28.05\{1 - \exp(-0.001P_a)\}P_a\right]$$

where S_{rm} is the seepage rate in kg/yr per waste package, P_a is the percolation flux in mm/yr, and H is the step function which equals 1 for $P_a - 1 \geq 0$ and 0 otherwise.

The model points and curve fit show that the seepage rate curve is convex over the range of percolation fluxes displayed in Figure 1. The asymptotic linear behavior of the seepage rate curve occurs at percolation fluxes in excess of 100 mm/yr.



Source: Model points from SNL 2007b, Tables 6-5[a] and 6-6[a].

Figure 1. Seepage Rate as a Function of Percolation Flux

The analysis from CNWRA (Manepally et al. 2007, Section 4.6) suggests two cases to evaluate transient infiltration effects on seepage. Case 1 is a bimodal episodic process defined by end members with percolation fluxes that are ±20% of the average percolation flux. Case 2 is a bimodal episodic process defined by end members with percolation fluxes that are ±50% of the average percolation flux. These two cases for the analysis are evaluated using the 10th, 30th, 50th, and 90th percentile infiltration cases and the glacial-transition climate. This climate was chosen because it has the longest duration of any climate state over the 10,000-year period evaluated for FEP 2.2.07.05.0A. These scenarios are referred to as the 10th, 30th, 50th, and 90th percentile infiltration cases because these cases yield corresponding percentiles of net infiltration in the output from the infiltration model prior to calibration with unsaturated zone temperature and chloride data (SNL 2007a, Section 6.8). Results for these two cases are given in Tables 2 and 3, showing that the mean seepage rate for steady-state processes is less than the equivalent transient process. In addition to the percolation fluxes and mean seepage rates for the steady flow and transient processes, each table displays the weights applied in TSPA after calibration, used here for computing averages and standard deviations. These weights are calibrated probabilities for infiltration uncertainty cases accounting for unsaturated zone temperature and chloride data (SAR Section 2.3.2.4.1.2.4.5). As can be seen in Tables 2 and 3, differences in mean seepage rate between transient and episodic flow processes are approximately 2% to 3% for Case 1, and approximately 13% to 18% for Case 2. By comparison, the uncertainty for mean seepage rate associated with uncertainty in percolation flux is 137%. Furthermore, the response to RAI 3.2.2.1.3.6-007 has shown that a minor increase in mean percolation flux, and the associated minor increase in mean seepage rate, would have a negligible effect on estimates of repository performance for 10,000 years after closure. Therefore, the effects of temporal fluctuations in percolation flux within a climate state have a negligible effect on the mean seepage rate, supporting the low consequence exclusion of FEP 2.2.07.05.0A.

Table 2. Case 1: Seepage Results for Transient Flow Variations in Percolation Flux of ±20%

Glacial Transition Uncertainty Scenarios	Steady Flow Percolation Rate (mm/yr)	Steady Flow Process Mean Seepage Rate (kg/yr per waste package)	Transient Flow Process Mean Seepage Rate (kg/yr per waste package)	TSPA Weighting Factors	Percent Difference in Mean Seepage Rate
10th percentile	12.2	15.6	16.0	0.6191	2.9
30th percentile	26.3	62.6	64.2	0.1568	2.6
50th percentile	36.2	109.8	112.5	0.1645	2.4
90th percentile	69.7	338.0	345.1	0.0596	2.1
Average	21.8	57.7	59.1		2.4
Standard deviation	15.2	78.9	80.6		2.1
Coefficient of variation	70%	137%	136%		

Table 3. Case 2: Seepage Results for Transient Flow Variations in Percolation Flux of ±50%

Glacial Transition Uncertainty Scenarios	Steady Flow Percolation Rate (mm/yr)	Steady Flow Process Mean Seepage Rate (kg/yr per waste package)	Transient Flow Process Mean Seepage Rate (kg/yr per waste package)	TSPA Weighting Factors	Percent Difference in Mean Seepage Rate
10th percentile	12.2	15.6	18.4	0.6191	18.2
30th percentile	26.3	62.6	72.7	0.1568	16.2
50th percentile	36.2	109.8	126.7	0.1645	15.3
90th percentile	69.7	338.0	382.9	0.0596	13.3
Average	21.8	57.7	66.5		15.2
Standard deviation	15.2	78.9	89.4		13.3
Coefficient of variation	70%	137%	135%		

1.2 TRITIUM DATA AND EPISODIC FLOW

1.2.1 Fast Transport from the Ground Surface and the Conceptual Flow Model in the Unsaturated Zone.

The unsaturated zone flow model has been used to investigate the possibility of rapid transport between the ground surface and the repository level for comparison to observations of ^{36}Cl (SAR 2.3.2.3.4.3). The investigation was based on the steady-flow conceptual model over the entire model domain. In that study, approximately 1% of the tracer released at the ground surface arrived at the level of the repository within a 50-year time period. The study further showed that fast transport was principally facilitated by faults. Thus, a small fraction of water that entered the unsaturated zone during the time of nuclear device testing in the 1950s and 1960s, when atmospheric ^{36}Cl levels rose significantly, can be expected to be present at the repository level, particularly in faults. Therefore, the presence of modern water (water that entered the unsaturated zone since 1952 when nuclear device testing began at the Nevada Test Site) at the repository level can be explained within the framework of the steady-flow approximation.

As a result of heterogeneity in rock properties and stratigraphy, heterogeneity in infiltration, and diffusion and dispersion mechanisms, it is generally expected that some small fraction of water that entered the unsaturated zone within the last 50 years has penetrated to the repository level. This fraction is larger in faults because the hydrogeologic properties of faults result in greater fracture flow through the PTn hydrogeologic unit than in the general fractured rock mass.

1.2.2 Factors That May Lead to the Appearance of Modern Water in the Deep Unsaturated Zone

The main processes and boundary conditions that can lead to the appearance of tritium in the deep unsaturated zone (in the lower PTn hydrogeologic unit and below), consistent with the conceptual model for unsaturated zone flow and transport, are the following:

(1) Transport through faults

(2) Partial penetration of the PTn hydrogeologic unit in the fractured rock mass (other than faults) by episodic fracture flow

(3) Spatially variable infiltration patterns

(4) Heterogeneous hydrologic properties within unsaturated zone flow model layers

(5) Hydrodynamic dispersion.

The conceptual model and model parameterization of the unsaturated zone flow model leads to significant fracture flow through the PTn hydrogeologic unit in some fault locations but not in the fractured rock mass. Therefore, rapid transport through and beneath the PTn hydrogeologic unit is most pervasive in faults. Predominant matrix flow and transport in the fractured rock mass below the repository are limited to the vitric portion of the CHn hydrogeologic unit and to a lesser degree in some of the devitrified and welded units lower in the CHn (Prow Pass) and Crater Flat undifferentiated (CFu) hydrogeologic units.

Observations at UE-25 UZ#4 in Pagany Wash (see Section 1.3.2) and model calculations (SNL 2007a, Section 6.9) indicate that episodic flow in fractures located in the Tiva Canyon welded hydrogeologic unit (TCw) can transport water into the PTn hydrogeologic unit. Monitoring data indicate that the water entered the Yucca Mountain Tuff lithostratigraphic unit (a component of the PTn hydrogeologic unit), but evidence of episodic flow below the Yucca Mountain Tuff was not observed over two additional years of data collection (LeCain et al. 2002). Therefore, this episodic event appeared to be damped within the PTn hydrogeologic unit.

Additional factors can lead to the appearance of elevated tritium levels in the deep unsaturated zone (i.e., PTn and below). These include spatially variable infiltration and smaller-scale heterogeneity in hydrologic properties within the unsaturated zone, which can lead to spatially variable percolation fluxes and transport velocities. Dispersion can also be important because this mechanism advances low concentrations faster than the average transport velocity.

1.2.3 Source of Tritium

Tritium originates in the atmosphere through natural processes at a natural tritium concentration level of about 6 tritium units (TU) for precipitation at Yucca Mountain (BSC 2006, Section 5). In addition to natural processes, nuclear device testing during the 1950s and 1960s elevated atmospheric tritium levels (bomb-pulse tritium) with peak levels of about 1,900 TU (Figure 2) measured in precipitation at Albuquerque, New Mexico. Local data in the vicinity of Yucca Mountain over this entire time period are not available. Tritium decays with a half-life of about 12.3 years (BSC 2006, Section 5).

Because unsaturated zone tritium measurements at Yucca Mountain were made during the period 1993 through 2002, source term decay must be considered. When corrected for decay to 1995, peak tritium level decreases to about 300 TU. Decay-corrected tritium levels above 100 TU only occur for years 1963 and 1964. Decay-correction to 2002 reduces the maximum tritium concentrations to about 200 TU. The threshold tritium level indicating the presence of modern water (post 1952) was determined to be in the range of 1.4 to 2 TU (BSC 2006, Sections 5.4.1 and 5.4.2), which is approximately the background level of 6 TU decayed over 2 half-lives. For this discussion, the 1.4 TU threshold is used in order to ensure that the potential presence of modern water is not underestimated.

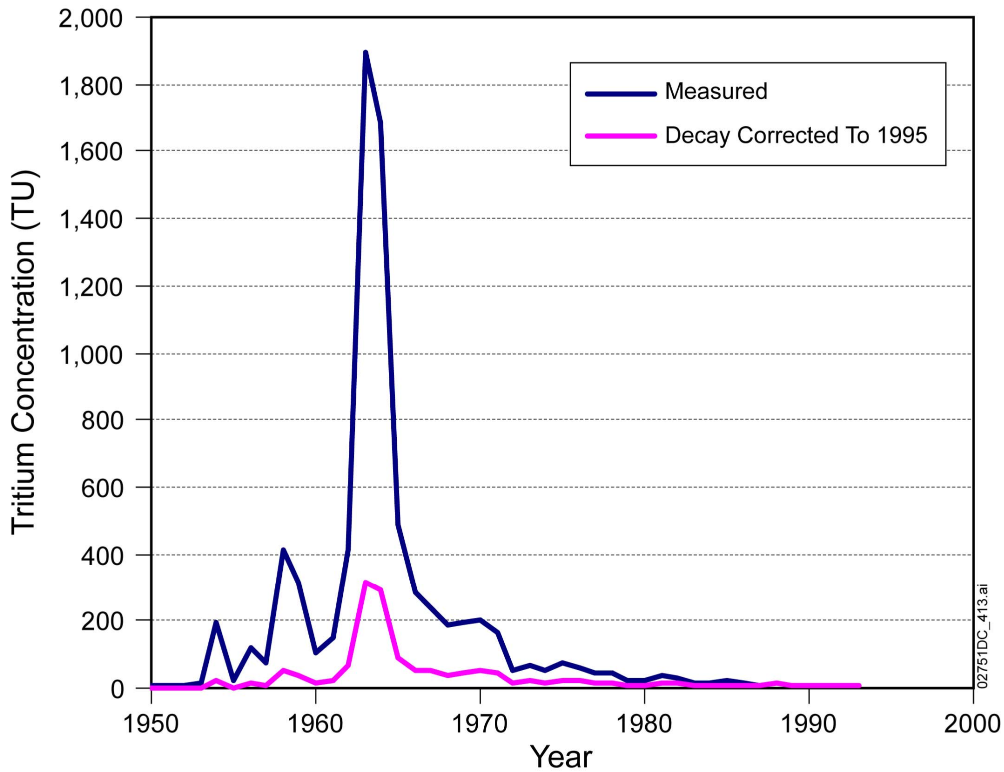


Figure 2. Atmospheric Tritium Levels at Albuquerque, New Mexico

To quantitatively assess the fraction of modern water represented by a tritium concentration above the threshold, it is necessary to know the tritium levels of infiltrating waters over the past 50 years, using the source term curve presented in Figure 2, for Albuquerque, New Mexico. However, a new analysis of existing information presented below indicates that the tritium concentrations in infiltrating water at Yucca Mountain must have been higher than the data derived from the Albuquerque measurements would suggest. If so, the fraction of modern water necessary to achieve a given tritium concentration would be correspondingly reduced.

1.2.4 Tritium Measurements on Unsaturated Zone Samples

Tritium was measured for approximately 860 samples from the unsaturated zone at Yucca Mountain. Measurement techniques changed over time, which generally resulted in improved detection limits (Peterman 2003; BSC 2006). The tritium data are divided into two categories representing samples from surface-based boreholes (Table 4) and samples from the Exploratory Studies Facility (ESF) and Enhanced Characterization of the Repository Block (ECRB) drifts (Table 5). (Because of their length, these tables are located at the end of the response following the summary in Section 1.6.) Because the detection limits of 8.2 to 17.1 TU for this analysis exceeded the threshold for the presence of modern water, measured tritium values that lie below the detection limit are not considered interpretable relative to the presence of modern water and are not included in Table 4.

Data in Table 5 present the tritium measurements from the ESF and the ECRB drifts. The majority of the data from the ESF and all of the ECRB samples were analyzed using a more sensitive technique having a detection limit of 0.4 to 1 TU (BSC 2006, Section 5.4.2). A limited number of measurements from the ESF were analyzed using the less sensitive method. For these data, as for the surface-based borehole data, any ESF samples with measured tritium levels below the detection limits of 8.2 to 17.1 TU are not included in Table 5. Measurements using the more sensitive technique were not screened based on detection limits. With the exception of nine values, the data presented in Table 5 are for samples analyzed using the more sensitive technique. The screening based on detection limits excludes approximately 500 of the 860 total samples from Tables 4 and 5.

Uncertainty in the less sensitive method is a combination of both "internal" and "external" uncertainties. The internal error, based on counting statistics, is estimated to be about ±4 TU (Peterman 2003). The external error was estimated, using 29 duplicate and 6 triplicate analyses, to be 5.7 TU. The internal and external uncertainties are combined to yield the total uncertainty using:

$$\sigma_{total} = (\sigma_{internal}^2 + \sigma_{external}^2)^{0.5}$$

to yield a combined 1σ error of about ±7 TU (2σ = ±14 TU). When estimates of detection limits and analytical uncertainty are combined, only analyses having uncertainties greater than 22 to 31 TU can be considered to contain tritium that is detectable above analytical background at the 95% confidence interval (Table 4). Note that this cutoff eliminates post-bomb pulse waters that have returned to pre-bomb-pulse levels, and hence does not screen directly for modern waters (TU ~ 6TU).

In Table 4, samples with tritium concentrations above the 95th percentile confidence limit from the surface-based boreholes are highlighted in yellow. These measurements are considered interpretable and indicate the presence of bomb-pulse water. In Table 5, samples from the ESF and ECRB with tritium concentrations greater than or equal to 1.4 TU are highlighted in yellow. These measurements indicate the presence of modern water.

Tables 4 and 5 provide additional information for the tritium measurements, including sample identification and location, date, extraction method, stratigraphy, unsaturated zone flow model layer, and qualification status.

1.2.5 Qualitative Assessment of Tritium Information from Surface-Based Boreholes

Table 4 presents the measurements of tritium from the surface-based boreholes that are above detection limits. Tritium values above the 95th percentile confidence limit were found in boreholes UE-25 UZ-16, USW WT-24, USW SD-6, USW NRG-6, USW UZ-14, USW SD-12, and USW NRG-7a. Distances between boreholes and faults are based on Figure 6.1-1 of *UZ Flow Models and Submodels* (SNL 2007a). A large number of measured values from the surface-based boreholes lie below detection limits. To provide information on the coverage of the measurements, Figures 3, 4, and 5 also include non-negative values that are below detection limits.

Borehole UE-25 UZ-16

Thirty-two elevated measurements of tritium were found for borehole UE-25 UZ-16 within the ptn21, tsw31-tsw32, tsw34 through tsw38, ch2-ch5, and pp4 unsaturated zone flow model layers (Figure 3). The borehole lies about 160 m west of the Imbricate Fault, about 300 m east of the Dune Wash Fault, and more than a kilometer east of waste emplacement areas. Geologic maps of the ESF South Ramp, which lies about a kilometer south of the borehole, identified additional (unnamed) faults east of the Dune Wash Fault (BSC 2006, Figure 5-5). The presence of faults in the immediate vicinity of UE-25 UZ-16 is uncertain because of alluvial cover. The highest levels of tritium in the unsaturated zone were found in two samples in the tsw34 at levels of 300 to nearly 500 TU. These samples were collected in 1995. The maximum possible levels based on the source term for tritium is about 300 TU when decay-corrected to 1995. Furthermore, even a value of 300 TU is highly unlikely, because the source was at this level for only two years (1963 and 1964) and the samples are from depths of over 180 meters. The high values of tritium found in UE-25 UZ-16 are concluded to be due to the proximity of Yucca Mountain to the source of atmospheric tritium, the Nevada Test Site. These values would have been greater than those estimated from the regional information collected in Albuquerque, New Mexico.

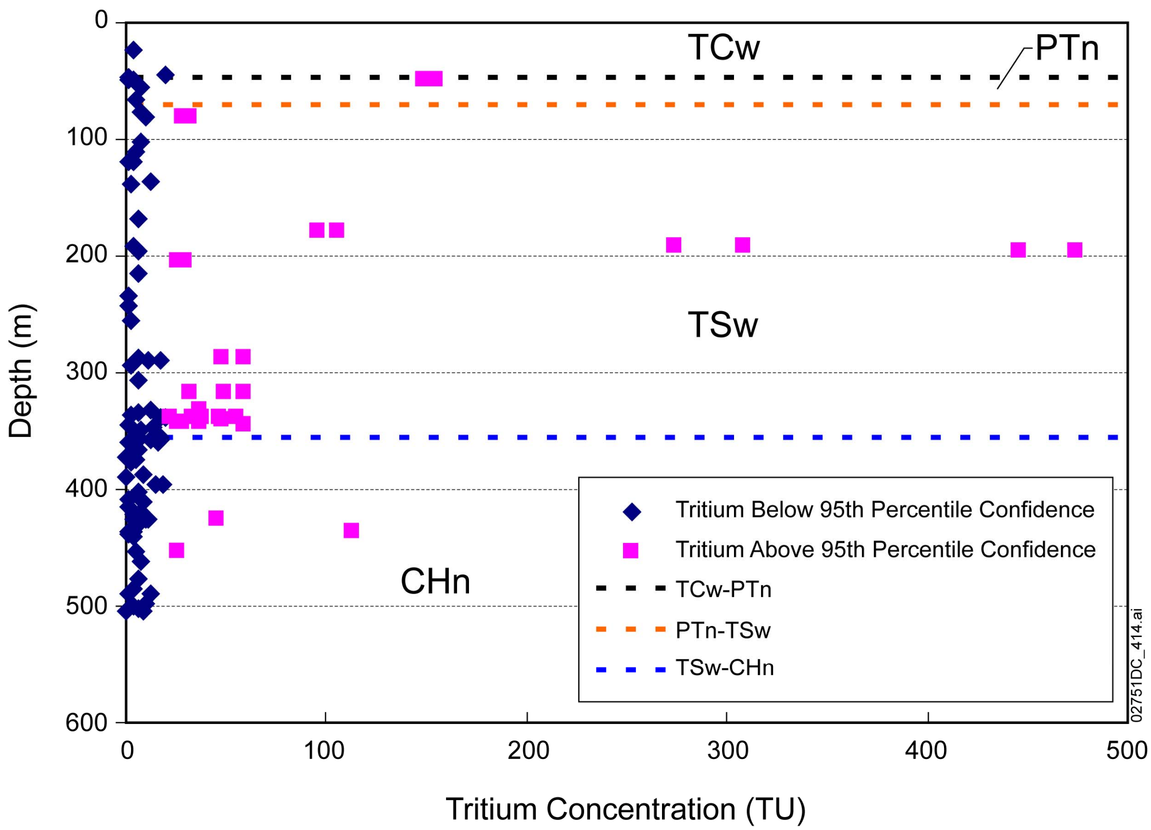


Figure 3. Tritium Measurements in Borehole UE-25 UZ-16

Borehole USW WT-24

Twenty-one elevated measurements of tritium were found for borehole USW WT-24 within the tsw38 and ch2-ch5 unsaturated zone flow model layers (Figure 4). Measurements from this borehole are limited to the lower portion of the Topopah Spring welded (TSw) hydrogeologic unit and the CHn hydrogeologic unit. Most of the values are either at or near perched water levels at the TSw-CHn hydrogeologic unit interface or at or near the water table. The borehole lies about 150 m northeast of Pagany Wash Fault. The high levels of tritium near the TSw-CHn hydrogeologic unit interface suggest that fast transport down the Pagany Wash Fault may have been diverted near USW WT-24 along perched water and along the water table. Strong lateral flow is expected in areas where the CHn hydrogeologic unit is highly zeolitized, as it is at USW WT-24.

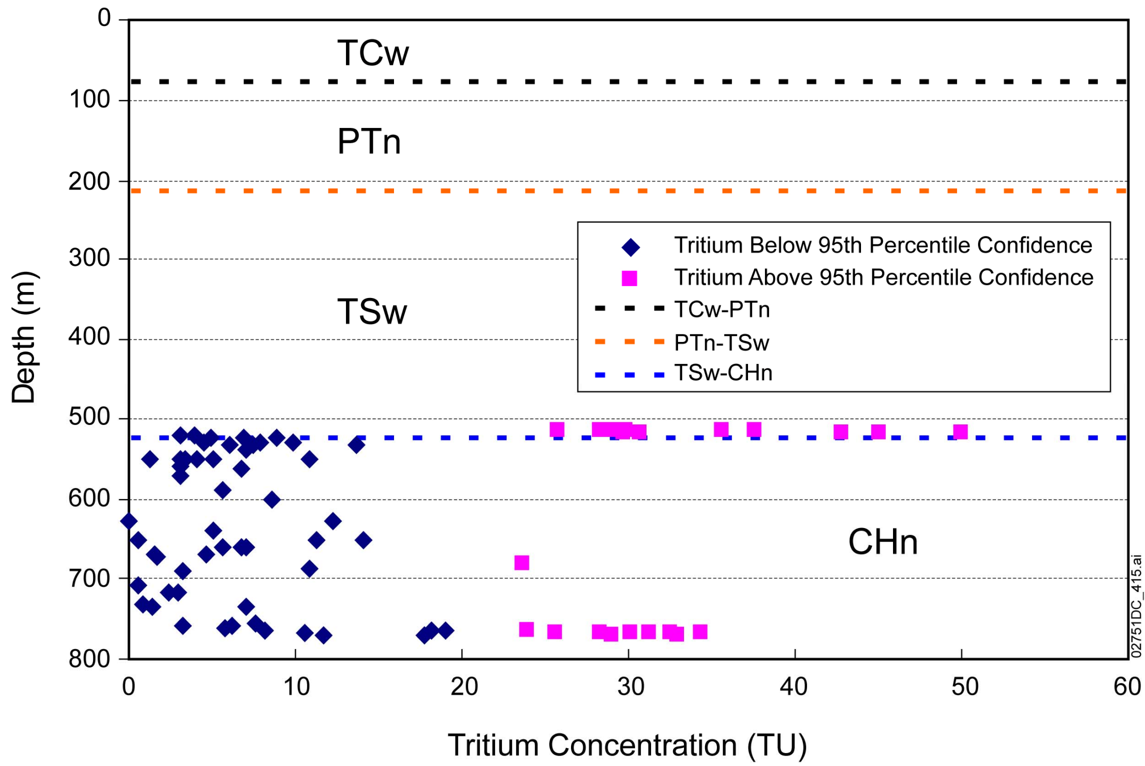


Figure 4. Tritium Measurements in Borehole USW WT-24

Borehole USW SD-6

Ten elevated measurements of tritium were found for borehole USW SD-6 within the tsw37 and pp3 unsaturated zone flow model layers (Figure 5). The borehole lies about 400 m east of the Solitario Canyon Fault. The PTn is relatively thin in this area (about 21 m) and higher tritium levels may be attributed to small-scale lateral diversion within the PTn and partial penetration of episodic flow through the PTn, in addition to fast transport through the fault. Results from the unsaturated zone flow model are consistent with the presence of small amounts of modern water at the repository level near USW SD-6.

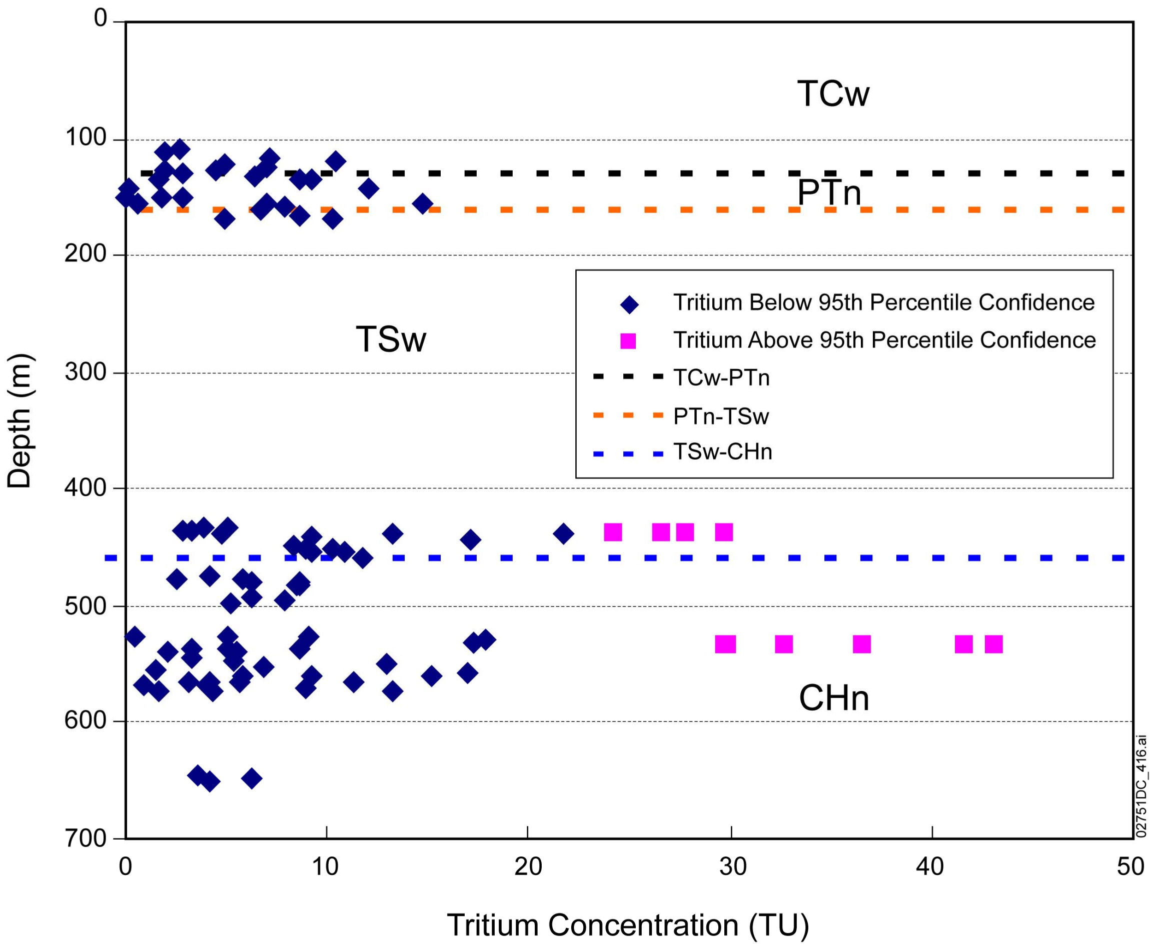


Figure 5. Tritium Measurements in Borehole USW SD-6

Borehole USW NRG-6

Eight elevated measurements of tritium were found for borehole USW NRG-6 within the ptn25 and ptn26 unsaturated zone flow model layers (Table 4). As for USW UZ-14, partial penetration of the PTn hydrogeologic unit by episodic flow as observed in Pagany Wash is the likely explanation for the presence of elevated tritium values in this borehole.

Borehole USW UZ-14

Three elevated measurements of tritium were found for borehole USW UZ-14 within the ptn25 unsaturated zone flow model layer (Table 4). The possibility of partial penetration of the PTn hydrogeologic unit by episodic flow as observed in Pagany Wash is the likely explanation for the presence of elevated tritium values in this borehole.

Borehole USW SD-12

Two elevated measurements of tritium were found for borehole USW SD-12 within the pp3 unsaturated zone flow model layer (Table 4). The borehole lies about 180 m west of the Ghost Dance Fault. The elevated levels of tritium below perched water in USW SD-12 suggest rapid transport along the fault with lateral redistribution within the more permeable pp3.

Borehole USW NRG-7a

One elevated measurement of tritium was found for borehole USW NRG-7a within the tsw31-tsw32 unsaturated zone flow model layers (Table 4). The borehole is about 260 m southwest of Drill Hole Wash Fault.

In summary, elevated levels of tritium indicative of bomb-pulse water have been found in surface based boreholes associated with faults or in samples within the PTn hydrogeologic unit. In some cases, the presence of modern water may be a result of episodic flow and transport through the upper portion of the PTn hydrogeologic unit, combined with dispersive transport through the lower portion. This could allow a small fraction of modern water to enter the TSw, particularly if the region is subject to percolation fluxes that are above average values.

1.2.6 Qualitative Assessment of Tritium Information from the ESF and ECRB

Table 5 presents the measurements of tritium from the ESF and ECRB. Values given in Table 5 that were measured with the less sensitive technique (ESF only, see Section 1.2.4) are restricted to values that lie above detection limits. Samples with tritium levels in excess of both the 95th percentile confidence limit and the 1.4 TU threshold indicating the presence of modern water are assessed in this section in response to the RAI. Information about distances between measurements and fault locations were taken from Figures 5-3, 5-5, and 5-6 of *Chlorine-36 Validation Study at Yucca Mountain, Nevada* (BSC 2006).

ESF

Most of the measurements in the ESF were conducted using the more sensitive technique described in Section 1.2.4. Measurements made using this technique were not screened on detection limit for Table 5. A smaller number of measurements were made using the less sensitive technique. Nine values measured with this technique lie above detection limits and are shown in Table 5. Figure 6 only displays ESF data from Table 5. Thirty-nine samples from the ESF were found to be greater than or equal to 1.4 TU, indicating the presence of modern water (Figure 6).

ESF North Ramp

Eight elevated measurements of tritium are from the Bow Ridge Fault area (Station 1+68) and lie in the tcw12 unsaturated zone flow model layer or other layers above the PTn hydrogeologic unit (Figure 6). One value from the ESF, at Station 7+54, measured with the less sensitive technique (see Section 1.2.4) is above the detection limit but below the 95th percentile confidence level. Two elevated measurements of tritium were found near the intersection of the Drill Hole Wash Fault in the tsw33 unsaturated zone flow model layer at Stations 19+30 and 19+50.

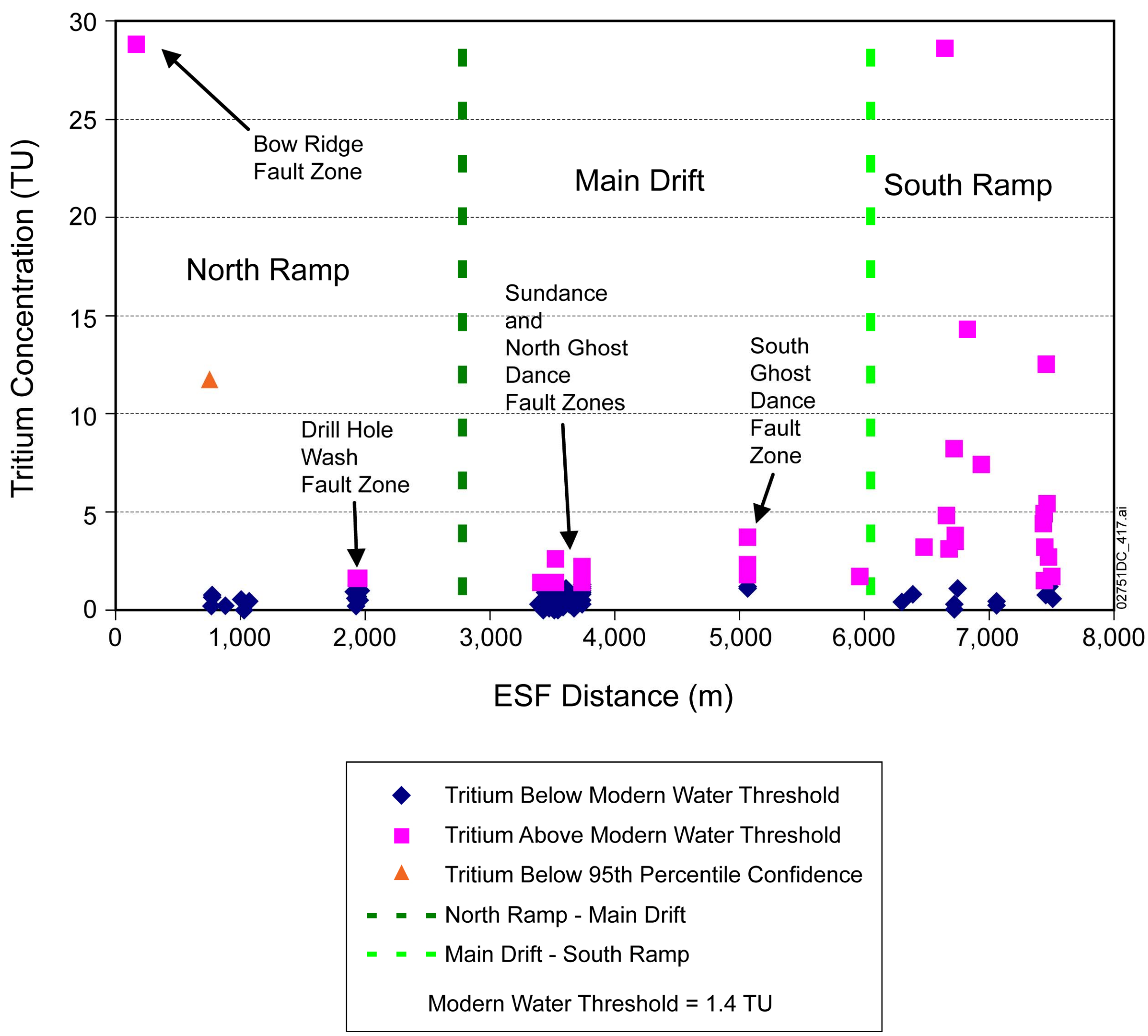
ESF Main Drift

Eight elevated measurements of tritium were found near the Sundance and north Ghost Dance faults in the tsw34 between Stations 34+10 and 37+37. Three elevated tritium values were found near the southern Ghost Dance Fault in the tsw34 at Station 50+64. A single elevated tritium concentration value of 1.7 TU was found at Station 59+65 in the tsw34 (at the corner of the Main Drift and South Ramp), possibly linked to the numerous high values found in the ESF South Ramp.

ESF South Ramp

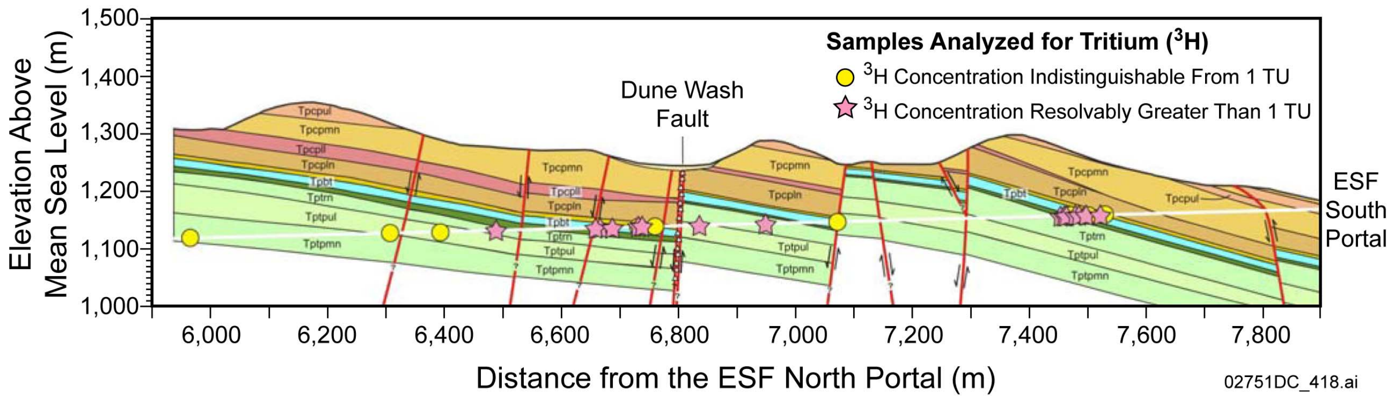
More elevated tritium levels were found in the South Ramp than in either the North Ramp or Main Drift of the ESF. This area is characterized by a greater density of faults and a thin PTn hydrogeologic unit. Notably, a seepage event into the ESF was observed after several months of unusually heavy precipitation in February 2005 (SNL 2007b, Section 7.1[a]). No other locations in the underground tunnels were found to have seepage, which suggests that the region of the South Ramp may be unique and more readily affected by fast transport from the ground surface.

A single elevated tritium concentration value of 3.2 TU was found at Station 64+80 in the tsw33, within 40 m of an unnamed fault (Figure 7). Three elevated tritium concentrations were found at Stations 66+48, 66+58, and 66+80, respectively. These lie within the ptn26 with offsets of approximately 0 to 30 m from an unnamed fault. Three elevated measurements of tritium were found in the tcw12 at Stations 67+21 and 67+30, about 30 to 40 m from an unnamed fault. A single elevated tritium concentration value was found at Station 68+26 in the tsw33, about 30 m from the Dune Wash Fault. A single elevated tritium concentration value of 7.4 TU was found at Station 69+37 in the tsw31-tsw32, about 140 m from an unnamed fault. A tritium concentration value of 4.4 TU was found at Station 74+35 in the tsw31-tsw32, about 200 m from an unnamed fault. Seven elevated measurements of tritium were found at Stations 74+41 to 75+03 in the ptn26, ptn24, and tcw12, about 200 m from an unnamed fault.



NOTE: Seven values at Station 1+68 are not shown in the figure because they are above 30 TU.

Figure 6. Tritium Measurements in the Exploratory Studies Facility



Quaternary

- Qac — Alluvial and Colluvial Deposits

Paintbrush Group (Miocene)

Tiva Canyon Tuff

Crystal-poor Member

- Tpcpul — Upper Lithophysal Zone
- Tpcpum — Upper Lithophysal Zone and Middle Nonlithophysal Zone Undivided
- Tpcpmn — Middle Nonlithophysal Zone
- Tpcpll — Lower Lithophysal Zone
- Tpcpln — Lower Nonlithophysal Zone
- Tpcpv — Crystal-poor Vitric Zone

Bedded Tuffs

- Tpbt — Includes: pre-Tiva Canyon Tuff Bedded Tuff (Tpbt4), Yucca Mountain Tuff (Tpy), pre-Yucca Mountain Tuff Bedded Tuff (Tpbt3), Pah Canyon Tuff (Tpp), and pre-Pah Canyon Tuff Bedded Tuff (Tpbt2)

Topopah Spring Tuff

Crystal-rich Member

- Tptrv — Vitric Zone
- Tptrn — Nonlithophysal Zone

Crystal-poor Member

- Tptpul — Upper Lithophysal Zone
- Tptpmn — Middle Nonlithophysal Zone

NOTE: A limit of 1 TU instead of 1.4 TU was used as a threshold for high and low tritium values in this figure.

Source: BSC 2006, Figure 5-5.

Figure 7. Geologic Section of the ESF South Ramp Showing Locations of Samples Analyzed for Tritium

ECRB

All of the ECRB measurements were made using the more sensitive technique. Therefore, all ECRB measurements are shown in Table 5 and on Figure 8. Eleven samples from the ECRB were found to be greater than or equal to 1.4 TU (Figure 8). Four elevated values of tritium concentration ranging from 1.7 to 6.5 TU at Stations 7+50 to 9+50 were found in the tsw33. Five elevated values of tritium concentration ranging from 1.5 to 10.3 TU at Stations 13+51 and 14+99 (three duplicate samples) were found in the tsw34. Two elevated values of tritium concentration with values of 3.6 and 9.8 TU at Stations 19+50 to 21+49 were found in the tsw35. All of the ECRB samples with elevated tritium concentrations were 200 m or more from mapped major faults. Despite the relatively large distances between the elevated tritium measurements and major faults in the ECRB, lateral movement from faulted areas could occur during transport from the base of the PTn hydrogeologic unit to the ECRB.

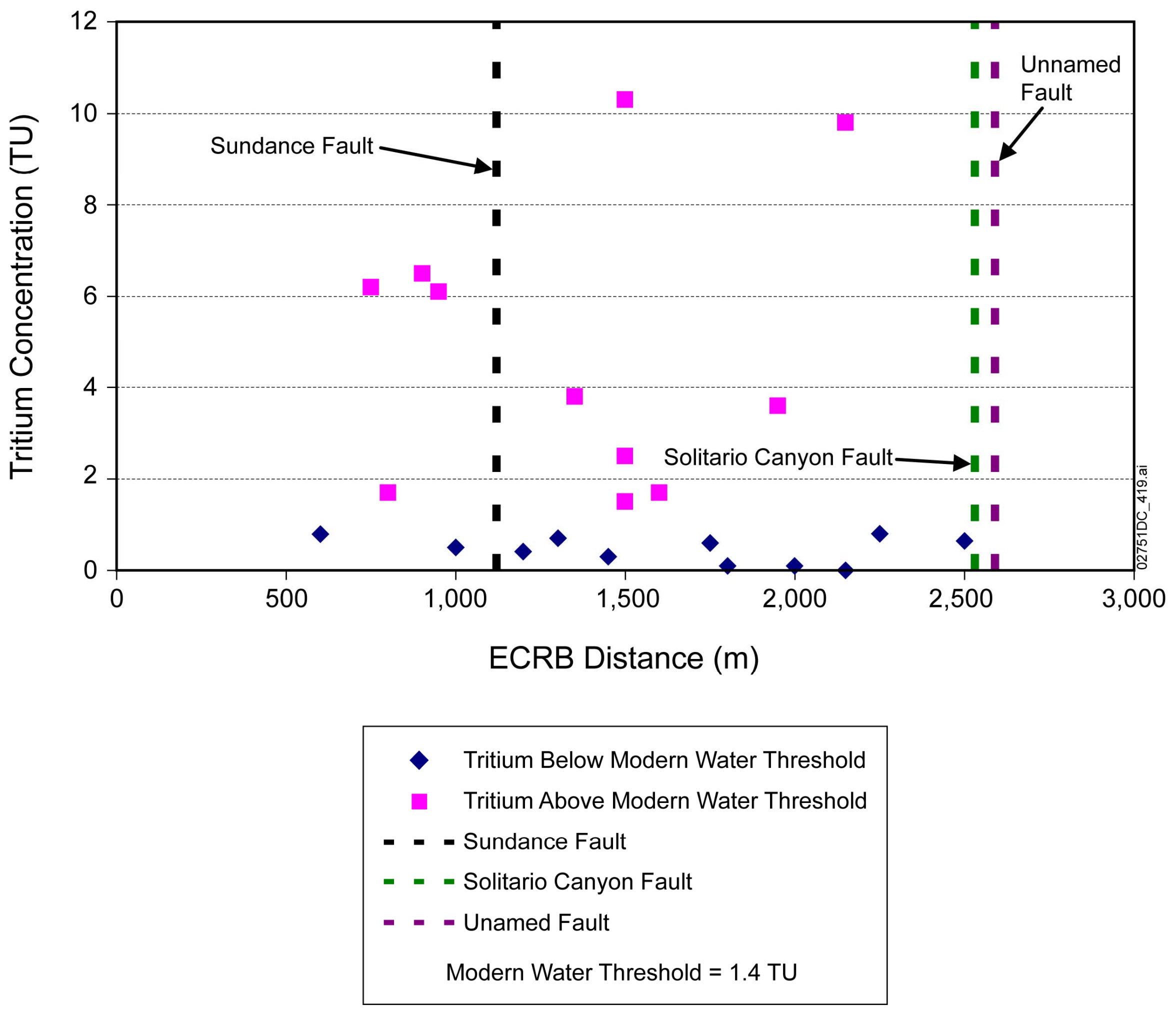


Figure 8. Tritium Measurements in the ECRB

In summary, nearly all of the elevated tritium concentrations found in samples from the ESF were either in close proximity to faults or were taken from TCw or PTn hydrogeologic units. In contrast, the samples with elevated tritium concentration from the ECRB all lie within repository units of the TSw hydrogeologic unit and were not found to be associated with faults. In addition, the highest levels of tritium were found in faulted areas of the ESF North and South Ramps; tritium values found in the ESF Main Drift and the ECRB are 10 TU or less. The PTn hydrogeologic unit above the ECRB is roughly 40 m in thickness (SNL 2008b, Figures D-1 and D-3). Episodic flow and transport through the upper portion of the PTn, combined with dispersive transport through the lower portion could allow a small fraction of modern water to enter the TSw, particularly if the region is subject to percolation fluxes that are above average. Fracture-dominated transport in the TSw hydrogeologic unit would allow for penetration of a small fraction of this water into the repository horizon.

1.2.7 Example of Enhanced Transport through the PTn Hydrogeologic Unit

The data discussed in Sections 1.2.5 and 1.2.6 suggest that in a few cases, water with tritium concentration in excess of 1.4 TU may have moved through the PTn hydrogeologic unit in the general rock mass (i.e., without moving through a fault). This raises the issue as to whether these cases could only be explained by an episodic flow event that penetrates the PTn hydrogeologic unit. It is possible for water with a tritium concentration in excess of 1.4 TU to penetrate the general rock mass of the PTn hydrogeologic unit under steady flow conditions in the lower part of the PTn hydrogeologic unit.

Consider a case where the PTn hydrogeologic unit is 40 m thick, similar to the stratigraphy above the ECRB. The present-day average percolation flux for the 10th percentile scenario is about 3 mm/yr (SNL 2007a, Table 6.1-2), and the water content in the PTn is about 0.2, which gives a transport velocity of about 15 mm/yr. A calculation of tritium transport to the base of the PTn hydrogeologic unit requires a longitudinal dispersivity. A value of 5 m is used, based on reported ranges of field-scale dispersivities for saturated flow conditions (Gelhar et al. 1992) and enhanced disperivities found for unsaturated flow conditions as compared with saturated flow conditions (Toride et al. 2003). Assume that episodic flow can quickly transport tritium through the TCw hydrogeologic unit. Furthermore, based on observations at Pagany Wash and model results showing sustained fracture flow in the ptn21 model layer, assume that transport is fast through the first 10 m of the PTn hydrogeologic unit before fracture water is substantially imbibed into the matrix. Transport through the remainder of the PTn hydrogeologic unit is in the matrix. This is modeled using a one-dimensional, single-continuum, advection-dispersion transport process for a series of instantaneous, annual releases over the 500-year period from 1496 to 1995. Releases prior to this period are not included because they have a negligible effect on the computed tritium concentrations. The concentration for a series of annual, instantaneous point source releases of mass is given by (Bear 1972, p. 629, Equation (10.6.12) and p. 613, Equation (10.4.16)):

$$c(z,t) = \sum_{i=1}^{499} \frac{M(\tau_i)\exp[-\lambda(t-\tau_i)]}{\sqrt{4\pi\alpha\, v(t-\tau_i)}} \exp\left[-\frac{\{z - v(t-\tau_i)\}^2}{4\alpha\, v(t-\tau_i)}\right]$$

where c is the tritium concentration in TU, z is the depth in meters, t is the time of observation in years (which is 1995), τ_i is the time of tracer release at the ground surface, (which ranges from 1496 to 1994), $M(\tau_i)$ is the amount of tritium per square meter (in TU-m) entering the unsaturated zone at time τ_i, v is the transport velocity (equal to the percolation flux divided by the water content) in meters/year, α is the dispersivity in meters, and λ is the decay constant per year. The amount of tritium released per square meter of wetted surface area over one year is:

$$M(\tau_i) = vc_s(\tau_i)$$

where $c_s(\tau_i)$ is the source concentration of tritium (TU) at the ground surface at time τ_i.

The tritium concentration at the base of the PTn is computed using the source profile given in Figure 2 and assuming a 6 TU source concentration for the period prior to 1952. Table 6 gives the results for a hypothetical sample collected in 1995. The results are computed for a range of transport velocities that vary from 15 to 675 mm/yr, considering both infiltration and hydrogeologic property variability that could result in faster transport. A maximum factor of 45 was used for transport velocity variations. This is based on a factor of 9 variation in the average infiltration flux for the present-day 10th and 90th infiltration cases (SNL 2007a, Table 6.1-2) and hydrogeologic property variability, which could lead to another factor of 5 variation in transport velocity.

Table 6. Tritium Concentrations at the Base of the PTn

Transport Velocity Multiplier	Tritium Concentration (TU)	Tritium Concentration (TU) with 10× Source (1954 to 1970)	Tritium Concentration (TU) with 100× Source (1954 to 1970)
1	5.9×10^{-11}	5.9×10^{-11}	5.9×10^{-11}
8	0.0039	0.018	0.16
20	1.7	16	160
45	20	180	1800

The source term is also uncertain, particularly over the period significantly affected by nuclear device testing from 1954 through 1970. As discussed earlier, with respect to the high values of tritium found in borehole UE-25 UZ-16, a source concentration may have been higher than shown in Figure 2. Table 6 shows cases where the source tritium concentration between 1954 and 1970 is increased by factors of 10 and 100. The results show that for certain conditions, tritium concentrations above the threshold for the presence of modern water can penetrate the general rock mass of the PTn hydrogeologic unit. Therefore, the presence of modern water below the PTn hydrogeologic unit does not necessarily imply that episodic flow has penetrated the PTn hydrogeologic unit.

1.2.8 Summary of Tritium Evaluations

Data from the surface-based boreholes indicate that only a small number of the total measurements can be confirmed as representative of bomb-pulse water. Similarly, data from the ESF and ECRB analyzed using more a sensitive technique show that most of the measured concentrations lie below the threshold for the presence of modern water. A few high levels of tritium measured from borehole UE-25 UZ-16 indicate that, during the period of nuclear device testing, the source levels of tritium at Yucca Mountain were higher than available decay-corrected atmospheric measurements at Albuquerque, New Mexico. Because of the uncertainty in the source concentration, the amount of modern water required to raise tritium concentrations in subsurface samples above the threshold is uncertain.

Many of the cases where tritium concentrations indicate the presence of modern water were taken from locations in or near faults. These cases are consistent with transport simulations using the unsaturated zone flow model, which indicate a small fraction of mass arrivals between the ground surface and the repository level can occur through fault pathways within 50 years. In a few cases, such as in the ECRB, the presence of modern water is indicated at locations not associated with faults. An analysis of tritium transport through the PTn hydrogeologic unit show that for certain conditions, tritium concentrations above the threshold for the presence of modern water can penetrate the general rock mass of the PTn hydrogeologic unit. Conditions that lead to this result are higher average percolation flux, localized flow focusing, reduced water content associated with localized areas of higher permeability, and enhanced atmospheric tritium levels. Therefore, the presence of modern water below the PTn hydrogeologic unit does not necessarily imply that episodic flow has penetrated the PTn hydrogeologic unit.

1.3 TEMPERATURE DATA AND EPISODIC FLOW

1.3.1 Discussion of Temperature Logs from Borehole UE-25 a#7

Temperature logs in borehole UE-25 a#7 (referred to here as a#7) suggest movement of water originating as surface runoff from major precipitation events, into the subsurface at depths greater than 100 m, within a few days. Multiple precipitation events were recorded in the vicinity of Yucca Mountain during the period spanned by the logs, and are represented in the temperature variations. This response discusses the temperature transients observed within borehole a#7 and provides the bases for the interpretation that these are artifacts of water moving through the borehole and not deep percolation flux driven by transient infiltration in response to precipitation/streamflow events.

Borehole a#7 was drilled in 1979 and 1980 to a depth of 305.5 m (1,002 ft) and at an angle of nominally 26° from vertical. The hole has steel surface casing, and grouted plastic casing to 40.9 m (134 ft) (Table 7). The borehole was opened to 12-1/4" diameter to a depth of 42.0 m (138 ft), prior to grouting of the plastic casing to 40.9 m (134 ft). Below 42.0 m depth, the hole was drilled in two core sizes, reducing from 5.5" to 3.875" diameter at a depth of 153.0 m (502 ft). At completion of the hole, a string of tubing (2-3/8" diameter, water-filled) was installed from the surface to 291.5 m (956 ft) depth for temperature logging. Depths to stratigraphic contacts for borehole a#7 are shown in Table 8. Note that only part of the alluvium section is cased, leaving approximately 9.4 m uncased immediately above the reported alluvium–bedrock contact at 50.3 m depth.

Table 7. Construction of Borehole UE25 a#7

Borehole			Casing		
From	To	Size	From	To	Size
0	3.0 m (10 ft)	15"	0	3.0 m (10 ft)	13-3/8" OD (steel)
3.0 m (10 ft)	42.0 m (138 ft)	12-1/4"	0	40.9 m (134 ft)	7.625" ID (plastic)
42.0 m (138 ft)	152.4 m (500 ft)	5-1/2"(core)	N/A	291.5 m (956 ft)	2-3/8" OD (steel tubing)
152.4 m (500 ft)	153.0 m (502 ft)	4-1/2"	N/A		
153.0 m (502 ft)	305.5 m (1,002 ft)	3.875"(core)	0		

NOTE: Depths are uncorrected for borehole slant. ID = inside diameter; OD = outside diameter.

Table 8. Stratigraphic Picks for Borehole UE25 a#7

Lithology	Lithostratigraphy	Symbol	Contact Depth (m)[a]	Contact Type
Alluvium	Not described	Qa	0.0	Ground surface
Tiva Canyon welded	Tiva Canyon Tuff (Tpc) nondivided	Tpc-un	50.3	Partially eroded
	Tpc, crystal-poor vitric densely welded subzone	Tpcpv3	51.8	Not formed
	Tpc, crystal-poor vitric moderately welded subzone	Tpcpv2	51.8	Crystallization-vitric
	Tpc, crystal-poor vitric nonwelded to partially welded subzones	Tpcpv1	53.6	Welding
Nonwelded	Pre-Tiva Canyon Tuff; bedded tuff	Tpbt4	57.9	Deposition
	Yucca Mountain Tuff; nondivided	Tpy	59.2	Deposition
	Pre-Yucca Mountain Tuff; bedded tuff	Tpbt3	64.6	Deposition
	Pah Canyon Tuff; nondivided	Tpp	69.0	Deposition
	pre-Pah Canyon Tuff; bedded tuff	Tpbt2	81.3	Deposition
Topopah Spring welded	Topopah Spring Tuff (Tpt) crystal-rich vitric nonwelded to partially welded zones	Tplrv3	89.0	Deposition
	Tpt, crystal-rich vitric moderately welded zone	Tplrv2	92.6	Welding
	Tpt, crystal-rich vitric densely welded zone	Tplrv1	92.8	Welding
	Tpt, crystal-rich nonlithophysal zone	Tptrn	94.8	Vitric-crystallization
	Tpt, crystal-rich lithophysal zone	Tptrl	147.3	Crystallization
	Tpt, crystal-poor upper lithophysal zone	Tptpul	154.9	Crystallization
	Tpt, crystal-poor middle nonlithophysal zone	Tptpmn	234.8	Crystallization
	Tpt, crystal-poor lower lithophysal zone	Tptpll	267.9	Crystallization

[a] Depth to upper contact, uncorrected for borehole slant.

The borehole pad for a#7 is located in the lowest portion of Drill Hole Wash (Sass et al. 1988, Figure 3). The elevation of the ground surface and the top of the casing for borehole a#7 were both recorded originally as 4,004.6 ft. Recent observation of the borehole showed that the top of the casing is level with the ground surface, with the access tubing protruding above the casing. The tubing was capped, but the surface casing is open, possibly allowing flow of surface water directly into the hole. The pad was reworked for other uses after the logging study of Sass et al. (1988), and there is no additional information available on the configuration of the wellhead during that study.

The first of the temperature logs was acquired on 3/17/1981 (Sass et al. 1988). Later logs were acquired on 4/29/1981, 12/30/1981, 3/8/1983, and 3/6/1984. The temperature log of 12/30/1981 reflects the highest temperatures because it was acquired more than a year after drilling operations ceased, and precipitation was limited in the latter part of 1981, so there was more time for temperature transients to dissipate. Accordingly, the log of 12/30/1981 was selected as a reference, and it was depth-matched and subtracted from each of the other logs for plotting (Figure 9). In this plot, temperature transients associated with precipitation and possible streamflow in Drill Hole Wash are negative, and converge to zero with depth.

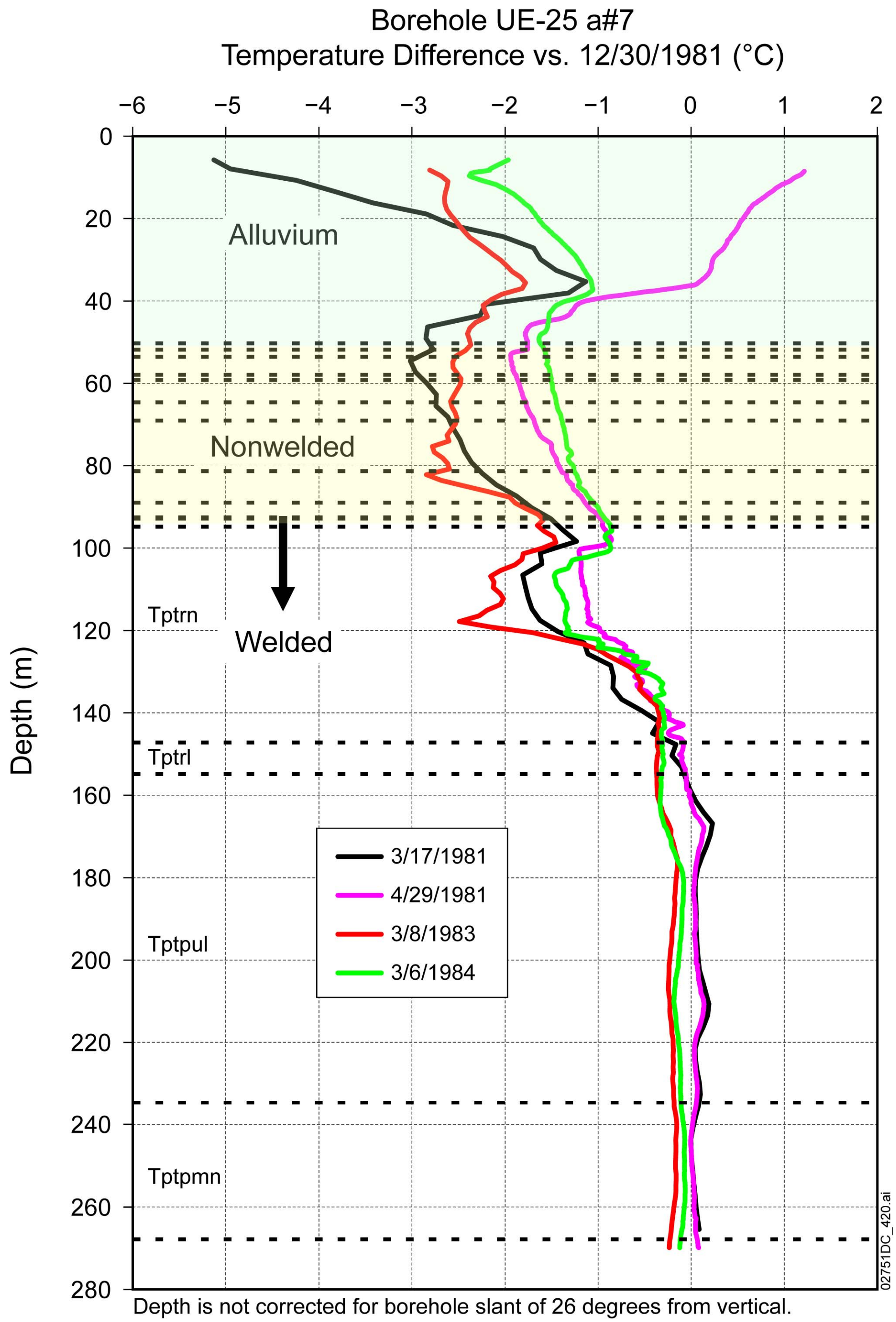
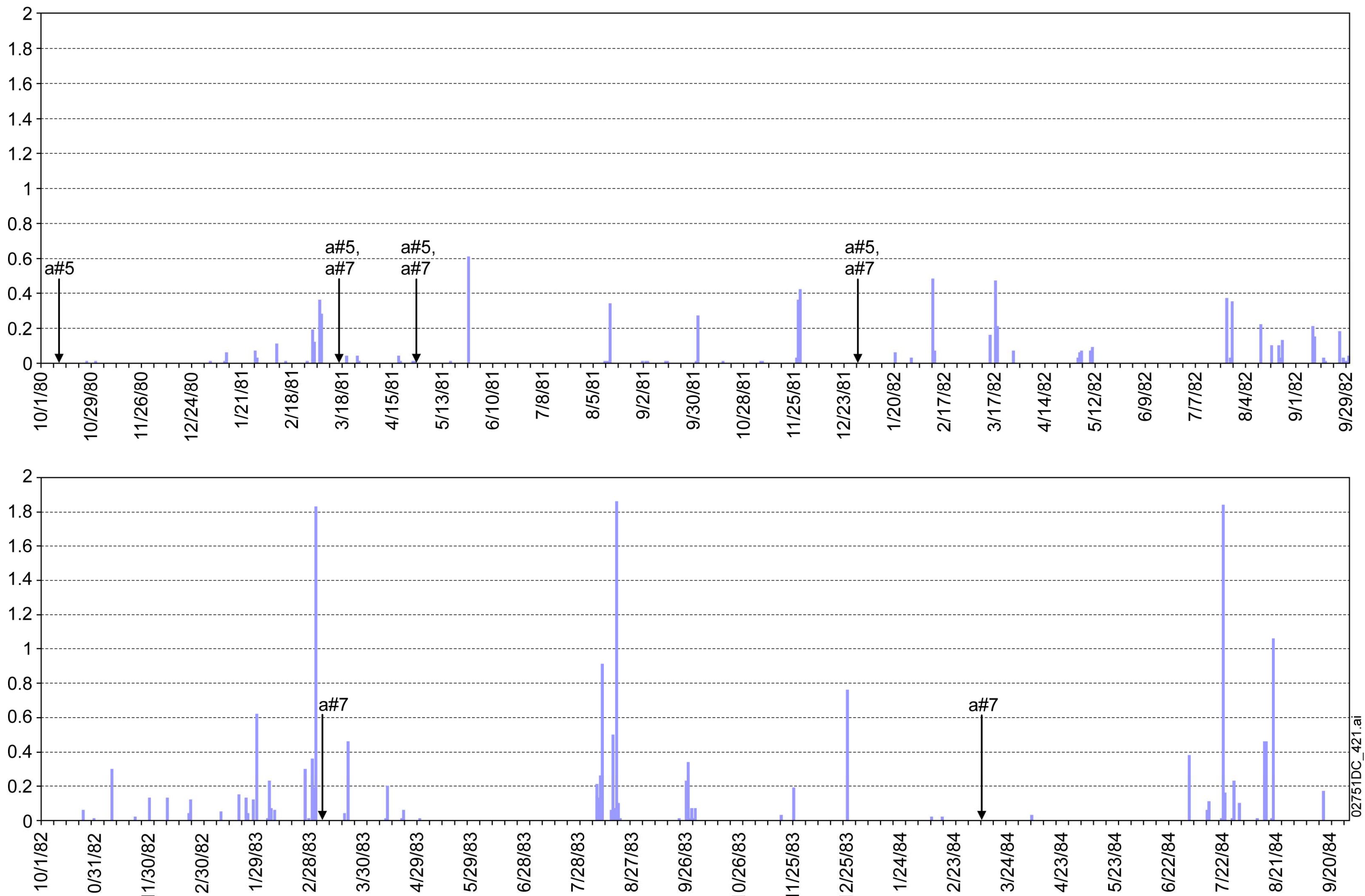


Figure 9. Temperature Logs for UE-25 a#7 Plotted as Differences, Subtracting the Log of 12/30/1981

The dates for some of the temperature logs were timed to follow precipitation events in March 1981 and March 1983 (Figure 10). These events likely produced streamflow in Drill Hole Wash. In particular, for a sequence of precipitation events that occurred during the first three days of March 1983, the effects were seen in the temperature log of March 8th. Another precipitation event occurred in August 1983, which apparently influenced the subsequent temperature log from March 1984. All of these logs exhibit transitions to cooler temperatures in the vicinity of the bottom of the casing at 40.9 m depth. Two alternative interpretations are considered here, that the temperature logs from borehole a#7 represent: (1) capture of flow within the borehole, at the surface or the alluvium–bedrock contact, and drainage back into the tuff sequence below; or (2) vertical percolation of water through the alluvium of Drill Hole Wash, and into the underlying welded and nonwelded tuffs (not involving flow in the borehole).



NOTE: Precipitation at Amargosa Farms (Garey) for Water Years 1981 through 1984. Approximate times where temperature surveys were conducted at UE-25 a#5 and UE-25 a#7 are shown with arrows.

Figure 10. Precipitation Records for Amargosa Farms from 1981 to 1984

Capture of Flow in the Borehole – The first, and most likely, interpretation involves flow of surface water into the borehole, or accumulation of water at the alluvium–bedrock contact at 50.3 m (Table 8), with flow into the open (uncased) borehole at or below the bottom of the casing at 40.9 m depth (Table 7). Water accumulation at the alluvium–bedrock contact has been observed in other, nearby boreholes that were monitored for investigation of infiltration processes.

After precipitation events, the thermal perturbations in borehole a#7 diffused to pre-event temperatures in a few months to a year, which is feasible if the scale of diffusive heat transfer is not more than a few meters (see the scoping calculation below). Specifically, the perturbation recorded on 3/17/1981 was significantly decreased by 4/29/1981. Also, the perturbations associated with precipitation events in August 1983 (if assumed to be similar to the events in early March 1983) were much smaller by the time of the next temperature log on 3/6/1984. As stated by Sass et al. (1988, Appendix 1, p. 24), "The primary conduit may have been the annulus between casing and borehole wall, but the persistence of the disturbance for at least a year indicates that significant lateral infiltration occurred near or in this well." Thus, the borehole served as a conduit for water penetration to depth, and the water infiltrated the formation, altering its temperature in a region of up to a few meters around the borehole.

The role of borehole a#7 as the conduit for water penetration to depth, as opposed to infiltration through the alluvium and tuff, is supported by results from hydrologic studies in Pagany Wash (LeCain et al. 2002). By the time the infiltration pulse in Pagany Wash moved 9.2 m through the alluvium accessed by borehole UZ#4, the water had come into temperature equilibrium with the alluvium (LeCain et al. 2002, Figure 7). Thus, it is unlikely that an infiltration pulse could move through 42 m of alluvium in Drill Hole Wash, plus tens of meters of tuff, and cause a temperature decrease of more than 1°C at depth. The Pagany Wash infiltration study indicated that once the infiltration pulse gets below the first few meters, the downward flow velocity in the alluvium is on the order of 1 m/day (LeCain et al. 2002, Figure 7). Another study in neutron borehole UZN#13 recorded an infiltration pulse associated with the precipitation event of 7/22/84, which penetrated 11.5 m into the Pagany Wash alluvium over a period of 76 days, indicating an average flux rate of 0.15 m/day. The alluvium in Drill Hole Wash is similar, so movement of an infiltration pulse through 42 m of alluvium in 7 days or less (i.e., from 3/1/1983 to 3/8/1983) is unlikely.

Comparing borehole a#7 to temperature profiles for other boreholes from Drill Hole Wash acquired by Sass et al. (1988, Figures 1-2 through 1-5) shows that only borehole UE25 a#5 exhibited a similar response. The deflection in the 3/16/1981 log (Sass et al. 1988, Figure 1-3) corresponds to the bottom of the cemented casing at 36.6 m (120 ft) depth, which is located within the Tiva Canyon welded tuff approximately 9.2 m below the alluvium–bedrock contact. The logs indicate that an infiltration pulse associated with the precipitation events on March 1st through 3rd, 1981, passed through 27.4 m of alluvium and into the upper TCw within approximately 18 days. The larger temperature drop measured on the 4/29/1981 log shows that infiltration continued and additional water reached the upper Tiva Canyon welded tuff over the period March 17, 1981, to April 29, 1981. Thus, percolation through the alluvium was much slower than suggested by the rapid penetration in borehole a#7.

Percolation Through the Alluvium and Bedrock – An alternative interpretation of the temperature logs from borehole a#7 is that the transient infiltration rapidly flowed deeply through the alluvium and bedrock, and cooled the bedrock. This requires that the infiltrating water absorbed enough heat to cool a 100-m thickness of rock by approximately 3°C. Using a bulk density of 2,000 kg/m^3 and specific heat of 10^3 J/kg-K for the alluvium and rock, and assuming the infiltrating water was 10°C cooler than the ground surface, requires infiltration of approximately 14 m^3/m^2 of water for a sequence of precipitation events such as occurred in early March 1983. A smaller temperature difference for infiltrating water would require proportionately greater infiltration. While such recharge is possible, it would effectively saturate the alluvial thickness, and would be limited in lateral extent to the width of the wash, whereas borehole a#7 slants away from the wash at an angle of 26 degrees. Accumulation of such amounts of water at the alluvium–bedrock contact would produce substantial flow into the uncased section of borehole a#7, thus leading to the first alternative interpretation. After initial drainage from the alluvium–tuff sequence, water flow greatly slowed as indicated by the persistent shape of the temperature profiles over several months (Figure 9). Thermal equilibration occurred as heat diffused back into the cooler rock. The time scale (Δt) for thermal diffusion can be estimated from the length scale (L) and the diffusivity (κ) as $\Delta t = L^2 / \kappa$. Using $\kappa = 2 \times 10^{-6}$ m^2/s and choosing $L = 30$ m as the length scale for thermal dissipation, the time scale $\Delta t = 1.5$ years. The temperature transients in borehole a#7 equilibrated faster than this, indicating that they occurred on a smaller length scale than permitted by this second interpretation.

Finally, it is important to note that Drill Hole Wash is fault-controlled, and is represented explicitly as a fault in the unsaturated zone flow model. Core recovery records indicate poor recovery from 24 to 53 m, and therefore the Drill Hole Wash Fault may intercept the upper part of the borehole, directing water from the ground surface (possibly originating as sheet flow from rock slopes) into the borehole at depth. Such behavior would be consistent with the first interpretation, in that downward flow in the borehole is needed to account for thermal effects observed.

In summary, the temperature logs in borehole a#7 indicate movement of water originating as surface runoff from major precipitation events into the subsurface at depths greater than 100 m within a few days. The water cooled the borehole by as much as 3°C which dissipated over time periods from a few months to approximately a year, as shown from repeated logging. Multiple precipitation events were recorded in the vicinity of Yucca Mountain during the period spanned by the logs, and are represented in the temperature variations. The construction of borehole a#7 suggests that water readily flowed from the wash directly into the borehole or it may have infiltrated the alluvium and ponded at the bedrock contact where it entered the borehole through an uncased section. Analogous studies in Pagany Wash, scoping thermal analysis, and comparison with temperature logs in nearby borehole a#5 indicate that the water penetrated within the borehole. Percolation through the alluvium is too slow, and the zone of thermal influence from the water in borehole a#7 was too limited, for rapid flow in the alluvium and the underlying tuffs to have been an important factor.

1.3.2 Subsurface Temperature and Other Evidence for Infiltration at Borehole UE-25 UZ#4

Borehole UE-25 UZ#4 (referred to here as UZ#4) was instrumented in July 1995 to measure temperature, pressure, and humidity as functions of depth as part of a hydrologic monitoring program that determined *in situ* moisture conditions and monitored the progress of transient infiltration after precipitation/streamflow events (LeCain et al. 2002). Sensors were installed at discrete depths (stations) isolated by grouted intervals. Borehole UZ#4 is located in the alluvium of Pagany Wash, close to the active channel, and recorded the effects from infiltration in response to precipitation and streamflow in February 1998. The depths to geologic contacts in UZ#4 are shown in Table 9.

Table 9. Geology of Borehole UZ #4

Lithostratigraphic Unit	Contact Depth (m)
Alluvium (Qa)	0.00
Tiva Canyon Tuff (Tpc) nondivided (Tpc_un)	11.89
Tpc, crystal-poor vitric moderately welded subzone (Tpcpv2)	21.76
Tpc, crystal-poor vitric nonwelded to partially welded subzones (Tpcpv1)	23.77
pre-Tiva Canyon Tuff bedded tuff (Tpbt4)	30.18
Yucca Mountain Tuff nondivided (Tpy)	32.31
pre-Yucca Mountain Tuff bedded tuff (Tpbt3)	46.18
Pah Canyon Tuff nondivided (Tpp)	53.00
pre-Pah Canyon Tuff bedded tuff (Tpbt2)	92.96
Topopah Spring Tuff (Tpt) crystal-rich vitric nonwelded to partially welded zones (Tptrv3)	101.50
Tpt, crystal-rich vitric moderately welded zone (Tptrv2)	104.55
Tpt, crystal-rich vitric densely welded zone (Tptrv1)	105.16
Tpt, crystal-rich nonlithophysal zone (Tptrn)	105.46 (to total depth of 127.7 m)

The active channel of Pagany Wash is approximately 1 to 2 m wide and streamflow has been documented in response to precipitation events that occur every few years, lasting for a day or two with each event. Rain gauges at WT-2 Wash and Jackass Flats recorded precipitation values of 173 mm (6.8 in.) and 135 mm (5.3 in.), respectively, for the 23-day period ending February 25, 1998 (LeCain et al. 2002). The Nevada Test Site precipitation station at Jackass Flats (4JA) recorded monthly precipitation of 159 mm (6.26 in.) for February 1998, with maximum daily precipitation of 43 mm (1.70 in.) on February 23rd.

A sharp temperature drop was observed on February 24, 1998, in alluvium at 3 m depth in borehole UZ#4, in response to infiltration of surface water from the active channel of Pagany Wash. Comparing to the precipitation records, the infiltration water apparently reached this depth in less than a day. A much smaller temperature drop was observed at a depth of 6.1 m (the next instrumented station) approximately six days later. The next two stations in the alluvium (9.2 and

11.1 m depths) exhibited longer term, attenuated temperature responses detected as slight depressions of the annual temperature wave (LeCain et al. 2002).

These observations are similar to neutron logs from borehole UZN#13, which is located in the active channel at the mouth of Pagany Wash, and in which a pulse of water was observed to percolate through 13.4 m of alluvium and contact bedrock, during the winter of 1984 to 1985.

Bedrock stations in UZ#4 also exhibited slight temperature responses (less than 0.05°C) that were interpreted by LeCain et al. (2002) to have been caused by the infiltration pulse and occurred one to two months later. Pressure sensors in borehole UZ #4 also recorded movement of the infiltration pulse by successive isolation of the monitored stations from atmospheric pressure fluctuations. The pressure data indicate that the infiltration pulse remained in the nonwelded Yucca Mountain Tuff (Tpy) between stations at 35.2 m and 45.0 m, for at least two years following the precipitation/streamflow event.

In summary, the investigations in borehole UZ#4 showed that penetration of infiltration pulses from surface streamflow is slow, on the order of 1 m/day, and that temperature differences are substantially attenuated after the pulse has penetrated on the order of 10 m (LeCain et al. 2002). The episodic flow observed to move through the alluvium and Tiva Canyon Tuff appears to have been dampened within the Tpy, which is part of the PTn hydrogeologic unit.

1.4 ALCOVE 4 TESTING AND EPISODIC FLOW

The potential for damping episodic infiltration in the PTn hydrogeologic unit was investigated through liquid release experiments conducted in Alcove 4 of the ESF (BSC 2004a, Section 6.7). These experiments included multiple releases of tracer-laced water into isolated zones located along three horizontal boreholes which accessed either faulted or undisturbed portions of PTn hydrogeologic unit matrix exposed in the Alcove 4 test bed. The zones into which traced water was released were selected based on air-permeability measurements conducted over 0.3-m sections of the boreholes, indicating if the borehole intercepted the fault or undisturbed portions of the rock mass. The plumes that developed following the liquid release were monitored via six separate horizontal boreholes, and the resulting water travel times, lateral dispersion (as seen along the length of the horizontal boreholes), and changes in saturation and water potential were continuously recorded by an automated data acquisition system. Inter-borehole distances were on the order of 1 to 3 meters. A constant-head boundary condition was maintained during injection to determine the maximum rates at which a targeted zone could take in water.

The liquid release rates employed during the tests (up to 138 mL/min) were considerably larger (approximately equal to 10^6 mm/yr) than typical percolation fluxes expected under ambient conditions. Despite the high water release rates, no water was observed to enter the slot excavated immediately below the test bed to record any seepage resulting from gravity drainage of the liquid releases in the horizontal boreholes. Water that imbibed into the matrix was retained for long periods (at least several months for the given test conditions). The observed wetting front migration pattern provides evidence of substantial matrix imbibition from the fault and matrix flow, demonstrating the ability to effectively damp liquid pulses in the PTn hydrogeologic unit. This conclusion is also consistent with field observations from water release tests for a similar nonwelded unit (the vitric Calico Hills nonwelded hydrogeologic unit) at the Busted Butte test facility (SAR Section 2.3.2.3.2.4).

1.5 CARBON-14 MEASUREMENTS AND EPISODIC FLOW

Measurements of ^{14}C in the unsaturated zone pore water and atmosphere provide information relevant to the residence time (i.e., the age) of the ^{14}C, and in most cases, this age is also considered to be a good approximation of solute and water residence time. Carbon-14 measurements conducted in boreholes USW UZ-1 and USW SD-12 are used to validate the unsaturated zone flow model (SNL 2007a, Figures 7.5-1 and 7.5-2). These data provide evidence of long residence times within the PTn hydrogeologic unit matrix where, due to the large storage capacity, thousands of years are required to traverse the unit (SAR Section 2.3.2.3.4.2). The matrix properties of the PTn hydrogeologic unit (high porosity and low fracture density) have acted to retard the movement of water through the formation, as evidenced by the long ^{14}C residence times observed. These same properties will also act to attenuate any episodic surface infiltration events from rapidly reaching the repository horizon and, as such, these measurements provide additional field evidence of the effectiveness of the PTn hydrogeologic unit as a barrier to the rapid transport of percolating water.

1.6 SUMMARY

Drift seepage for a transient process results in a larger mean seepage rate than the equivalent steady-flow process. Although the PTn hydrogeologic unit is effective at damping episodic flow, longer-term transient flow effects have been shown to penetrate the PTn hydrogeologic unit (Manepally et al. 2007). The increment in the mean seepage rate was found to be relatively small in comparison with other uncertainties included in the model for performance assessment (Section 1.1.3).

Tritium data collected from surface-based boreholes and a small subset of data collected from the ESF (Section 1.2) were analyzed using a technique that has high detection limits and uncertainty levels relative to the threshold for the presence of modern water. Because of this, the only interpretable data from these samples necessarily lie above the threshold for modern water. A more sensitive technique was used for most of the tritium measurements from the ESF and for all data from the ECRB. This data set shows that most of the measured concentrations lie below the threshold for the presence of modern water. A few high levels of tritium measured from borehole UE-25 UZ-16 indicate that, during the period of nuclear device testing, the source levels of tritium at Yucca Mountain were higher than available decay-corrected atmospheric measurements at Albuquerque, New Mexico. Because of the uncertainty in the source concentration, the amount of modern water required to raise tritium concentrations in subsurface samples above the threshold is uncertain.

Many of the cases where tritium concentrations indicate the presence of modern water were taken from locations in or near faults. These cases are consistent with transport simulations using the unsaturated zone flow model, which indicate a small fraction of mass arrivals between the ground surface and the repository level can occur through fault pathways within 50 years. In a few cases, such as in the ECRB, the presence of modern water is indicated at locations not associated with faults. An analysis of tritium transport through the PTn hydrogeologic unit was conducted for a location with a PTn hydrogeologic unit thickness of 40 m, similar in magnitude to the thickness of the PTn hydrogeologic unit above the ECRB, and for episodic flow damping within the upper 10 m of the PTn hydrogeologic unit. The analysis allows for uncertainty in percolation, hydrogeologic properties, and source concentration. The results show that for certain conditions, tritium concentrations above the threshold for the presence of modern water can penetrate the general rock mass of the PTn hydrogeologic unit. Therefore, the presence of modern water below the PTn hydrogeologic unit does not necessarily imply that episodic flow has penetrated the PTn hydrogeologic unit.

Subsurface temperature measurements from borehole UE-25 a#7, located in Drill Hole Wash, showed penetration of episodic flow below the PTn hydrogeologic unit associated with strong precipitation and runoff events at Yucca Mountain. However, the observations suggest that this penetration was a result of: (1) runoff in Drill Hole Wash flowing directly into the borehole and (2) water rapidly infiltrating the alluvium, ponding at the bedrock contact, and entering the borehole through an uncased section.

Another episodic flow event at borehole UE-25 UZ#4, located in Pagany Wash, was observed using subsurface temperature and pneumatic pressure measurements. These measurements showed penetration of episodic flow through the alluvium, TCw hydrogeologic unit, and into the PTn hydrogeologic unit. However, the episodic flow behavior was not observed below the Yucca Mountain Tuff (Tpy) lithostratigraphic unit, which is a component of the PTn hydrogeologic unit. Therefore, the observations at this borehole are consistent with the conceptual model that episodic flow is damped, leading to steady flow below the PTn hydrogeologic unit.

Observations of episodic flow behavior in the PTn hydrogeologic unit at Alcove 4 and observations of ^{14}C in the unsaturated zone also provide evidence concerning the behavior of episodic flow in the unsaturated zone. Liquid release tests in faulted or undisturbed portions of PTn hydrogeologic unit matrix exposed in the Alcove 4 test bed showed substantial matrix imbibition, demonstrating the ability to effectively damp liquid pulses in the PTn hydrogeologic unit. The ^{14}C data from boreholes USW UZ-1 and USW SD-12 provide evidence of long residence times within the matrix of the PTn hydrogeologic unit requiring thousands of years to traverse the PTn hydrogeologic unit.

Analysis of the subject technical basis information supplied in this RAI response supports the low consequence exclusion justification for FEP 2.2.07.05.0A. The analysis shows that episodic flow in the unsaturated zone is not prevalent in the repository area. Furthermore, any effects of localized episodic flow would not have a significant adverse effect on performance.

Table 4. Surface-Based Borehole Samples

SPC Number	Location	Sampled Depth (m)	Date of Analysis	Extraction Method	Lithostratigraphic Unit	Unsaturated Zone Flow Model Layer	Tritium Abundance (TU)[a]	Uncertainty (+/-)	Tritium Detection Limits (TU)[b]	Level Required for Samples to Be Considered above Background (95% confidence level)[c]	Q Status
SPC00020584	USW UZ-16	43.83 to 43.92	7/12/1993	D	Tpcpv2	tcw13	19.7	6[d]	8.2	22.2	Q
SPC00020609	USW UZ-16	48.28 to 48.37	10/9/1993	D	Tpcpv1	ptn21	154.7	6[d]	8.2	22.2	Q
SPC00020609	USW UZ-16	48.28 to 48.37	1/14/1994	D	Tpcpv1	ptn21	148.2	6[d]	8.2	22.2	Q
SPC00020679	USW UZ-16	80.10 to 80.22	10/9/1993	D	Tptrn	tsw31, tsw32	32.4	6[d]	8.2	22.2	Q
SPC00020679	USW UZ-16	80.10 to 80.22	1/14/1994	D	Tptrn	tsw31, tsw32	28.1	6[d]	8.2	22.2	Q
SPC00020679	USW UZ-16	80.22 to 80.35	2/3/1994	UP/D	Tptrn	tsw31, tsw32	9.3	6[d]	8.2	22.2	Q
SPC00020863	USW UZ-16	136.12 to 136.18	1/26/1994	D	Tptpul	tsw33	12	6[d]	8.2	22.2	Q
SPC00020942	USW UZ-16	177.70 to 177.76	8/15/1995	D	Tptpmn	tsw34	95.8	5.3	10.5	24.5	Q
SPC00020942	USW UZ-16	177.70 to 177.76	7/27/1995	D	Tptpmn	tsw34	105.9	6.1	10.5	24.5	Q
SPC00020991	USW UZ-16	192.12 to 192.21	8/15/1995	D	Tptpmn	tsw34	273.8	7.4	10.5	24.5	Q
SPC00020991	USW UZ-16	192.12 to 192.21	7/27/1995	D	Tptpmn	tsw34	307.8	8.4	10.5	24.5	Q
SPC00021000	USW UZ-16	196.08 to 196.14	8/15/1995	D	Tptpmn	tsw34	445.6	11.4	10.5	24.5	Q
SPC00021000	USW UZ-16	196.08 to 196.14	7/27/1995	D	Tptpmn	tsw34	474.3	10.2	10.5	24.5	Q
SPC00021028	USW UZ-16	203.91 to 204.12	6/17/1993	D	Tptpll	tsw35	29.5	6[d]	8.2	22.2	Q
SPC00021028	USW UZ-16	203.91 to 204.12	6/25/1993	D	Tptpll	tsw35	25.6	6[d]	8.2	22.2	Q
SPC00021550	USW UZ-16	288.04 to 288.16	8/15/1995	D	Tptpln	tsw36	48.2	4.7	10.5	24.5	Q
SPC00021550	USW UZ-16	288.04 to 288.16	7/27/1995	D	Tptpln	tsw36	59.1	5.6	10.5	24.5	Q
SPC00021553	USW UZ-16	288.92 to 289.01	8/15/1995	D	Tptpln	tsw36	10.8	4.1	10.5	24.5	Q
SPC00021553	USW UZ-16	288.92 to 289.01	7/27/1995	D	Tptpln	tsw36	17.6	4.9	10.5	24.5	Q
SPC00021696	USW UZ-16	317.36 to 317.48	9/28/1994	UP/D	Tptpln	tsw36	58.6	6[d]	8.2	22.2	Q
SPC00021696	USW UZ-16	317.36 to 317.48	10/7/1994	UP/D	Tptpln	tsw36	48.8	6[d]	8.2	22.2	Q
SPC00021696	USW UZ-16	317.57 to 317.63	12/10/1994	D	Tptpln	tsw36	31.8	6[d]	8.2	22.2	Q
SPC00021790	USW UZ-16	332.41 to 332.48	11/8/1994	D	Tptpln	tsw37	36.8	6[d]	8.2	22.2	Q
SPC00021790	USW UZ-16	332.41 to 332.48	12/19/1994	D	Tptpln	tsw37	12.2	6[d]	8.2	22.2	Q
SPC00021790	USW UZ-16	332.48 to 332.54	12/27/1994	D	Tptpln	tsw37	11.9	6[d]	8.2	22.2	Q
SPC00021822	USW UZ-16	338.51 to 338.60	9/28/1994	D	Tptpv3	tsw38	22.3	6[d]	8.2	22.2	Q
SPC00021822	USW UZ-16	338.51 to 338.60	10/7/1994	UP/D	Tptpv3	tsw38	33.2	6[d]	8.2	22.2	Q
SPC00021822	USW UZ-16	338.60 to 338.69	8/15/1995	D	Tptpv3	tsw38	20.1	4.3	10.5	24.5	Q
SPC00021822	USW UZ-16	338.60 to 338.69	7/27/1995	D	Tptpv3	tsw38	17.6	4.9	10.5	24.5	Q
SPC00021825	USW UZ-16	339.30 to 339.39	12/10/1994	D	Tptpv3	tsw38	38.2	6[d]	8.2	22.2	Q
SPC00021825	USW UZ-16	339.30 to 339.39	11/8/1994	D	Tptpv3	tsw38	55.2	6[d]	8.2	22.2	Q
SPC00021825	USW UZ-16	339.30 to 339.39	12/19/1994	D	Tptpv3	tsw38	46.8	6[d]	8.2	22.2	Q
SPC00021825	USW UZ-16	339.43 to 339.49	12/10/1994	D	Tptpv3	tsw38	47.4	6[d]	8.2	22.2	Q
SPC00021828	USW UZ-16	341.99 to 342.05	12/27/1994	**NA**	Tptpv3	tsw38	25.6	6[d]	8.2	22.2	Q
SPC00021828	USW UZ-16	342.05 to 342.14	11/8/1994	D	Tptpv3	tsw38	37.4	6[d]	8.2	22.2	Q
SPC00021828	USW UZ-16	342.05 to 342.14	12/10/1994	D	Tptpv3	tsw38	28.3	6[d]	8.2	22.2	Q

Table 4. Surface-Based Borehole Samples (Continued)

SPC Number	Location	Sampled Depth (m)	Date of Analysis	Extraction Method	Lithostratigraphic Unit	Unsaturated Zone Flow Model Layer	Tritium Abundance (TU)[a]	Uncertainty (+/-)	Tritium Detection Limits (TU)[b]	Level Required for Samples to Be Considered above Background (95% confidence level)[c]	Q Status
SPC00021828	USW UZ-16	342.05 to 342.14	12/19/1994	D	Tptpv3	tsw38	28.6	6[d]	8.2	22.2	Q
SPC00021831	USW UZ-16	344.27 to 344.36	7/27/1995	D	Tptpv3	tsw38	58.7	5.5	10.5	24.5	Q
SPC00021842	USW UZ-16	347.41 to 347.53	5/25/1995	D	Tptpv3	tsw38	13.0	3.5	10.5	24.5	Q
SPC00021955	USW UZ-16	355.46 to 355.52	11/8/1994	UP/D	Tptpv2	tsw39 (vit,zeo)	16.7	6[d]	8.2	22.2	Q
SPC00021957	USW UZ-16	356.71 to 356.80	11/8/1994	D	Tptpv2	tsw39 (vit,zeo)	17	6[d]	8.2	22.2	Q
SPC00021957	USW UZ-16	356.80 to 356.83	12/10/1994	D	Tptpv2	tsw39 (vit,zeo)	12.4	6[d]	8.2	22.2	Q
SPC00021958	USW UZ-16	359.45 to 359.54	12/10/1994	D	Tptpv1	ch1 (vit,zeo)	16.4	6[d]	8.2	22.2	Q
SPC00022288	USW UZ-16	386.94 to 387.07	9/13/1993	UP/D	Tac	ch2–ch5(vit,zeo)	8.4	6[d]	8.2	22.2	Q
SPC00022320	USW UZ-16	395.26 to 395.33	1/1/1994	D	Tac	ch2–ch5(vit,zeo)	14.3	6[d]	8.2	22.2	Q
SPC00022320	USW UZ-16	395.26 to 395.33	1/14/1994	D	Tac	ch2–ch5(vit,zeo)	18.5	6[d]	8.2	22.2	Q
SPC00022429	USW UZ-16	409.68 to 409.74	8/2/1994	UP/D	Tac	ch2–ch5(vit,zeo)	8.9	6[d]	8.2	22.2	Q
SPC00023003	USW UZ-16	423.49 to 423.55	6/17/1993	UP/D	Tac	ch2–ch5(vit,zeo)	9.6	6[d]	8.2	22.2	Q
SPC00023008	USW UZ-16	425.35 to 425.47	8/2/1994	UP/D	Tac	ch2–ch5(vit,zeo)	9.4	6[d]	8.2	22.2	Q
SPC00023010	USW UZ-16	426.02 to 426.11	9/13/1993	UP/D	Tac	ch2–ch5(vit,zeo)	45.8	6[d]	8.2	22.2	Q
SPC00023010	USW UZ-16	426.14 to 426.20	3/8/1994	UP/D	Tac	ch2–ch5(vit,zeo)	11.3	6[d]	8.2	22.2	Q
SPC00023145	USW UZ-16	437.17 to 437.27	9/13/1993	UP/D	Tac	ch2–ch5(vit,zeo)	112.6	6[d]	8.2	22.2	Q
SPC00023186	USW UZ-16	453.21 to 453.33	1/1/1994	D	Tcpuv	pp4	25.7	6[d]	8.2	22.2	Q
SPC00023667	USW UZ-16	490.15 to 490.21	3/8/1994	UP/D	Tcpm	pp1	11.8	6[d]	8.2	22.2	Q
SPC00023754	USW UZ-16	498.68 to 498.77	3/8/1994	UP/D	Tcpm	pp1	10.4	6[d]	8.2	22.2	Q
SPC01005475	USW WT-24	514.75 to 514.87	4/12/1999	D	Tptpv3	tsw38	37.6	3.3	8.2	22.2	Q
SPC01005475	USW WT-24	514.90 to 514.99	2/1/1999	D	Tptpv3	tsw38	35.6	3	8.2	22.2	Q
SPC01005478	USW WT-24	515.26 to 515.36	5/15/1999	D	Tptpv3	tsw38	28.3	3	8.2	22.2	Q
SPC01005478	USW WT-24	515.26 to 515.36	5/29/1999	D	Tptpv3	tsw38	29.1	3	8.2	22.2	Q
SPC01005480	USW WT-24	516.45 to 516.88	2/19/1998	PW/D	Tptpv3	tsw38	29.9	3.9	8.2	22.2	Q
SPC00021825	USW UZ-16	339.30 to 339.39	11/8/1994	D	Tptpv3	tsw38	55.2	6[d]	8.2	22.2	Q
SPC00021825	USW UZ-16	339.30 to 339.39	12/19/1994	D	Tptpv3	tsw38	46.8	6[d]	8.2	22.2	Q
SPC00021825	USW UZ-16	339.43 to 339.49	12/10/1994	D	Tptpv3	tsw38	47.4	6[d]	8.2	22.2	Q
SPC00021828	USW UZ-16	341.99 to 342.05	12/27/1994	**NA**	Tptpv3	tsw38	25.6	6[d]	8.2	22.2	Q
SPC00021828	USW UZ-16	342.05 to 342.14	11/8/1994	D	Tptpv3	tsw38	37.4	6[d]	8.2	22.2	Q
SPC00021828	USW UZ-16	342.05 to 342.14	12/10/1994	D	Tptpv3	tsw38	28.3	6[d]	8.2	22.2	Q
SPC00021828	USW UZ-16	342.05 to 342.14	12/19/1994	D	Tptpv3	tsw38	28.6	6[d]	8.2	22.2	Q
SPC00021831	USW UZ-16	344.27 to 344.36	7/27/1995	D	Tptpv3	tsw38	58.7	5.5	10.5	24.5	Q
SPC00021842	USW UZ-16	347.41 to 347.53	5/25/1995	D	Tptpv3	tsw38	13.0	3.5	10.5	24.5	Q
SPC00021955	USW UZ-16	355.46 to 355.52	11/8/1994	UP/D	Tptpv2	tsw39 (vit,zeo)	16.7	6[d]	8.2	22.2	Q
SPC00021957	USW UZ-16	356.71 to 356.80	11/8/1994	D	Tptpv2	tsw39 (vit,zeo)	17	6[d]	8.2	22.2	Q
SPC00021957	USW UZ-16	356.80 to 356.83	12/10/1994	D	Tptpv2	tsw39 (vit,zeo)	12.4	6[d]	8.2	22.2	Q
SPC00021958	USW UZ-16	359.45 to 359.54	12/10/1994	D	Tptpv1	ch1 (vit,zeo)	16.4	6[d]	8.2	22.2	Q

Table 4. Surface-Based Borehole Samples (Continued)

SPC Number	Location	Sampled Depth (m)	Date of Analysis	Extraction Method	Lithostratigraphic Unit	Unsaturated Zone Flow Model Layer	Tritium Abundance (TU)[a]	Uncertainty (+/-)	Tritium Detection Limits (TU)[b]	Level Required for Samples to Be Considered above Background (95% confidence level)[c]	Q Status
SPC00022288	USW UZ-16	386.94 to 387.07	9/13/1993	UP/D	Tac	ch2–ch5(vit,zeo)	8.4	6[d]	8.2	22.2	Q
SPC00022320	USW UZ-16	395.26 to 395.33	1/1/1994	D	Tac	ch2–ch5(vit,zeo)	14.3	6[d]	8.2	22.2	Q
SPC00022320	USW UZ-16	395.26 to 395.33	1/14/1994	D	Tac	ch2–ch5(vit,zeo)	18.5	6[d]	8.2	22.2	Q
SPC00022429	USW UZ-16	409.68 to 409.74	8/2/1994	UP/D	Tac	ch2–ch5(vit,zeo)	8.9	6[d]	8.2	22.2	Q
SPC00023003	USW UZ-16	423.49 to 423.55	6/17/1993	UP/D	Tac	ch2–ch5(vit,zeo)	9.6	6[d]	8.2	22.2	Q
SPC00023008	USW UZ-16	425.35 to 425.47	8/2/1994	UP/D	Tac	ch2–ch5(vit,zeo)	9.4	6[d]	8.2	22.2	Q
SPC00023010	USW UZ-16	426.02 to 426.11	9/13/1993	UP/D	Tac	ch2–ch5(vit,zeo)	45.8	6[d]	8.2	22.2	Q
SPC00023010	USW UZ-16	426.14 to 426.20	3/8/1994	UP/D	Tac	ch2–ch5(vit,zeo)	11.3	6[d]	8.2	22.2	Q
SPC00023145	USW UZ-16	437.17 to 437.27	9/13/1993	UP/D	Tac	ch2–ch5(vit,zeo)	112.6	6[d]	8.2	22.2	Q
SPC00023186	USW UZ-16	453.21 to 453.33	1/1/1994	D	Tcpuv	pp4	25.7	6[d]	8.2	22.2	Q
SPC00023667	USW UZ-16	490.15 to 490.21	3/8/1994	UP/D	Tcpm	pp1	11.8	6[d]	8.2	22.2	Q
SPC00023754	USW UZ-16	498.68 to 498.77	3/8/1994	UP/D	Tcpm	pp1	10.4	6[d]	8.2	22.2	Q
SPC01005475	USW WT-24	514.75 to 514.87	4/12/1999	D	Tptpv3	tsw38	37.6	3.3	8.2	22.2	Q
SPC01005475	USW WT-24	514.90 to 514.99	2/1/1999	D	Tptpv3	tsw38	35.6	3	8.2	22.2	Q
SPC01005478	USW WT-24	515.26 to 515.36	5/15/1999	D	Tptpv3	tsw38	28.3	3	8.2	22.2	Q
SPC01005478	USW WT-24	515.26 to 515.36	5/29/1999	D	Tptpv3	tsw38	29.1	3	8.2	22.2	Q
SPC01005480	USW WT-24	516.45 to 516.88	2/19/1998	PW/D	Tptpv3	tsw38	29.9	3.9	8.2	22.2	Q
SPC01005480	USW WT-24	516.45 to 516.88	4/21/1998	PW/D	Tptpv3	tsw38	25.8	3.2	8.2	22.2	Q
SPC01005483	USW WT-24	517.43 to 517.52	5/15/1999	D	Tptpv3	tsw38	50	3.2	8.2	22.2	Q
SPC01005483	USW WT-24	517.43 to 517.52	5/29/1999	D	Tptpv3	tsw38	42.8	3.2	8.2	22.2	Q
SPC01005487	USW WT-24	518.07 to 518.53	5/14/1998	PW/D	Tptpv3	tsw38	29.7	3.2	8.2	22.2	Q
SPC01005487	USW WT-24	518.07 to 518.53	6/1/1998	PW/D/trap 2	Tptpv3	tsw38	30.7	3.2	8.2	22.2	Q
SPC01005490	USW WT-24	519.04 to 519.14	5/1/1999	D	Tptpv3	tsw38	45.1	3.2	8.2	22.2	Q
SPC01005505	USW WT-24	524.23 to 524.32	5/14/1998	PW/D	Tptpv3	tsw38	8.9	3	8.2	22.2	Q
SPC01005528	USW WT-24	531.82 to 531.88	2/19/1998	UP/D	Tptpv1	ch1 (vit,zeo)	9.8	3.7	8.2	22.2	Q
SPC01005528	USW WT-24	531.88 to 531.94	5/14/1998	UP/D	Tptpv1	ch1 (vit,zeo)	13.6	3	8.2	22.2	Q
SPC01007207	USW WT-24	551.63 to 551.69	9/18/1998	UP/D	Tac	ch2–ch5(vit,zeo)	10.8	3.1	8.2	22.2	Q
SPC01009120	USW WT-24	600.30 to 600.40	2/1/1999	D	Tac	ch2–ch5(vit,zeo)	8.6	2.7	8.2	22.2	Q
SPC01009779	USW WT-24	628.50 to 628.59	5/29/1999	D	Tac	ch2–ch5(vit,zeo)	12.2	2.9	8.2	22.2	Q
SPC01009868	USW WT-24	652.21 to 652.27	8/1/1998	UP/D	Tac	ch2–ch5(vit,zeo)	14.1	3.7	8.2	22.2	Q
SPC01009868	USW WT-24	652.21 to 652.27	8/11/1998	UP/D	Tac	ch2–ch5(vit,zeo)	11.2	3.1	8.2	22.2	Q
SPC01010071	USW WT-24	680.28 to 680.37	5/29/1999	D	Tac	ch2–ch5(vit,zeo)	23.6	3	8.2	22.2	Q
SPC01010100	USW WT-24	688.54 to 688.60	9/18/1998	UP/D	Tac	ch2–ch5(vit,zeo)	10.9	3.1	8.2	22.2	Q
SPC01010465	USW WT-24	764.13 to 764.19	1/4/1999	D	Tac	ch2–ch5(vit,zeo)	24	2.8	8.2	22.2	Q
SPC01010465	USW WT-24	764.13 to 764.19	5/1/1999	D	Tac	ch2–ch5(vit,zeo)	18.1	2.9	8.2	22.2	Q
SPC01010468	USW WT-24	765.02 to 765.08	5/15/1999	D	Tac	ch2–ch5(vit,zeo)	19	2.9	8.2	22.2	Q
SPC01010468	USW WT-24	765.02 to 765.08	5/29/1999	D	Tac	ch2–ch5(vit,zeo)	8.2	2.9	8.2	22.2	Q

Table 4. Surface-Based Borehole Samples (Continued)

SPC Number	Location	Sampled Depth (m)	Date of Analysis	Extraction Method	Lithostratigraphic Unit	Unsaturated Zone Flow Model Layer	Tritium Abundance (TU)[a]	Uncertainty (+/-)	Tritium Detection Limits (TU)[b]	Level Required for Samples to Be Considered above Background (95% confidence level)[c]	Q Status
SPC01010471	USW WT-24	765.96 to 766.02	5/15/1999	D	Tac	ch2–ch5(vit,zeo)	10.6	2.8	8.2	22.2	Q
SPC01010475	USW WT-24	766.85 to 766.94	5/15/1999	D	Tac	ch2–ch5(vit,zeo)	34.3	3	8.2	22.2	Q
SPC01010475	USW WT-24	766.85 to 766.94	5/29/1999	D	Tac	ch2–ch5(vit,zeo)	31.2	3.1	8.2	22.2	Q
SPC01010475	USW WT-24	766.85 to 766.94	6/14/1999	D	Tac	ch2–ch5(vit,zeo)	28.3	3	8.2	22.2	Q
SPC01010478	USW WT-24	767.82 to 767.88	6/14/1999	D	Tac	ch2–ch5(vit,zeo)	30.2	3	8.2	22.2	Q
SPC01010481	USW WT-24	768.77 to 768.83	5/1/1999	UP/D	Tac	ch2–ch5(vit,zeo)	25.7	3	8.2	22.2	Q
SPC01010481	USW WT-24	768.77 to 768.83	5/29/1999	UP/D	Tac	ch2–ch5(vit,zeo)	32.6	3.1	8.2	22.2	Q
SPC01010481	USW WT-24	769.04 to 769.10	4/12/1999	UP/D	Tac	ch2–ch5(vit,zeo)	11.7	2.8	8.2	22.2	Q
SPC01010481	USW WT-24	769.19 to 769.25	2/1/1999	D	Tac	ch2–ch5(vit,zeo)	17.7	2.8	8.2	22.2	Q
SPC01010484	USW WT-24	769.71 to 769.77	10/2/1998	UP/D	Tac	ch2–ch5(vit,zeo)	29	3.3	8.2	22.2	Q
SPC01010484	USW WT-24	769.92 to 769.99	10/2/1998	UP/D	Tac	ch2–ch5(vit,zeo)	33	3.3	8.2	22.2	Q
SPC01006490	USW SD-6	125.43 to 125.52	3/24/1998	D	Tpc_un	tcw11-tcw13	10.4	3.4	8.2	22.2	Q
SPC01006558	USW SD-6	143.56 to 143.65	5/14/1998	UP/D	Tpbt3	ptn24	9.2	3	8.2	22.2	Q
SPC01006558	USW SD-6	143.65 to 143.74	5/14/1998	UP/D	Tpbt3	ptn24	8.7	3	8.2	22.2	Q
SPC01006558	USW SD-6	143.77 to 143.87	5/14/1998	UP/D	Tpbt3	ptn24	12	3	8.2	22.2	Q
SPC01006605	USW SD-6	161.88 to 161.97	3/24/1998	D	Tptrn	tsw31, tsw32	14.7	5.1	8.2	22.2	Q
SPC01006638	USW SD-6	169.68 to 169.80	3/24/1998	D	Tptrn	tsw31, tsw32	8.6	3.4	8.2	22.2	Q
SPC01009309	USW SD-6	433.09 to 433.15	6/15/1998	D	Tptpln	tsw37	10.2	3	8.2	22.2	Q
SPC01009329	USW SD-6	437.78 to 437.88	2/12/1999	D	Tptpln	tsw37	21.7	2.8	8.2	22.2	Q
SPC01009329	USW SD-6	438.15 to 438.24	6/15/1998	D	Tptpln	tsw37	26.7	3.2	8.2	22.2	Q
SPC01009334	USW SD-6	438.82 to 438.91	7/2/1998	D	Tptpln	tsw37	24.3	3.1	8.2	22.2	Q
SPC01009334	USW SD-6	438.91 to 439.00	2/12/1999	D	Tptpln	tsw37	27.9	2.8	8.2	22.2	Q
SPC01009334	USW SD-6	439.13 to 439.25	2/1/1999	D	Tptpln	tsw37	29.7	2.9	8.2	22.2	Q
SPC07009338	USW SD-6	439.67 to 439.77	6/15/1998	D	Tptpln	tsw37	13.3	3.1	8.2	22.2	Q
SPC01009359	USW SD-6	448.82 to 448.94	7/2/1998	D	Tptpv3	tsw38	9.3	3	8.2	22.2	Q
SPC01009374	USW SD-6	451.38 to 451.47	7/2/1998	D	Tptpv3	tsw38	17.1	3.1	8.2	22.2	Q
SPC01009379	USW SD-6	452.17 to 452.29	7/2/1998	D	Tptpv3	tsw38	8.3	3	8.2	22.2	Q
SPC01009383	USW SD-6	453.02 to 453.12	7/2/1998	D	Tptpv3	tsw38	8.9	3.4	8.2	22.2	Q
SPC01009387	USW SD-6	453.88 to 454.00	7/2/1998	D	Tptpv3	tsw38	10.3	3	8.2	22.2	Q
SPC01009420	USW SD-6	460.10 to 460.22	9/18/1998	D	Tptpv2	tsw39 (vit,zeo)	10.8	3.1	8.2	22.2	Q
SPC01009447	USW SD-6	473.78 to 473.87	3/15/1999	D	Tpbt1	ch1 (vit,zeo)	9.3	2.7	8.2	22.2	Q
SPC01009451	USW SD-6	476.34 to 476.43	2/12/1999	D	Tac	ch2–ch5(vit,zeo)	11.7	2.7	8.2	22.2	Q
SPC01009480	USW SD-6	483.32 to 483.41	5/1/1999	D	Tac	ch2–ch5(vit,zeo)	8.6	2.8	8.2	22.2	Q
SPC01009486	USW SD-6	491.58 to 491.64	3/1/1999	D	Tac	ch2–ch5(vit,zeo)	8.7	2.7	8.2	22.2	Q
SPC01009491	USW SD-6	494.29 to 494.39	3/1/1999	D	Tac	ch2–ch5(vit,zeo)	8.5	2.7	8.2	22.2	Q
SPC01009517	USW SD-6	529.22 to 529.29	4/12/1999	D	Tcpuv	pp4	9.1	2.7	8.2	22.2	Q

Table 4. Surface-Based Borehole Samples (Continued)

SPC Number	Location	Sampled Depth (m)	Date of Analysis	Extraction Method	Lithostratigraphic Unit	Unsaturated Zone Flow Model Layer	Tritium Abundance (TU)[a]	Uncertainty (+/-)	Tritium Detection Limits (TU)[b]	Level Required for Samples to Be Considered above Background (95% confidence level)[c]	Q Status
SPC01009533	USW SD-6	533.19 to 533.28	5/15/1999	D	Tcpuc	pp3	29.9	3	8.2	22.2	Q
SPC01009533	USW SD-6	533.19 to 533.28	6/14/1999	D	Tcpuc	pp3	29.7	3	8.2	22.2	Q
SPC01009538	USW SD-6	533.70 to 533.77	4/12/1999	D	Tcpuc	pp3	43.2	3.1	8.2	22.2	Q
SPC01009538	USW SD-6	534.04 to 534.13	2/12/1999	D	Tcpuc	pp3	41.6	2.9	8.2	22.2	Q
SPC01009538	USW SD-6	534.04 to 534.13	5/1/1999	D	Tcpuc	pp3	32.7	3.5	8.2	22.2	Q
SPC01009542	USW SD-6	534.65 to 534.74	12/18/1998	D	Tcpuc	pp3	36.6	3.3	8.2	22.2	Q
SPC01009546	USW SD-6	535.56 to 535.63	2/12/1999	D	Tcpuc	pp3	17.8	2.7	8.2	22.2	Q
SPC01009546	USW SD-6	535.93 to 536.02	12/18/1998	D	Tcpuc	pp3	17.3	3.1	8.2	22.2	Q
SPC10009563	USW SD-6	539.56 to 539.65	6/14/1999	D	Tcpuc	pp3	8.6	2.8	8.2	22.2	Q
SPC01009636	USW SD-6	555.32 to 555.35	6/30/1999	D	Tcpuc	pp3	13	3.1	8.2	22.2	Q
SPC01009653	USW SD-6	559.13 to 559.19	4/12/1999	D	Tcpuc	pp3	16.9	2.8	8.2	22.2	Q
SPC01009669	USW SD-6	563.97 to 564.03	12/18/1998	D	Tcpuc	pp3	15.2	9.5	8.2	22.2	Q
SPC01009669	USW SD-6	564.03 to 564.09	2/12/1999	D	Tcpuc	pp3	9.3	3	8.2	22.2	Q
SPC01009684	USW SD-6	568.15 to 568.21	12/18/1998	D	Tcpuc	pp3	11.3	11.9	8.2	22.2	Q
SPC01009712	USW SD-6	572.99 to 573.08	3/1/1999	D	Tcpm	pp1	8.9	2.7	8.2	22.2	Q
SPC01009716	USW SD-6	573.94 to 574.03	7/2/1998	UP/D	Tcpm	pp1	13.2	3	8.2	22.2	Q
SPC00022087	USW NRG-6	50.47 to 50.51	4/2/1996	D	Tpbt3	ptn24	11.8	4.6	10.5	24.5	Q
SPC00022058	USW NRG-6	52.12 to 52.21	9/22/1994	UP/D	Tpbt3	ptn24	10	6[d]	8.2	22.2	Q
SPC00022058	USW NRG-6	52.12 to 52.21	9/12/1994	UP/D	Tpbt3	ptn24	11.2	6[d]	8.2	22.2	Q
SPC00022058	USW NRG-6	52.24 to 52.36	9/22/1994	UP/D	Tpbt3	ptn24	20.7	6[d]	8.2	22.2	Q
SPC00022058	USW NRG-6	52.24 to 52.36	9/12/1994	UP/D	Tpbt3	ptn24	12.7	6[d]	8.2	22.2	Q
SPC00022063	USW NRG-6	53.52 to 53.64	9/22/1994	UP/D	Tpp	ptn25	42.4	6[d]	8.2	22.2	Q
SPC00022063	USW NRG-6	53.52 to 53.64	9/12/1994	UP/D	Tpp	ptn25	33.6	6[d]	8.2	22.2	Q
SPC00022084	USW NRG-6	64.13 to 64.16	4/2/1996	D	Tpp	ptn25	139.9	5.8	10.5	24.5	Q
SPC00022084	USW NRG-6	64.13 to 64.16	7/23/1996	D	Tpp	ptn25	117.3	5.8	10.5	24.5	Q
SPC00022100	USW NRG-6	67.03 to 67.12	12/27/1994	UP/D	Tpp	ptn25	121.9	6[d]	8.2	22.2	Q
SPC00022100	USW NRG-6	67.15 to 67.24	12/27/1994	UP/D	Tpp	ptn25	171.5	6[d]	8.2	22.2	Q
SPC00022108	USW NRG-6	69.92 to 69.95	4/2/1996	D	Tpbt2	ptn26	30.2	4.7	10.5	24.5	Q
SPC00022108	USW NRG-6	69.92 to 69.95	7/23/1996	D	Tpbt2	ptn26	23.1	4.8	10.5	24.5	Q
SPC00022119	USW NRG-6	74.55 to 74.68	5/15/1995	UP/D	Tpbt2-Tptrv3	ptn26	176	6[d]	10.5	24.5	Q
SPC00024455	USW UZ-14	17.34 to 17.53	8/24/1993	D	Tpy	ptn22, ptn23, ptn24	8.2	6[d]	8.2	22.2	Q
SPC00024493	USW UZ-14	25.97 to 26.09	9/28/1994	UP/D	Tpbt3	ptn24	12.6	6[d]	8.2	22.2	Q
SPC00024494	USW UZ-14	26.15 to 26.24	9/28/1994	UP/D	Tpbt3	ptn24	18.1	6[d]	8.2	22.2	Q
SPC00024504	USW UZ-14	29.32 to 29.44	11/8/1994	UP/D	Tpbt3	ptn24	15.9	6[d]	8.2	22.2	Q
SPC00024509	USW UZ-14	30.60 to 30.72	11/8/1994	UP/D	Tpbt3	ptn24	20.1	6[d]	8.2	22.2	Q
SPC00024534	USW UZ-14	38.22 to 38.34	7/14/1994	D	Tpp	ptn25	23	6[d]	8.2	22.2	Q

Table 4. Surface-Based Borehole Samples (Continued)

SPC Number	Location	Sampled Depth (m)	Date of Analysis	Extraction Method	Lithostratigraphic Unit	Unsaturated Zone Flow Model Layer	Tritium Abundance (TU)[a]	Uncertainty (+/-)	Tritium Detection Limits (TU)[b]	Level Required for Samples to Be Considered above Background (95% confidence level)[c]	Q Status
SPC00024543	USW UZ-14	41.12 to 41.27	7/14/1994	D	Tpp	ptn25	9	6[d]	8.2	22.2	Q
SPC00024544	USW UZ-14	41.30 to 41.39	11/8/1994	UP/D	Tpp	ptn25	31	6[d]	8.2	22.2	Q
SPC00024551	USW UZ-14	43.89 to 44.10	7/14/1994	D	Tpp	ptn25	10.5	6[d]	8.2	22.2	Q
SPC00024552	USW UZ-14	44.14 to 44.26	9/28/1994	UP/D	Tpp	ptn25	13.4	6[d]	8.2	22.2	Q
SPC00024556	USW UZ-14	44.87 to 45.02	7/14/1994	D	Tpp	ptn25	23.8	6[d]	8.2	22.2	Q
SPC00024653	USW UZ-14	68.70 to 68.82	8/24/1993	D	Tpp	ptn25	10.9	6[d]	8.2	22.2	Q
SPC00024654	USW UZ-14	68.85 to 68.95	9/28/1995	UP/D	Tpp	ptn25	13.4	3.7	10.5	24.5	Q
SPC00024676	USW UZ-14	74.62 to 74.77	9/8/1993	D	Tpbt2	ptn26	15.1	6[d]	8.2	22.2	Q
SPC00024677	USW UZ-14	74.83 to 74.92	9/28/1994	UP/D	Tpbt2	ptn26	9.3	6[d]	8.2	22.2	Q
SPC00024731	USW UZ-14	95.19 to 95.34	10/20/1993	D	Tptrn	tsw31, tsw32	12.9	6[d]	8.2	22.2	Q
SPC00024904	USW UZ-14	108.48 to 117.81	7/17/1997	D	Tptrn	tsw31, tsw32	11.6	4.4	8.2	22.2	Q
Multiple[e]	USW UZ-14	108.48 to 117.81	10/1/1997	D	Tptrn	tsw31, tsw32	22	4.8	8.2	22.2	Q
SPC00025294	USW UZ-14	183.46 to 183.64	4/23/1994	D	Tptpul	tsw33	14.7	6[d]	8.2	22.2	Q
SPC00025337	USW UZ-14	197.11 to 197.30	6/17/1994	D	Tptpul	tsw33	8.8	6[d]	8.2	22.2	Q
SPC00026534	USW UZ-14	246.98 to 251.55	7/17/1997	D	Tptpmn	tsw34	17.4	4.4	8.2	22.2	Q
SPC00026534, SPC00026548[f]	USW UZ-14	246.98 to 251.55	10/1/1997	D	Tptpmn	tsw34	12.3	4.7	8.2	22.2	Q
SPC00026586	USW UZ-14	264.90 to 265.08	4/23/1994	D	Tptpll	tsw35	10	6[d]	8.2	22.2	Q
SPC00026685	USW UZ-14	269.60 to 269.75	4/23/1994	D	Tptpll	tsw35	14.2	6[d]	8.2	22.2	Q
SPC00026848	USW UZ-14	293.77 to 293.95	4/23/1994	D	Tptpll	tsw35	8.9	6[d]	8.2	22.2	Q
SPC00027133	USW UZ-14	324.98 to 325.10	12/28/1993	D	Tptpll	tsw35	11.8	6[d]	8.2	22.2	Q
SPC00027266	USW UZ-14	342.60 to 342.72	1/27/1995	D	Tptpll	tsw35	11.6	6[d]	10.5	24.5	Q
SPC00027294	USW UZ-14	352.29 to 352.41	6/17/1994	D	Tptpln	tsw36	9	6[d]	8.2	22.2	Q
SPC00027386	USW UZ-14	366.28 to 366.43	6/17/1994	D	Tptpln	tsw36	10.3	6[d]	8.2	22.2	Q
SPC00028454	USW UZ-14	392.46 to 392.61	1/27/1995	D	Tptpv3	tsw38	19.1	6[d]	10.5	24.5	Q
SPC00028939	USW UZ-14	416.54 to 416.75	4/23/1994	D	Tptpv2	tsw39 (vit,zeo)	14	6[d]	8.2	22.2	Q
SPC00029837	USW UZ-14	424.04 to 424.22	7/14/1994	D	Tptpv1	ch1 (vit,zeo)	11.6	6[d]	8.2	22.2	Q
SPC00029113	USW UZ-14	429.57 to 429.69	5/25/1995	UP/D	Tpbt1	ch1 (vit,zeo)	11.2	3.5	10.5	24.5	Q
SPC00029114	USW UZ-14	429.74 to 429.86	5/25/1995	UP/D	Tpbt1	ch1 (vit,zeo)	14.5	3.5	10.5	24.5	Q
SPC00029844	USW UZ-14	433.55 to 433.73	1/27/1995	D	Tac	ch2–ch5(vit,zeo)	15.5	6[d]	10.5	24.5	Q
SPC00029851	USW UZ-14	435.92 to 436.08	9/2/1994	D	Tac	ch2–ch5(vit,zeo)	13.2	6[d]	8.2	22.2	Q
SPC00033822	USW UZ-14	477.62 to 477.77	11/28/1994	D	Tac	ch2–ch5(vit,zeo)	8.6	6[d]	8.2	22.2	Q
SPC00034258	USW UZ-14	529.32 to 529.47	1/27/1995	D	Tacbt	ch6 (vit,zeo)	12.7	6[d]	10.5	24.5	Q
SPC00035446	USW UZ-14	577.69 to 577.87	1/27/1995	D	Tcplc	pp2	14.1	6[d]	10.5	24.5	Q
SPC00033882	USW SD-12	87.60 to 87.63	9/23/1996	D	Tpp	ptn25	21.2	7	10.5	24.5	Q
SPC00035239	USW SD-12	174.62 to 174.74	6/1/1998	D	Tptpul	tsw33	12.8	3.8	8.2	22.2	Q
SPC00035343	USW SD-12	198.39 to 198.49	2/19/1998	D	Tptpul	tsw33	13.9	4.6	8.2	22.2	Q

Table 4. Surface-Based Borehole Samples (Continued)

SPC Number	Location	Sampled Depth (m)	Date of Analysis	Extraction Method	Lithostratigraphic Unit	Unsaturated Zone Flow Model Layer	Tritium Abundance (TU)[a]	Uncertainty (+/-)	Tritium Detection Limits (TU)[b]	Level Required for Samples to Be Considered above Background (95% confidence level)[c]	Q Status
SPC00035383	USW SD-12	211.53 to 211.62	6/26/1996	NA	Tptpmn	tsw34	11.5	4	10.5	24.5	Q
SPC00035406	USW SD-12	221.47 to 221.56	2/19/1998	D	Tptpmn	tsw34	8.5	4.5	8.2	22.2	Q
SPC00037039, SPC00037041[f]	USW SD-12	329.49 to 330.04	10/20/1997	PW/D	Tptpln	tsw36	9.3	4.4	8.2	22.2	Q
SPC00037198	USW SD-12	348.75 to 348.90	10/20/1997	PW/D	Tptpln	tsw36	9.5	4.4	8.2	22.2	Q
SPC00038005	USW SD-12	430.32 to 430.35	12/21/1995	UP/D	Tac	ch2–ch5(vit,zeo)	14.3	3.7	10.5	24.5	Q
SPC00038015	USW SD-12	433.55 to 433.56	12/21/1995	UP/D	Tac	ch2–ch5(vit,zeo)	13.7	3.8	10.5	24.5	Q
SPC00044335	USW SD-12	444.34 to 444.37	9/28/1995	D	Tac	ch2–ch5(vit,zeo)	13.0	3.5	10.5	24.5	Q
SPC01000104	USW SD-12	476.22 to 476.28	7/16/1998	UP/D	Tac	ch2–ch5(vit,zeo)	10.7	3.9	8.2	22.2	Q
SPC00047432, SPC00047433[f]	USW SD-12	524.62 to 525.02	10/1/1997	PW/D	Tcpuc	pp3	24.5	4.7	8.2	22.2	Q
SPC00047434	USW SD-12	525.02 to 525.17	10/1/1997	PW/D	Tcpuc	pp3	39.2	4.8	8.2	22.2	Q
SPC00047435	USW SD-12	525.44 to 525.51	10/20/1997	D	Tcpuc	pp3	16.8	4.5	8.2	22.2	Q
SPC00029406	USW NRG-7A	83.24 to 83.27	12/21/1995	D	Tpbt2	ptn26	11.4	4	10.5	24.5	Q
SPC00029406	USW NRG-7A	83.27 to 83.33	11/14/1997	D	Tpbt2	ptn26	8.4	4.5	8.2	22.2	Q
SPC00029412	USW NRG-7A	87.54 to 87.63	6/14/1996	D	Tptrv3	ptn26	11.7	4.2	10.5	24.5	Q
SPC00029559	USW NRG-7A	108.72 to 108.75	8/2/1996	D	Tptrn	tsw31, tsw32	46.8	8.6	10.5	24.5	Q
SPC00029643	USW NRG-7A	144.81 to 144.96	10/1/1997	PW/D	Tptrn	tsw31, tsw32	18	4.7	8.2	22.2	Q
SPC00029645	USW NRG-7A	145.18 to 145.33	10/20/1997	PW/D	Tptrn	tsw31, tsw32	9.7	4.4	8.2	22.2	Q
SPC00029983	USW NRG-7A	239.66 to 239.73	9/1/1996	D	Tptpmn	tsw34	13.1	5.2	10.5	24.5	Q
SPC00030174, SPC00030192[f]	USW NRG-7A	320.04 to 341.65	7/17/1997	D	Tptpll	tsw35	9.2	4.3	8.2	22.2	Q
SPC00030205	USW NRG-7A	351.59 to 351.71	7/17/1997	D	Tptpll	tsw35	12.3	4.3	8.2	22.2	Q
SPC00032153	USW NRG-7A	456.62 to 456.71	9/12/1994	UP/D	Tac	ch2–ch5(vit,zeo)	8.6	6[d]	8.2	22.2	Q
SPC00032158	USW NRG-7A	458.82 to 458.85	3/20/1996	D	Tac	ch2–ch5(vit,zeo)	18.1	4.3	10.5	24.5	Q
SPC00503632	USW NRG-7A	460.00	12/10/1994	Pumped/bailed?	Tac	ch2–ch5(vit,zeo)	10.3	6[d]	8.2	22.2	Q
SPC00039979	USW SD-7	49.04 to 49.10	12/1/1997	D	Tpc_un	tcw11-tcw13	8.7	4.2	8.2	22.2	Q
SPC00040707	USW SD-7	82.75 to 82.81	1/16/1998	D	Tpc_un	tcw11-tcw13	10.8	4.1	8.2	22.2	Q
SPC00040707	USW SD-7	82.75 to 82.81	1/7/1998	D	Tpc_un	tcw11-tcw13	10.3	—[g]	8.2	22.2	Q
SPC00041411	USW SD-7	201.05 to 201.11	1/16/1998	D	Tptpul	tsw33	12.5	4.2	8.2	22.2	Q
SPC01000455	USW SD-7	344.58 to 344.67	1/16/1998	PW/D	Tptpln	tsw37	11.8	4.1	8.2	22.2	Q
SPC01000455	USW SD-7	344.58 to 344.67	1/7/1998	PW/D	Tptpln	tsw37	11.4	—[g]	8.2	22.2	Q
SPC00046273	USW SD-7	357.99 to 358.02	9/23/1996	D	Tptpln	tsw37	18.5	6.6	10.5	24.5	Q
SPC00041949	USW SD-7	440.04 to 440.07	9/23/1996	D	Tac	ch2–ch5(vit,zeo)	14.5	6.6	10.5	24.5	Q
SPC00041997	USW SD-7	456.80 to 456.83	9/23/1996	UP/D	Tac	ch2–ch5(vit,zeo)	10.8	6.6	10.5	24.5	Q
SPC00042022	USW SD-7	464.82 to 464.84	4/2/1996	D	Tac	ch2–ch5(vit,zeo)	10.6	4.1	10.5	24.5	Q
SPC00035836	USW SD-9	46.91 to 46.94	6/3/1996	D	Tpbt3	ptn24	19.8	3.8	10.5	24.5	Q
SPC00036308	USW SD-9	213.82 to 213.88	1/16/1998	D	Tptpul	tsw33	14.6	4.3	8.2	22.2	Q
SPC00036335	USW SD-9	222.87 to 222.93	1/16/1998	D	Tptpmn	tsw34	12.7	4.3	8.2	22.2	Q
SPC00036354	USW SD-9	231.89 to 231.95	1/16/1998	D	Tptpmn	tsw34	20.9	4.4	8.2	22.2	Q

Table 4. Surface-Based Borehole Samples (Continued)

SPC Number	Location	Sampled Depth (m)	Date of Analysis	Extraction Method	Lithostratigraphic Unit	Unsaturated Zone Flow Model Layer	Tritium Abundance (TU)[a]	Uncertainty (+/-)	Tritium Detection Limits (TU)[b]	Level Required for Samples to Be Considered above Background (95% confidence level)[c]	Q Status
SPC00036354	USW SD-9	231.89 to 231.95	1/7/1998	D	Tptpmn	tsw34	19.5	—[g]	8.2	22.2	Q
SPC00036417	USW SD-9	259.78 to 259.84	8/2/1996	D	Tptpll	tsw35	14.7	4.2	10.5	24.5	Q
SPC00036479	USW SD-9	301.75 to 301.81	1/16/1998	D	Tptpll	tsw35	19	4.4	8.2	22.2	Q
SPC00037013	USW SD-9	447.60 to 447.69	7/25/1997	PW/D/TR2	Tpbt1	ch1 (vit,zeo)	10.5	4.2	8.2	22.2	Q
SPC00037450	USW SD-9	461.19 to 461.35	8/1/1998	PW/D	Tac	ch2–ch5(vit,zeo)	11.3	4.5	8.2	22.2	Q
SPC00037453	USW SD-9	461.68 to 461.80	8/1/1998	PW/D	Tac	ch2–ch5(vit,zeo)	12	4.5	8.2	22.2	Q
SPC00037453	USW SD-9	461.68 to 461.80	8/11/1998	PW/D	Tac	ch2–ch5(vit,zeo)	17.2	3.8	8.2	22.2	Q
SPC01001161	USW UZ-7a	67.30 to 67.36	6/1/1998	UP/D	Tpbt2	ptn26	13.3	3.6	8.2	22.2	Q
SPC01001173	USW UZ-7a	73.58 to 73.64	3/5/1998	UP/D	Tpbt2	ptn26	9.8	3.5	8.2	22.2	Q
SPC01001236	USW UZ-7a	117.62 to 117.68	11/14/1997	D	Tptpul	tsw33	14.5	3.8	8.2	22.2	Q
SPC01001238	USW UZ-7a	120.27 to 120.40	6/1/1998	D	Tptpul	tsw33	13.5	3.6	8.2	22.2	Q

[a] Values highlighted in yellow are above the 95th percentile confidence limit.
[b] Detection limits prior to 1/27/1995 are assigned the lowest calculated value, for the range between those dates, 8.2 TU.
[c] 95% confidence intervals before 1/27/1995 are assigned the lowest calculated value for the range between those dates, 22.2 TU.
[d] Counting error data not available. DTN provides only estimate of external error, based on replicate analyses, of approximately 6 TU.
[e] Small amounts of water from nine core segments (SPC00024904, SPC00024905, SPC00024916, SPC00024917, SPC00024919, SPC0024920, SPC0024930, SPC00024931, and SPC0024932) were combined to make one sample.
[f] Two adjacent or nearly adjacent core samples were distilled at the same time, yielding one water sample.
[g] Uncertainty information not available.

NOTES: UP = pore water obtained by uniaxial compression.

D = pore water distilled from rock.

PW/D = pore water distilled from rock using ^{14}C distillation system.

PW/CO2 = CO_2 gas (as HCO_3 in pore water) extracted from the pore water using the ^{14}C distillation system; trap 1 and trap 2 are the different cold traps present on the ^{14}C distillation system.

Q = qualified.

NA = not available.

Table 5. ESF and ECRB Drift Samples

SPC Number for Core Sample or Water Sample	Borehole Name	ESF Station[a]	Date of Analysis	Extraction Method	Sampled Interval (ft)	Lithostratigraphic Unit	Unsaturated Zone Flow Model Layer	Tritium Abundance (TU)[b]	Uncertainty 2σ (+/-)	Tritium Detection Limits (TU)	Threshold for Presence of Modern Water (TU)	Q Status
SPC00046014	ESF-AL#2-HPF#1	01+68	10/21/1996	UP/D	34.3 to 34.6[c]	Tpcpmn	tcw12	28.8	8.4	10.5	24.5[d]	Q
SPC00046017	ESF-AL#2-HPF#1	01+68	10/21/1996	UP/D	47.2 to 47.6[c]	Tpcpll	tcw12	30.9	8.4	10.5	24.5[d]	Q
SPC00046018	ESF-AL#2-HPF#1	01+68	10/21/1996	UP/D	50.5 to 50.7	Tpcpll	tcw12	118	19	10.5	24.5[d]	Q
SPC00046019	ESF-AL#2-HPF#1	01+68	10/21/1996	UP/D	55.4 to 55.7	Tpcpll	tcw12	128	10	10.5	24.5[d]	Q
SPC00046022	ESF-AL#2-HPF#1	01+68	10/21/1996	UP/D	58.9 to 59.0[c]	Tmr (pre -Raineer Mesa)	N/A	78.6	9.4	10.5	24.5[d]	Q
SPC00046025	ESF-AL#2-HPF#1	01+68	10/21/1996	UP/D	61.2 to 61.3[c]	Tmr (pre -Raineer Mesa)	N/A	65.3	9.2	10.5	24.5[d]	Q
SPC00046030	ESF-AL#2-HPF#1	01+68	10/21/1996	UP/D	68.6 to 68.9[c]	Tmr (pre -Raineer Mesa)	N/A	155	11	10.5	24.5[d]	Q
SPC00046032	ESF-AL#2-HPF#1	01+68	10/21/1996	UP/D	83.6 to 83.8[c]	Tmr (pre -Raineer Mesa)	N/A	32.9	8.6	10.5	24.5[d]	Q
SPC00045950	ESF-AL#3-RBT#4	07+54	6/3/1996	D	21.6 to 21.8	Tpcpln	tcw12	11.7	7.4	10.5	24.5[d]	Q
SPC01004190	ESF-NR-MOISTSTDY#3	07+68	10/29/1999	D	4.4 to 5.0	Tpcpln	tcw12	0.2	0.8	0.4 to 1	1.4	Q
SPC01004175 SPC01004179	ESF-NR-MOISTSTDY#4	07+73	4/8/1998	D	4.2 to 6.9[e]	Tpcpln	tcw12	0.76	0.24	0.4 to 1	1.4	UQ
SPC01004175 SPC01004179	ESF-NR-MOISTSTDY#4	07+73	4/8/1998	D	4.2 to 6.9[e]	Tpcpln	tcw12	0.66	0.2	0.4 to 1	1.4	UQ
SPC01004240 SPC01004244	ESF-NR-MOISTSTDY#10	08+80	10/29/1999	D	4.0 to 6.5[c,e]	Tpbt3	ptn24	0.22	0.3	0.4 to 1	1.4	Q
SPC01004301	ESF-NR-MOISTSTDY#13	10+07	1/14/1998	D	4.3 to 5.1	Tpp	ptn25	0.55	0.3	0.4 to 1	1.4	UQ
SPC01004381	ESF-LPCA-MOISTSTDY#2	10+28	10/29/1999	D	6.4 to 7.0	Tpbt2	ptn26	<0.1	0.29	0.4 to 1	1.4	Q
SPC01004340	ESF-NR-MOISTSTDY#16	10+70	4/14/1998	D	5.8 to 6.6	Tptrv2	ptn26	0.44	0.3	0.4 to 1	1.4	UQ
SPC03017194	ESF-DHW-CIV#10	19+10	6/28/2000	D	11.2 to 12.4	Tptpul	tsw33	0.94	0.48	0.4 to 1	1.4	Q
SPC03017198	ESF-DHW-CIV#9	19+20	6/28/2000	D	11.5 to 12.5	Tptpul	tsw33	0.6	1.2	0.4 to 1	1.4	Q
SPC03017190	ESF-DHW-CIV#8	19+25	6/28/2000	D	11.7 to 13.1	Tptpul	tsw33	0.2	1.0	0.4 to 1	1.4	Q
SPC03017184	ESF-DHW-CIV#7	19+30	6/28/2000	D	9.6 to 11.0	Tptpul	tsw33	1.6	0.8	0.4 to 1	1.4	Q
SPC03017180	ESF-DHW-CIV#6	19+35	6/28/2000	D	12.2 to 13.9	Tptpul	tsw33	0.48	0.56	0.4 to 1	1.4	Q
SPC03017150 SPC03017151	ESF-DHW-CIV#5	19+40	6/28/2000	D	26.7 to 28.7[f]	Tptpul	tsw33	0.7	0.6	0.4 to 1	1.4	Q
SPC03017159 SPC03017160	ESF-DHW-CIV#4	19+45	6/28/2000	D	12.3 to 13.7[c]	Tptpul	tsw33	0.9	0.6	0.4 to 1	1.4	Q
SPC03017171	ESF-DHW-CIV#3	19+50	6/28/2000	D	12.0 to 13.3	Tptpul	tsw33	1.6	0.8	0.4 to 1	1.4	Q
SPC03017162 SPC03017163	ESF-DHW-CIV#2	19+55	9/7/2000	D	6.5 to 8.2[f]	Tptpul	tsw33	0.5	1.4	0.4 to 1	1.4	Q
SPC03017174 SPC03017175	ESF-DHW-CIV#1	19+65	6/28/2000	D	10.9 to 13.2[f]	Tptpul	tsw33	1	0.8	0.4 to 1	1.4	Q
SPC02015927	ESF-SD-CIV#40	33+89	10/29/1999	D	12.3 to 13.3	Tptpmn	tsw34	0.3	0.32	0.4 to 1	1.4	Q
SPC02015932	ESF-SD-CIV#39	33+99	10/29/1999	D	11.2 to 12.7[c]	Tptpmn	tsw34	0.23	0.28	0.4 to 1	1.4	Q
SPC02015941	ESF-SD-CIV#38	34+10	10/29/1999	D	11.0 to 12.5[c]	Tptpmn	tsw34	1.4	1.6	0.4 to 1	1.4	Q
SPC02015936	ESF-SD-CIV#37	34+20	10/29/1999	D	9.7 to 11.2	Tptpmn	tsw34	0.28	0.26	0.4 to 1	1.4	Q
SPC02015943	ESF-SD-CIV#36	34+25	10/29/1999	D	6.7 to 8.1	Tptpmn	tsw34	<0.1	0.36	0.4 to 1	1.4	Q
SPC02015951	ESF-SD-CIV#35	34+30	10/29/1999	D	10.0 to 11.4[c]	Tptpmn	tsw34	0.29	0.44	0.4 to 1	1.4	Q

Table 5. ESF and ECRB Drift Samples (Continued)

SPC Number for Core Sample or Water Sample	Borehole Name	ESF Station[a]	Date of Analysis	Extraction Method	Sampled Interval (ft)	Lithostratigraphic Unit	Unsaturated Zone Flow Model Layer	Tritium Abundance (TU)[b]	Uncertainty 2σ (+/-)	Tritium Detection Limits (TU)	Threshold for Presence of Modern Water (TU)	Q Status
SPC02016034	ESF-SD-CIV#34	34+35	10/29/1999	D	10.5 to 12.0[c]	Tptpmn	tsw34	0.46	0.42	0.4 to 1	1.4	Q
SPC02016036	ESF-SD-CIV#33	34+40	10/29/1999	D	7.7 to 8.9	Tptpmn	tsw34	0.9	0.6	0.4 to 1	1.4	Q
SPC02016010	ESF-SD-CIV#32	34+45	10/29/1999	D	11.6 to 13.2[c]	Tptpmn	tsw34	0.31	0.46	0.4 to 1	1.4	Q
SPC02016004 SPC02016005	ESF-SD-CIV#31	34+50	7/19/2000	D	11.0 to 12.6[f]	Tptpmn	tsw34	0.3	0.8	0.4 to 1	1.4	Q
SPC02016001	ESF-SD-CIV#30	34+55	3/6/2000	D	12.2 to 13.4[c]	Tptpmn	tsw34	0.2	0.6	0.4 to 1	1.4	Q
SPC02015996	ESF-SD-CIV#29	34+60	10/29/1999	D	10.7 to 12.2[c]	Tptpmn	tsw34	0.28	0.34	0.4 to 1	1.4	Q
SPC02016018 SPC02016019 SPC02016021	ESF-SD-CIV#28	34+65	9/7/2000	D	8.0 to 11.3[e]	Tptpmn	tsw34	1.14	0.52	0.4 to 1	1.4	Q
SPC02016028	ESF-SD-CIV#27	34+70	10/29/1999	D	12.0 to 13.4	Tptpmn	tsw34	0.22	0.34	0.4 to 1	1.4	Q
SPC02016339	ESF-SD-CIV#26	34+73	3/30/2000	D	12.2 to 13.2	Tptpmn	tsw34	0.1	0.8	0.4 to 1	1.4	Q
SPC02016342	ESF-SD-CIV#25	34+90	4/26/2000	D	8.7 to 9.9	Tptpmn	tsw34	0.2	0.8	0.4 to 1	1.4	Q
SPC03017080	ESF-SD-CIV#24	34+95	4/26/2000	D	12.1 to 13.4	Tptpmn	tsw34	0.4	0.6	0.4 to 1	1.4	Q
SPC03017085	ESF-SD-CIV#23	35+00	3/30/2000	D	12.6 to 13.7	Tptpmn	tsw34	0.22	0.58	0.4 to 1	1.4	Q
SPC03017088	ESF-SD-CIV#22	35+05	3/30/2000	D	10.4 to 11.2[e]	Tptpmn	tsw34	0.15	0.54	0.4 to 1	1.4	Q
SPC03017094	ESF-SD-CIV#21	35+10	3/30/2000	D	9.8 to 11.1	Tptpmn	tsw34	0.4	0.56	0.4 to 1	1.4	Q
SPC03017101 SPC03017102	ESF-SD-CIV#20	35+15	4/26/2000	D	10.5 to 13.0[f]	Tptpmn	tsw34	<0.1	0.48	0.4 to 1	1.4	Q
SPC03017119	ESF-SD-CIV#19	35+20	3/30/2000	D	11.7 to 13.1	Tptpmn	tsw34	0.6	0.8	0.4 to 1	1.4	Q
SPC03017113	ESF-SD-CIV#18	35+25	6/28/2000	D	10.9 to 11.8	Tptpmn	tsw34	1.4	1.6	0.4 to 1	1.4	Q
SPC03017114	ESF-SD-CIV#18	35+25	3/30/2000	D	12.3 to 13.5	Tptpmn	tsw34	2.6	1.0	0.4 to 1	1.4	Q
SPC03017107	ESF-SD-CIV#17	35+31	4/26/2000	D	10.5 to 12.0	Tptpmn	tsw34	0.95	0.52	0.4 to 1	1.4	Q
SPC03017108	ESF-SD-CIV#17	35+31	4/26/2000	D	12.0 to 13.2	Tptpmn	tsw34	0.7	0.8	0.4 to 1	1.4	Q
SPC03017124 SPC03017125	ESF-SD-CIV#16	35+35	4/26/2000	D	12.0 to 13.2[c,f]	Tptpmn	tsw34	0.2	0.6	0.4 to 1	1.4	Q
SPC03017132	ESF-SD-CIV#15	35+40	4/26/2000	D	12.0 to 13.5[c]	Tptpmn	tsw34	0.6	1.0	0.4 to 1	1.4	Q
SPC03017136	ESF-SD-CIV#14	35+45	4/26/2000	D	11.6 to 13.4	Tptpmn	tsw34	<0.1	0.3	0.4 to 1	1.4	Q
SPC02016252 SPC02016253	ESF-SD-CIV#13	35+75	2/7/2000	D	30.5 to 32.3[c,f]	Tptpmn	tsw34	0.6	0.8	0.4 to 1	1.4	Q
SPC02016266	ESF-SD-CIV#12	35+80	3/6/2000	D	11.8 to 13.4[c]	Tptpmn	tsw34	0.20	0.54	0.4 to 1	1.4	Q
SPC02016260 SPC02016261	ESF-SD-CIV#11	35+85	3/6/2000	D	11.0 to 12.5[c,f]	Tptpmn	tsw34	0.15	0.56	0.4 to 1	1.4	Q
SPC02016257	ESF-SD-CIV#10	35+90	2/7/2000	D	11.8 to 13.0	Tptpmn	tsw34	0.37	0.58	0.4 to 1	1.4	Q
SPC02016277	ESF-SD-CIV#9	35+95	3/6/2000	D	10.1 to 11.5	Tptpmn	tsw34	0.2	0.6	0.4 to 1	1.4	Q
SPC02016271 SPC02016272	ESF-SD-CIV#8	36+00	2/7/2000	D	7.9 to 9.9[f]	Tptpmn	tsw34	0.6	0.6	0.4 to 1	1.4	Q
SPC02016268	ESF-SD-CIV#7	36+05	2/11/2000	D	8.1 to 9.7	Tptpmn	tsw34	0.3	0.8	0.4 to 1	1.4	Q
SPC02016304	ESF-SD-CIV#6	36+10	2/11/2000	D	9.3 to 10.5	Tptpmn	tsw34	1.1	1.0	0.4 to 1	1.4	Q

Table 5. ESF and ECRB Drift Samples (Continued)

SPC Number for Core Sample or Water Sample	Borehole Name	ESF Station[a]	Date of Analysis	Extraction Method	Sampled Interval (ft)	Lithostratigraphic Unit	Unsaturated Zone Flow Model Layer	Tritium Abundance (TU)[b]	Uncertainty 2σ (+/-)	Tritium Detection Limits (TU)	Threshold for Presence of Modern Water (TU)	Q Status
SPC02016299 SPC02016300	ESF-SD-CIV#5	36+20	2/7/2000	D	7.9 to 9.7[f]	Tptpmn	tsw34	0.71	0.46	0.4 to 1	1.4	Q
SPC02016297 SPC02016298	ESF-SD-CIV#4	36+35	2/11/2000	D	11.8 to 13.4[c]	Tptpmn	tsw34	0.3	0.8	0.4 to 1	1.4	Q
SPC02016289	ESF-SD-CIV#3	36+59	3/6/2000	D	10.7 to 11.4	Tptpmn	tsw34	0.6	0.6	0.4 to 1	1.4	Q
SPC02016281	ESF-SD-CIV#2	36+74	2/7/2000	D	8.0 to 9.9	Tptpmn	tsw34	0.1	0.6	0.4 to 1	1.4	Q
SPC02016331	ESF-SD-CIV#1	36+89	4/26/2000	D	11.5 to 12.6	Tptpmn	tsw34	0.5	0.8	0.4 to 1	1.4	Q
SPC01001916 SPC01001918 SPC01001920	ESF-NAD-GTB#1A	37+37	8/27/1998	D	98.4 to 101.0[e]	Tptpmn	tsw34	1.4	0.8	0.4 to 1	1.4	UQ
SPC01001947	ESF/NAD/GTB#1A	37+37	4/17/2001	D	114.0 to 115.0	Tptpmn	tsw34	0.5	0.6	0.4 to 1	1.4	Q
SPC01001960 SPC01001962	ESF/NAD/GTB#1A	37+37	4/17/2001	D	120.3 to 121.6[c,e]	Tptpmn	tsw34	1	0.8	0.4 to 1	1.4	Q
SPC01001964 SPC01001966	ESF-NAD-GTB#1A	37+37	8/27/1998	D	122.1 to 123.8[e]	Tptpmn	tsw34	1.2	0.8	0.4 to 1	1.4	UQ
SPC01001968 SPC01001970 SPC01001971	ESF-NAD-GTB#1A	37+37	8/27/1998	D	124.4 to 126.0[e]	Tptpmn	tsw34	1.2	0.8	0.4 to 1	1.4	UQ
SPC01001975 SPC01001976	ESF/NAD/GTB#1A	37+37	4/17/2001	D	127.0 to 129.0[e]	Tptpmn	tsw34	1.6	1.2	0.4 to 1	1.4	Q
SPC01001980 SPC01001982	ESF-NAD-GTB#1A	37+37	8/27/1998	D	130.2 to 131.9[e]	Tptpmn	tsw34	0.8	1.4	0.4 to 1	1.4	UQ
SPC01001991 SPC01001993 SPC01001995 SPC01001998	ESF-NAD-GTB#1A	37+37	8/27/1998	D	137.0 to 142.0[e]	Tptpmn	tsw34	0.3	0.8	0.4 to 1	1.4	UQ
SPC01002037 SPC01002038	ESF/NAD/GTB#1A	37+37	4/17/2001	D	165.8 to 166.7[f]	Tptpmn	tsw34	0.8	1.0	0.4 to 1	1.4	Q
SPC01002042 SPC01002045	ESF-NAD-GTB#1A	37+37	8/27/1998	D	168.0 to 169.8[e]	Tptpmn	tsw34	0.8	1.0	0.4 to 1	1.4	UQ
SPC01003284 SPC01003286	ESF-NDR-MF#1	37+37	8/27/1998	D	44.2 to 46.0[c,e]	Tptpmn	tsw34	1.6	1.0	0.4 to 1	1.4	UQ
SPC01003292 SPC01003294 SPC01003296	ESF-NDR-MF#1	37+37	8/27/1998	D	48.9 to 50.9[c,e]	Tptpmn	tsw34	2.2	1.2	0.4 to 1	1.4	UQ
SPC01003300 SPC01003302	ESF-AL6-NDR-MF#1	37+37	7/19/2000	D	53.9 to 55.6[e]	Tptpmn	tsw34	1.3	1.0	0.4 to 1	1.4	Q
SPC01003455 SPC01003457	ESF-AL6-NDR-MF#2	37+37	7/19/2000	D	42.3 to 43.9[e]	Tptpmn	tsw34	1.6	1.4	0.4 to 1	1.4	Q
SPC01003458 SPC01003460	ESF-AL6-NDR-MF#02	37+37	10/29/1999	D	47.3 to 49.0[c,e]	Tptpmn	tsw34	1.2	0.4	0.4 to 1	1.4	Q
SPC01003462 SPC01003464	ESF-AL6-NDR-MF#02	37+37	7/19/2000	D	49.3 to 51.3[e]	Tptpmn	tsw34	1.1	1.0	0.4 to 1	1.4	Q

Table 5. ESF and ECRB Drift Samples (Continued)

SPC Number for Core Sample or Water Sample	Borehole Name	ESF Station[a]	Date of Analysis	Extraction Method	Sampled Interval (ft)	Lithostratigraphic Unit	Unsaturated Zone Flow Model Layer	Tritium Abundance (TU)[b]	Uncertainty 2σ (+/-)	Tritium Detection Limits (TU)	Threshold for Presence of Modern Water (TU)	Q Status
SPC01003468 SPC01003470	ESF-AL6-NDR-MF#02	37+37	7/19/2000	D	55.3 to 57.0[e]	Tptpmn	tsw34	1	1.2	0.4 to 1	1.4	Q
SPC01003478 SPC01003480	ESF-AL6-NDR-MF#02	37+37	7/19/2000	D	61.1 to 62.9[e]	Tptpmn	tsw34	0.9	1.4	0.4 to 1	1.4	Q
SPC01002776	ESF/SAD/GTB#1	50+64	4/17/2001	D	103.4 to 104.1	Tptpmn	tsw34	3.7	1.4	0.4 to 1	1.4	Q
SPC01002800 SPC01002802	ESF/SAD/GTB#1	50+64	4/17/2001	D	124.3 to 125.9[e]	Tptpmn	tsw34	1.1	0.6	0.4 to 1	1.4	Q
SPC01002879 SPC01002897	ESF/SAD/GTB#1	50+64	4/17/2001	D	175.4 to 177.0[e]	Tptpmn	tsw34	1.8	1.4	0.4 to 1	1.4	Q
SPC01002956 SPC01002958	ESF/SAD/GTB#1	50+64	4/17/2001	D	214.5 to 216.9[e]	Tptpmn	tsw34	2.3	0.6	0.4 to 1	1.4	Q
SPC01002754	ESF/SAD/GTB#1	50+64	4/17/2001	D	85.1 to 86.0	Tptpmn	tsw34	1.2	1.0	0.4 to 1	1.4	Q
SPC01004630 SPC01004634	ESF-SR-MOISTSTDY#3	59+65	10/29/1999	D	2.9 to 5.7[e]	Tptpmn	tsw34	1.7	0.8	0.4 to 1	1.4	Q
SPC01004661 SPC01004665	ESF-SR-MOISTSTDY#5	63+00	4/16/1998	D	3.6 to 6.5[c,e]	Tptpmn	tsw34	0.42	0.3	0.4 to 1	1.4	UQ
SPC01004672 SPC01004676	ESF-SR-MOISTSTDY#6	63+89	4/21/1998	D	2.6 to 7.0[e]	Tptpul	tsw33	0.81	0.28	0.4 to 1	1.4	UQ
SPC01004686 SPC01004690	ESF-SR-MOISTSTDY#7	64+80	4/28/1998	D	3.8 to 7.0[e]	Tptrl	tsw33	3.2	0.4	0.4 to 1	1.4	UQ
SPC01004726 SPC01004728	ESF-SR-MOISTSTDY#10	66+48	10/29/1999	D	2.4 to 6.4[e]	Tptrv3	ptn26	28.6	3.6	0.4 to 1	1.4	Q
SPC01004759 SPC01004763	ESF-SR-MOISTSTDY#11	66+58	10/29/1999	D	3.2 to 6.9[e]	Tpbt2	ptn26	4.8	0.8	0.4 to 1	1.4	Q
SPC01004805	ESF-SR-MOISTSTDY#13	66+80	10/29/1999	D	6.0 to 6.8	Tpbt2	ptn26	3.1	0.5	0.4 to 1	1.4	Q
SPC01002421 SPC01002423	ESF-SR-MOISTSTDY#2	67+20	4/2/1998	D	2.2 to 3.9[e]	Tpcpv	tcw12	0.03	0.2	0.4 to 1	1.4	UQ
SPC01004786 SPC01004790	ESF-SR-MOISTSTDY#16	67+21	10/29/1999	D	4.6 to 6.8[c,e]	Tpcpv	tcw12	8.2	1.0	0.4 to 1	1.4	Q
SPC01002407 SPC01002409	ESF-SR-MOISTSTDY#1	67+22	3/31/1998	D	2.1 to 3.6[e]	Tpcpv	tcw12	0.3	0.3	0.4 to 1	1.4	UQ
SPC01004821	ESF-SR-MOISTSTDY#17	67+30	10/29/1999	D	5.8 to 6.7	Tpcpln	tcw12	3.8	0.6	0.4 to 1	1.4	Q
SPC01004821	ESF-SR-MOISTSTDY#17	67+30	10/29/1999	D	5.8 to 6.7	Tpcpln	tcw12	3.5	1.0	0.4 to 1	1.4	Q
SPC01004831 SPC01004835	ESF-SR-MOISTSTDY#18	67+48	10/29/1999	D	4.6 to 6.7[e]	Tpcpln	tcw12	1.1	0.8	0.4 to 1	1.4	Q
SPC01004844 SPC01004848	ESF-SR-MOISTSTDY#19	68+26	10/29/1999	D	4.5 to 6.9[e]	Tptpul	tsw33	14.3	2.0	0.4 to 1	1.4	Q
SPC01004858 SPC01004862	ESF-SR-MOISTSTDY#20	69+37	10/29/1999	D	4.2 to 6.8[e]	Tptrn	tsw31, tsw32	7.4	0.8	0.4 to 1	1.4	Q
SPC01005233	ESF-SR-MOISTSTDY#23	70+59	10/29/1999	D	16.2 to 17.0	Tptpmn	tsw34	0.45	0.30	0.4 to 1	1.4	Q
SPC01005233	ESF-SR-MOISTSTDY#23	70+59	10/29/1999	D	16.2 to 17.0	Tptpmn	tsw34	0.25	0.32	0.4 to 1	1.4	Q

Table 5. ESF and ECRB Drift Samples (Continued)

SPC Number for Core Sample or Water Sample	Borehole Name	ESF Station[a]	Date of Analysis	Extraction Method	Sampled Interval (ft)	Lithostratigraphic Unit	Unsaturated Zone Flow Model Layer	Tritium Abundance (TU)[b]	Uncertainty 2σ (+/-)	Tritium Detection Limits (TU)	Threshold for Presence of Modern Water (TU)	Q Status
SPC01004967 SPC01004970	ESF-SR-MOISTSTDY#25	74+35	10/29/1999	D	5.0 to 6.9[e]	Tptrn	tsw31, tsw32	4.4	0.8	0.4 to 1	1.4	Q
SPC01005175 SPC01005179	ESF-SR-MOISTSTDY#26	74+41	10/29/1999	D	7.4 to 9.6[e]	Tptrv2-Tptrv3	ptn26	4.9	0.5	0.4 to 1	1.4	Q
SPC01004921	ESF-SR-MOISTSTDY#27	74+44	10/29/1999	D	5.9 to 6.8	Tptrv3	ptn26	1.5	0.8	0.4 to 1	1.4	Q
SPC01004930 SPC01004936	ESF-SR-MOISTSTDY#28	74+47	10/29/1999	D	2.5 to 6.8[e]	Tptrv3	ptn26	3.2	0.8	0.4 to 1	1.4	Q
SPC01004949 SPC01004953	ESF-SR-MOISTSTDY#29	74+54	10/29/1999	D	4.5 to 6.8[e]	Tpbt2	ptn26	0.77	0.46	0.4 to 1	1.4	Q
SPC01005033 SPC01005037	ESF-SR-MOISTSTDY#30	74+60	10/29/1999	D	3.8 to 6.7[e]	Tpbt2	ptn26	12.5	1.2	0.4 to 1	1.4	Q
SPC01004981 SPC01004985	ESF-SR-MOISTSTDY#31	74+66	10/29/1999	D	4.7 to 7.0[e]	Tpbt2	ptn26	5.4	0.6	0.4 to 1	1.4	Q
SPC01005054	ESF-SR-MOISTSTDY#33	74+77	9/7/2000	D	5.9 to 6.9	Tpbt2-Tpp	ptn26	2.7	0.6	0.4 to 1	1.4	Q
SPC01005012	ESF-SR-MOISTSTDY#34	74+82	9/7/2000	D	5.9 to 6.8	Tpbt3	ptn24	1.2	0.5	0.4 to 1	1.4	Q
SPC01005099	ESF-SR-MOISTSTDY#38	75+03	9/7/2000	D	5.9 to 6.8	Tpcpv	tcw12	1.7	0.6	0.4 to 1	1.4	Q
SPC01005113	ESF-SR-MOISTSTDY#40	75+10	9/7/2000	D	5.9 to 6.9	Tpcpv	tcw12	0.58	0.32	0.4 to 1	1.4	Q
SPC02013439 SPC02013442	ECRB-SYS-CS0600	06+01	5/10/2002	D	3.2 to 6.0[f]	Tptpul	tsw33	0.79	0.58	0.4 to 1	1.4	Q
SPC02013547 SPC02013543	ECRB-SYS-CS0750	07+50	5/10/2002	D	3.6 to 6.2[f]	Tptpul	tsw33	6.2	1.0	0.4 to 1	1.4	Q
SPC02013530 SPC02013534	ECRB-SYS-CS0800	08+00	5/10/2002	UC/D	2.9 to 5.8[f]	Tptpul	tsw33	1.7	0.6	0.4 to 1	1.4	Q
SPC02013613 SPC02013617	ECRB-SYS-CS0900	09+01	5/10/2002	UC/D	3.5 to 6.4[f]	Tptpul	tsw33	6.5	1.2	0.4 to 1	1.4	Q
SPC02013628 SPC02013624	ECRB-SYS-CS0950	09+50	5/10/2002	UC/D	2.8 to 5.6[f]	Tptpul	tsw33	6.1	0.8	0.4 to 1	1.4	Q
SPC02013695	ECRB-SYS-CS1000	10+00	4/10/2002	D	17.4 to 18.2	Tptpul	tsw33	0.5	0.6	0.4 to 1	1.4	Q
SPC02014326 SPC02014330 SPC02014334	ECRB-SYS-CS1200	11+99	5/10/2002	D	2.9 to 6.9[f]	Tptpmn	tsw34	0.41	0.46	0.4 to 1	1.4	Q
SPC02014285 SPC02014289	ECRB-SYS-CS1300	13+01	8/2/2002	D	3.0 to 5.5[f]	Tptpmn	tsw34	0.7	1.4	0.4 to 1	1.4	Q
SPC02014299 SPC02014303	ECRB-SYS-CS1350	13+51	5/10/2002	UC/D	3.6 to 6.4[f]	Tptpmn	tsw34	3.8	1.0	0.4 to 1	1.4	Q
SPC02014349 SPC02014353	ECRB-SYS-CS1450	14+50	8/2/2002	D	4.0 to 6.5[f]	Tptpmn	tsw34	0.3	1.0	0.4 to 1	1.4	Q
SPC02014381 SPC02014385	ECRB-SYS-CS1500	14+99	4/10/2002	D	14.4 to 17.4[f]	Tptpmn	tsw34	2.5	0.8	0.4 to 1	1.4	Q
SPC02014361 SPC02014365	ECRB-SYS-CS1500	14+99	8/2/2002	D	4.3 to 7.1[f]	Tptpmn	tsw34	10.3	1.8	0.4 to 1	1.4	Q

Table 5. ESF and ECRB Drift Samples (Continued)

SPC Number for Core Sample or Water Sample	Borehole Name	ESF Station[a]	Date of Analysis	Extraction Method	Sampled Interval (ft)	Lithostratigraphic Unit	Unsaturated Zone Flow Model Layer	Tritium Abundance (TU)[b]	Uncertainty 2σ (+/-)	Tritium Detection Limits (TU)	Threshold for Presence of Modern Water (TU)	Q Status
SPC02014371 SPC02014375	ECRB-SYS-CS1500	14+99	8/2/2002	UC/D	9.5 to 12.1[f]	Tptpmn	tsw34	1.5	0.8	0.4 to 1	1.4	Q
SPC02014406	ECRB-SYS-CS1600	16+00	8/2/2002	D	3.4 to 4.3	Tptpmn	tsw34	1.7	1.8	0.4 to 1	1.4	Q
SPC02014436 SPC02014440	ECRB-SYS-CS1750	17+50	4/10/2002	D	3.3 to 5.9[f]	Tptpll	tsw35	0.6	0.8	0.4 to 1	1.4	Q
SPC02014450 SPC02014454	ECRB-SYS-CS1800	18+01	8/2/2002	D	3.6 to 6.1[f]	Tptpll	tsw35	0.1	1.6	0.4 to 1	1.4	Q
SPC02014486 SPC02014490	ECRB-SYS-CS1950	19+50	8/2/2002	D	4.0 to 6.5[f]	Tptpll	tsw35	3.6	1.0	0.4 to 1	1.4	Q
SPC02014623	ECRB-SYS-CS2000	19+99	4/10/2002	D	11.0 to 11.9	Tptpll	tsw35	0.1	1.0	0.4 to 1	1.4	Q
SPC02014661	ECRB-SYS-CS2150	21+49	8/2/2002	D	3.4 to 4.1	Tptpll	tsw35	<0.1	1.8	0.4 to 1	1.4	Q
SPC02014665	ECRB-SYS-CS2150	21+49	5/10/2002	UC/D	5.5 to 6.7	Tptpll	tsw35	9.8	1.0	0.4 to 1	1.4	Q
SPC02014683	ECRB-SYS-CS2250	22+50	5/10/2002	D	2.9 to 3.9	Tptpll	tsw35	0.8	0.8	0.4 to 1	1.4	Q
SPC02014774 SPC02014778	ECRB-SYS-CS2500	25+00	4/10/2002	D	16.7 to 19.8[f]	Tptpln	tsw36, tsw37	0.64	0.6	0.4 to 1	1.4	Q

[a] Sample locations in the main tunnel of the ESF are given in meters relative to the last construction station (CS xx + yy).
[b] highighted values above threshold for presence of modern water.
[c] Interval used for tritium analysis is smaller than the interval traceable to the Sample Management Facility barcode identifier; a portion of the core sample was removed in the laboratory and set aside for other analyses.
[d] 95th percentile confidence level.
[e] Non-adjacent intervals combined to obtain sufficient sample volume.
[f] Adjacent intervals combined to obtain sufficient sample volume.

NOTES: TU = tritium unit.

AL = Alcove.

CS xx+yy = Construction Station, in meters, as surveyed by the Management and Operating Contractor.

ESF = Exploratory Studies Facility – main tunnel.

ECRB = Enhanced Characterization of the Repository Block.

HPF#*n*= Hydrologic properties of faults – Borehole #*n*.

UP = pore water obtained by uniaxial compression.

UC = pore water obtained by ultracentrifugation.

D = pore water distilled from rock.

Q = qualified.

UQ = unqualified.

2. COMMITMENTS TO NRC

None.

3. DESCRIPTION OF PROPOSED LA CHANGE

None.

4. REFERENCES

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NOTES: [a]Provided as an enclosure to letter from Williams to Sulima, dtd 06/01/09, "Yucca Mountain – Request for Additional Information – Safety Evaluation Report, Volume 3 – Postclosure Chapter 2.2.1.3.6 – Flow Paths in the Unsaturated Zone, Set 1 – (Department of Energy's Safety Analysis Report Sections 2.3.2 and 2.3.3)."

[b]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)."