THE U.S. NUCLEAR REGULATORY COMMISSION OFFICE OF NUCLEAR MATERIAL SAFETY AND SAFEGUARDS REVIEW OF THE U.S. DEPARTMENT OF ENERGY AGREEMENT RESPONSES RELATED TO THE POTENTIAL GEOLOGIC REPOSITORY AT YUCCA MOUNTAIN, NEVADA: KEY TECHNICAL ISSUE AGREEMENTS EVOLUTION OF THE NEAR-FIELD ENVIRONMENT 2.03, RADIONUCLIDE TRANSPORT 1.01, 3.02, UNSATURATED AND SATURATED FLOW UNDER ISOTHERMAL CONDITIONS 4.04, TOTAL SYSTEM PERFORMANCE ASSESSMENT AND INTEGRATION 3.22, 3.24, 3.26, 2.02 (COMMENTS 3, 4, 12, J–20, and J–23), AND GENERAL 1.01 (COMMENTS 24, 69, and 106)

1.0 INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) issue resolution goal during this interim prelicensing period is to ensure the U.S. Department of Energy (DOE) has assembled enough information about a given issue for NRC to accept a license application for review. Resolution by the NRC staff during prelicensing does not prevent anyone from raising any issue for NRC consideration during the licensing proceedings. Also, and just as important, resolution of an issue by the NRC staff during prelicensing does not prejudge the NRC staff evaluation of the issue during the licensing review. Issues are resolved by the NRC staff during prelicensing when the staff have no further questions or comments about how DOE is addressing an issue. Pertinent new information could raise new questions or comments about a previously resolved issue.

By a letter dated May 28, 2004, DOE submitted a report titled “Technical Basis Document No. 2: Unsaturated Zone Flow,” (Bechtel SAIC Company, LLC, 2004a) that contains responses to several key technical issue (KTI) agreements in Appendixes A–G. DOE also provided agreement responses in Appendixes H and I, which were submitted by separate letters (Ziegler, 2004a,b) for inclusion in Bechtel SAIC Company, LLC (2004a). DOE’s agreement responses provided in Appendixes A–I of Technical Basis Document No. 2 are reviewed in the following subsections of this attachment.

2.0 REVIEW OF TECHNICAL BASIS DOCUMENT NO. 2, APPENDIX A: DOE RESPONSE TO AGREEMENT RADIONUCLIDE TRANSPORT (RT).1.01

Appendix A of Bechtel SAIC Company, LLC (2004a), provides the combined DOE response to Agreements RT.1.01 and General (GEN).1.01 (Comment 26). Agreement RT.1.01 was reached at a meeting held December 5–7, 2000, to discuss the Radionuclide Transport KTI (Reamer, 2000a). The wording of this agreement is as follows:

RT.1.01

“Provide the basis for the proportion of fracture flow through the Calico Hills non-welded vitric. DOE will revise the AMR UZ Flow Models and Submodels and the AMR Calibrated Properties Model to provide the technical basis for the proportion of fracture flow through the Calico Hills nonwelded vitric. These reports will be available to the NRC in FY 2002. In addition, the field data description will be documented in the AMR *In-Situ* Field Testing of Processes in FY 2002.”

Agreement GEN.1.01 was reached at a meeting held September 18–19, 2001, to discuss the range of thermal operating temperatures (Reamer, 2001a). Comment 26 would need to be addressed if DOE adopts a lower temperature operating mode, and as such, DOE's response to this comment will not be reviewed here.

2.1 Relevance to Repository Performance

Agreement RT.1.01 requests that DOE provide additional technical bases to support the modeling of flow through the Calico Hills nonwelded vitric unit as all matrix flow rather than some combination of matrix flow and fracture flow as is modeled for all other tuff layers below the potential repository. The uncertainty from lack of data should be included in the abstraction of flow paths for performance assessment calculations, unless information is available to demonstrate that this uncertainty does not significantly affect the results of performance assessment calculations. Risk insights developed by NRC (2004) ranked the processes of flow and transport in the unsaturated zone as being of medium significance to waste isolation, with specific attention to the potential retardation of radionuclides in the matrix of the Calico Hills nonwelded vitric unit. Although related to this topic, Agreement RT.1.01 is considered to be of low significance to waste isolation because other uncertainties about flow paths and transport below the repository are more likely to affect performance estimates. These include uncertainties in: (i) the spatial extent of flow in permeable nonwelded vitric tuff layers, where flow through rock matrix is relatively slow; and (ii) the spatial extent of low-permeability zeolitic layers that lead to the formation of perched water bodies, lateral diversion, and subsequent transport to the water table through fault zones. These two uncertainties are addressed by Agreements RT.3.02 and Total System Performance Assessment and Integration (TSPAI).3.24, which are reviewed in Section 3.0 of this attachment. Additional perspective about the relative importance of the distribution of flow in the Calico Hills nonwelded vitric layer and the rationale for the related uncertainty to be of low significance is provided in the staff reviews of related agreement items in Sections 3.0, 4.0, and 5.0 of this attachment.

2.2 NRC Evaluation and Comment

Most hydrogeologic layers below the potential repository are represented in DOE's performance assessment model as dual-permeability features, with components of flow in both fractures and in rock matrix. The Calico Hills nonwelded vitric layers, however, are modeled as a single-porosity matrix because they are assumed to have matrix permeability orders of magnitude larger than permeability of welded tuffs. DOE's response (Bechtel SAIC Company, LLC, 2004a, Appendix A) explains that the conceptual model of matrix flow only in the vitric tuff units is supported by observations from the Busted Butte field tests in nonwelded vitric tuff and from the Alcove 4 test bed in the Paintbrush nonwelded tuff layer, which has porous matrix properties similar to the Calico Hills nonwelded vitric layers.

The test results from the Busted Butte study focus on visual observation of the development of a sodium fluorescein plume following injection into a borehole near the contact of subunits Tptpv1 and Tpbt1 (both within the Calico Hills nonwelded vitric unit). A small fracture that diagonally transects the plume is used for comparison of matrix and fracture flow. Although the plume interacts with the fracture in both subunits and travels a short distance along the fracture in the lower subunit (Bechtel SAIC Company, LLC, 2004a, Figure A–8), the interaction is considered by DOE to be negligible when compared with perturbations in the plume caused by heterogeneity in the rock matrix. Test results from the Alcove 4 field study indicate that water injected along a fault in the Paintbrush nonwelded tuff layer is imbibed into the relatively dry matrix in contact with the fault surface causing the wetting front along the fault to advance more slowly than would be expected without imbibition. The test results presented in DOE's response do not provide information regarding the relative amounts of flow in the fault and the matrix.

The current staff understanding of DOE's approach is that the Calico Hills nonwelded vitric layer is the only unsaturated tuff layer below the potential repository considered to have sufficient matrix saturated hydraulic conductivity to allow water to flow predominantly within the rock matrix for the entire range of anticipated percolation rates. That is, water flow in the Calico Hills nonwelded vitric layer is expected to remain in the matrix (i.e., no fracture flow) and be slow. As noted in DOE's response, the Busted Butte results provide evidence from one experiment at one location. There is no additional information to support the implied assumption that the fracture at the Busted Butte Phase 1A test is typical of fractures in the Calico Hills nonwelded vitric unit. Nevertheless, the large differences in matrix permeability and fracture densities between vitric units and welded tuffs support the concept of matrix flow in the vitric units, and the flow rates of tracers injected during the Phase 1A test far exceed the range of expected percolation rates. Consequently, the staff consider the information presented by DOE (Bechtel SAIC Company, LLC, 2004a, Appendix A) sufficient to satisfy Agreement RT.1.01.

3.0 REVIEW OF TECHNICAL BASIS DOCUMENT NO. 2, APPENDIX B: DOE RESPONSE TO AGREEMENTS RT.3.02, TSPAI.3.24, AND GEN.1.01 (Comment 106)

Appendix B of Bechtel SAIC Company, LLC (2004a) provides the combined DOE response to Agreements RT.3.02, TSPAI.3.24, and GEN.1.01 (Comment 106). Agreement RT.3.02 was reached at a meeting held December 5–7, 2000, to discuss the Radionuclide Transport KTI (Reamer, 2000a). The wording of this agreement is as follows:

RT.3.02

"Provide the analysis of geochemical data used for support of the flow field below the repository. DOE will provide the analysis of geochemical data used for support of the fluid flow patterns in the AMR Unsaturated Zone Flow Models and Submodels, available to the NRC in FY 2002."

Agreement TSPAI.3.24 was reached at a meeting held August 6–10, 2001, to discuss the TSPAI KTI (Reamer, 2001b). The wording is as follows:

TSPAI.3.24

"Provide the analysis of geochemical and hydrological data (water content, water potential, and temperature) used for support of the flow field below the repository, particularly in the Calico Hills, Prow Pass, and Bullfrog hydrostratigraphic layers. Demonstrate that potential bypassing of matrix flow pathways below the area of the proposed repository, as opposed to the entire site-scale model area, is adequately incorporated for performance assessment, or provide supporting analyses that the uncertainties are adequately included in the TSPA [total system performance assessment] (UZ2.3.3). DOE will provide an analysis of available geochemical and hydrological data (water content, water potential, and temperature) used for support of the flow field below the repository, particularly in the Calico Hills, Prow Pass, and Bullfrog hydrostratigraphic layers. The analyses will demonstrate that potential bypassing of matrix flow pathways below the area of the proposed repository, as opposed to the entire site-scale model area, is adequately incorporated for performance assessment, or provide supporting analyses that the uncertainties are adequately included in the TSPA. These analyses will be documented in the Unsaturated Zone Flow Models and Submodels AMR (MDL–NBS–HS–000006), *In-Situ* Field Testing of Processes AMR (ANL–NBS–HS–000005), and Calibrated Properties Model AMR (MDL–NBS–HS–000003) expected to be available to NRC in FY 2003."

Agreement GEN.1.01 was reached at a meeting held September 18–19, 2001, to discuss the range of thermal operating temperatures (Reamer, 2001a). The wording of Comment 106 is as follows:

<u>Comment 106</u>

"The DOE needs to provide additional technical bases for excluding uncertainties in infiltrating water compositions that are associated with the coupled THC [thermal-hydrological-chemical] model from TSPA [total system performance assessment] analyses. The DOE has not adequately demonstrated that the initial water compositions used in sensitivity studies in the coupled THC models are appropriate and bounding (Chapters 3 and 6). What are the technical bases for selecting these particular water compositions selected for the analysis? Do they differ from one another in significant ways? Do they represent the full range of ground water compositions that have been collected and measured from Yucca Mountain and vicinity? How do variations in infiltrating water composition influence the in-drift salts/evaporation models?"

3.1 <u>Relevance to Repository Performance</u>

Agreements RT.3.02 and TSPAI.3.24 request DOE to provide data or analyses to support the modeled flow paths in the unsaturated zone below the potential repository. Risk insights developed by NRC staff (NRC, 2004) ranked the process of flow and transport in the unsaturated zone as being of medium significance to waste isolation. The uncertainties related to flow paths below the repository that are most likely to affect performance estimates include: (i) the spatial extent of flow in permeable nonwelded vitric tuff layers, where flow through rock matrix is relatively slow; and (ii) the spatial extent of low-permeability zeolitic layers that lead to the formation of perched water bodies, lateral diversion, and subsequent transport to the water table through fault zones. Agreements RT.3.01 and TSPAI.3.24 were identified by NRC staff as low-risk and medium-risk significant, respectively (Travers, 2003).

Agreement GEN.1.01 (Comment 106) pertains to understanding the composition of infiltrating water, which directly affects waste package and drip shield performance. The environmental conditions to which the waste package and drip shield are subjected to and the chemical evolution of water play a substantial role in determining the potential for corrosion of these engineered barriers. Although Agreement GEN.1.01 was identified as high-risk significance (Travers, 2003), the individual comments within GEN.1.01 were not separately categorized with the significance framework.

3.2 NRC Evaluation and Comment

The hydrogeologic layers below the potential repository include the middle and lower parts of Topopah Spring, Calico Hills, Prow Pass, and Bullfrog tuff layers. The Calico Hills nonwelded unit is subdivided into zones assumed to be either vitric or zeolitic, and the vitric zones are modeled by DOE as single-porosity matrix because of their high matrix porosity and permeability. Hence, flow in vitric units is expected to be slow, and sorption of radionuclides onto mineral surfaces within vitric units can be significant because of the large surface area associated with the rock pores. Conversely, fracture pathways have relatively limited surface area and thus exhibit limited sorption effects. The spatial distribution of vitric and zeolitic regions used in DOE's unsaturated zone flow model were selected based on rock core permeability data, rock-property data from boreholes within the model area, and the locations of faults with significant vertical offset, as described by Bechtel SAIC Company, LLC (2003a). Hydrogeologic properties for the unsaturated zone flow model layers were initially calibrated using one-dimensional inversions of field-measured saturation, water potential, and gas pressure data (Bechtel SAIC Company, LLC, 2003b). Because the one-dimensional inversions cannot account for lateral flow, the site-scale model was further adjusted to match observations of perched water in the northern area of the potential repository.

The amount of hydrologic data available for model calibrations varies for each data type (Bechtel SAIC Company, LLC, 2003b). For example, rock matrix saturation measurements were collected from 13 boreholes distributed throughout the model region, representing all rock types. Conversely, water-potential data are available from only three boreholes, and no water potential data are available below the potential repository. Because there are fewer data to constrain flow fields below the repository, there is greater uncertainty related to the calibrated hydrogeologic properties of fractures and rock matrix. DOE's response explains that, in the northern part of the domain, the modeled flow fields are less sensitive to the calibrated properties because perched water and low-permeability zeolitic units result in lateral flow that is focused into major faults zones. For example, the model for the mean glacial transition climate state shows that the percentage of fault zone flow within the model domain increases from 24 percent at the potential repository level to 62 percent at the water table (Bechtel SAIC Company, LLC, 2004a, Table 4-2). The percentage of water reaching the saturated zone through fault zones does not vary substantially for the different calibrated models representing lower and upper-bound infiltration rates or for the models representing different climate states.

DOE's response also provides a summary of data used to support the modeled flow fields. DOE's response provides a summary of transport models used to simulate chloride and strontium concentrations for comparison to field-measured, pore-water concentrations. Analyses of precipitated calcite in the unsaturated zone also provide information to support the modeled percolation flux. Modeling analyses of temperature data from nine surface-based boreholes provide additional support for the range of percolation fluxes simulated by the unsaturated zone flow model. These supporting analyses all produce model results that compare reasonably well to the observed data. It should be noted, however, that the borehole temperature data set is the only supporting data set that represents a significant portion of the model volume below the potential repository horizon.

Because there are relatively few supporting data sources for flow paths below the repository, the uncertainty from limited data should either be included in the abstraction of flow paths for performance assessment calculations or information should be provided to demonstrate that this uncertainty does not significantly affect the results of performance assessment calculations. DOE's abstraction of flow path below the potential repository considers uncertainty mainly by developing calibrated flow model scenarios for low-, medium-, and high-infiltration cases.

Although this approach does not explicitly include the "lack-of-data" uncertainty, it does result in a range of modeled flow path distributions. The effect of these different flow path distributions on radionuclide transport was evaluated by DOE in tracer transport model simulations conducted using the different flow fields generated from the calibrated unsaturated zone flow model (Bechtel SAIC Company, LLC, 2004c, Section 6.7.3). For example, simulations for the glacial-transition climate state resulted in 10-percent mass breakthrough times of 1, 4, and 43 years for the high-, medium-, and low-infiltration cases for a nonsorbing radionuclide released at the repository horizon in the fracture continuum. The 10-percent breakthrough times are representative of relatively fast flow paths. The respective 50-percent breakthrough times were 34, 110, and 3,900 years for the three infiltration cases. The 50-percent breakthrough times generally represent the median flow path traveltime to the water table, but these estimates may be biased to higher breakthrough times because solutes released in fractures are additionally delayed by matrix diffusion. These transport simulation results indicate the range of uncertainty considered by DOE abstraction of unsaturated zone transport pathways spans approximately two orders of magnitude in transport time for a nonsorbing radionuclide. Additionally, all unsaturated zone flow model scenarios considered in the performance assessment abstraction include a significant fraction of fast pathways from the repository to the water table, as indicated by the early estimated arrival times for the 10-percent mass breakthrough of a nonsorbing radionuclide.

In summary, available data are insufficient to determine conclusively that uncertainties related to the spatial distribution and thicknesses of zeolitic and vitric portions of the Calico Hills hydrogeologic unit are bounded. Results of tracer transport simulations, however, suggest that the range of uncertainty considered in the abstraction of unsaturated flow paths for performance assessment does include a significant fraction of fast flow pathways from the potential repository to the water table. Thus, it appears DOE's repository performance assessment calculations are not significantly biased by a lack of data to definitively characterize flow paths below the repository. DOE has provided a summary of the geochemical information used to support the flow paths beneath the potential repository, as requested in Agreements RT.3.02 and TSPAI.3.24. Staff conclude that this information, combined with available process modeling and performance assessment analyses will be sufficient to permit a detailed review of a potential license application. However, DOE should consider the representation of technical information detailing and differentiating unsaturated flow below the area of the proposed repository, separate from the representation of the entire site-scale model area. Staff consider the information provided in Bechtel SAIC Company, LLC (2004a) and supporting documents to be responsive to the NRC staff requests for information to support the flow fields below the potential repository horizon, as stated in Agreements RT.3.02 and TSPAI.3.24.

Agreement GEN.1.01 (Comment 106) requests DOE to provide a basis for excluding uncertainties in infiltrating water compositions and for selecting the particular water compositions used in its coupled thermal-hydrological-chemical model for the total system performance assessment analyses. DOE response (Bechtel SAIC Company, LLC, 2004a,

Appendix B) indicates that five water compositions based on actual pore water from unsaturated regions within or above the repository units were selected to represent the range of potential composition of infiltrating water. DOE acknowledged the five water compositions are based on samples mainly collected from the Enhanced Characterization Repository Block Cross-Drift, and the spatial coverage of the data is too small to derive a probability of occurrence for the selected water compositions. These water compositions are used as input to the Drift-Scale Coupled Processes Models (Bechtel SAIC Company, LLC, 2003c) to calculate a range of dilute water chemistries that may seep into drifts. Published data about pore-water samples collected by the U.S. Geological Survey from the unsaturated zone of the Yucca Mountain area (Yang, et al., 2003, 1998, 1996) show a much broader range in composition than the five samples selected by DOE as input to its coupled thermal-hydrological-chemical model. The range in unsaturated zone pore-water compositions reported the U.S. Geological Survey, however, do not necessarily represent the potential range in chemistry of infiltrating waters at the potential repository level. Although only 5 water compositions were used by DOE, the chemical compositions resulting from the coupled thermal-hydrological-chemical model encompass a broad range of chemistry, grouped by DOE into 11 bins (Bechtel SAIC Company, LLC, 2003d,e), and cover all 3 brine types—calcium chloride, sulfate, and carbonate—that could evolve by evaporation of initially dilute infiltrating waters. Staff, therefore, consider the information provided in Bechtel SAIC Company, LLC (2004a) sufficient to satisfy Agreement GEN.1.01 (Comment 106).

4.0 REVIEW OF TECHNICAL BASIS DOCUMENT NO. 2, APPENDIX C: DOE RESPONSE TO AGREEMENT TSPAI.3.26

Appendix C of Bechtel SAIC Company, LLC (2004a) provides DOE's response to Agreement TSPAI.3.26. Agreement TSPAI.3.26 was reached at a meeting held August 6–10, 2001, to discuss the TSPAI KTI (Reamer, 2001b). The wording of this agreement is as follows:

TSPAI.3.26

"Calibrate the UZ flow model using the most recent data on saturations and water potentials, and clearly document the sources of calibration data and data collection methods (UZ2.3.5). DOE will calibrate the UZ flow model using the most recent data on saturations and water potentials, and document the sources of calibration data and data collection methods. The results will be documented in the Calibrated Properties Model AMR (MDL–NBS–HS–000003) expected to be available to NRC in FY 2003."

4.1 Relevance to Repository Performance

NRC was concerned that measured data used to calibrate ambient unsaturated zone flow models did not reflect ambient conditions. NRC (2004) ranked the processes of unsaturated flow above and below the repository as being of medium significance to waste isolation. Data presented in Rousseau, et al. (1999) suggested that conditions had not returned to ambient in many of the instrumented boreholes. Drying of the rock during drilling and prior to sensor installation, and a slow rewetting to ambient conditions, were indicated by continually increasing measurements of water potential. In addition, measurements in the Enhanced Characterization of the Repository Block Cross-Drift suggest wetter ambient conditions compared with the surface-based borehole data. Water evaporating from cores during the drilling and sample collection process also was believed to be significant. Using data that had not returned to ambient conditions in a model calibration could affect the modeled distribution of water in the matrix and fracture continua of the dual-permeability models. The total flux of water in the unsaturated zone would not change, however, because it is controlled by the values of net infiltration applied to the top model boundaries of the mountain- and drift-scale unsaturated flow models. Additionally, relatively small changes in the saturation of rock matrix in units with low matrix permeability would not likely have a significant effect on the modeled distribution of flow in fractures and matrix. Accordingly, Agreement TSPAI.3.26 is considered to be of low significance to waste isolation (Travers, 2003).

4.2 NRC Evaluation and Comment

DOE's response to Agreement TSPAI.3.26 summarizes the approach used for estimating ambient water potential and water saturation for calibration of the site-scale unsaturated zone flow model. The amount of water estimated to be lost from cores by evaporation is added to the standard and measurement errors to calculate an estimate of total error (Bechtel SAIC Company, LLC, 2003b). The inverse of the total errors is used for weighting the saturation data used in the inverse calibration algorithm such that greater emphasis is placed on matching the data points with the least estimated error.

Plots of *in-situ* water potential measurements from four surface-based boreholes are presented by DOE in Appendix C (Bechtel SAIC Company, LLC, 2004a). The plots include data from replicate sensors at numerous depths in each of four surface-based boreholes and DOE's estimate of ambient water potentials. DOE attempted to extrapolate the temporal water potential data as a means for estimating ambient conditions. The NRC staff believe, however, that the criteria used by DOE in extrapolating these data are not transparent. Many DOE estimates of water potential shown in Figures C–1 to C–4 of Bechtel SAIC Company, LLC (2004a) do not appear to be extrapolated from asymptotic portions of the temporal curves. Also, some water potential estimates fall above, in between, and below data from the two replicated sensors.

In addition, it is not clear to the NRC staff how three additional sources of uncertainty are considered in the estimates of ambient water potential. First, the calibrated accuracy of the thermocouple psychrometers is either 0.8 or 1.0 bars (both are stated by DOE), with low precision in the near-saturation range (less than 1 bar). Second, water potentials measured with heat dissipation probes in the Enhanced Characterization of the Repository Block Passive Test (Bechtel SAIC Company, LLC, 2003f; Figure 6.10.2-4) generally indicate higher water potentials (i.e., wetter rock matrix) than the estimates used in the model calibration. DOE's response discounts these data by noting these measurements may not be representative across the mountain. Contrary to this position, DOE refers to newer water potential data from surface-based boreholes that also suggest wetter conditions compared with the older data used in the model calibration. DOE notes, however, these newer data are not yet qualified and, therefore, are not presented. Third, the NRC staff believe oscillations and perturbations in a few of the temporal data plots, particularly those at greater depths, represent an additional source of uncertainty in the estimation of steady-state ambient water potentials.

Water saturations measured on cores were adjusted by DOE using a diffusion-based mass transfer equation for a spherical body with 100 percent of the surface covered by water. Evaporation during handling is included, whereas evaporation caused by drilling with compressed air is not. The NRC staff believe the model for estimating evaporation during core handling is sufficient for the intended use of the data (i.e., for estimating handling errors to determine weights in the inverse calibration algorithm).

In summary, DOE's response presents approaches for estimating the ambient hydrological variables of water potential and saturation and states DOE now uses estimated conditions in the calibration of the mountain and drift-scale unsaturated flow models. It is clear that sources of data uncertainty remain that are not explicitly addressed in performance assessment calculations. From the NRC staff's review of DOE's seepage model, however, it appears that the percolation flux input used to estimate seepage is the total percolation flux below the interface of the Paintbrush Tuff nonwelded (PTn) and Topopah Spring welded (TSw) hydrogeologic units, which consists combined fracture and matrix flow (Bechtel SAIC Company, LLC, 2003i). It would, therefore, follow that the effect of calibrating the model to different matrix saturation data should not have an effect on the input fluxes used for the seepage abstraction. The effect of calibrating the UZ flow model to different saturation data on the distribution of water between the fracture and matrix continua is still relevant in terms of radionuclide transport below the repository. As discussed in the staff review for Agreement TSPAI.3.24, however, simulations for the high-, medium-, and low-infiltration cases for the glacial-transition climate state produce differences in median unsaturated zone transport times that are relatively fast and vary by more than two orders of magnitude. This range of uncertainty can reasonably be expected to be much greater than any transport time differences that might result from a calibrating the unsaturated zone model to slightly different matrix saturation values. Compared to the effects of the uncertainty already considered for net infiltration, the data uncertainty in rock matrix saturation data is of relatively lower significance to the modeled distribution of water in matrix and fractures. Staff, therefore, conclude that information regarding data used in DOE's calibration of the site-scale unsaturated zone flow model satisfactorily addresses Agreement TSPAI.3.26.

5.0 REVIEW OF TECHNICAL BASIS DOCUMENT NO. 2, APPENDIX D: DOE RESPONSE TO AGREEMENT TSPAI.3.22

Appendix D of Bechtel SAIC Company, LLC (2004a) provides DOE's response to Agreement TSPAI.3.22. This agreement was reached at a meeting held August 6–10, 2001, to discuss the TSPAI KTI (Reamer, 2001b). The wording of this agreement is as follows:

TSPAI.3.22

"Provide an assessment or discussion of the uncertainty involved with using a hydrological property set obtained by calibrating a model on current climate conditions and using that model to forecast flow for future climate conditions (UZ2.3.1). DOE will provide an assessment or discussion of the uncertainty involved with using a hydrological property set obtained by calibrating a model on current climate conditions and using that model to forecast flow for future climate conditions. This assessment will be documented in the UZ Flow Models and Submodels AMR (MDL–NBS–HS–000006) expected to be available to NRC in FY 2003."

Agreement TSPAI.3.22 was initially addressed (Ziegler, 2002) using a performance assessment analysis to show the requested information is not significant to waste isolation. The NRC review of this response resulted in the following request for additional information (Schlueter, 2003).

TSPAI.3.22–AIN

“Satisfactory information to address the technical topic of the agreement would be sufficient to complete Agreement TSPAI.3.22. DOE had proposed to compare modeling predictions with actual test results from field tests (such as Alcove 8–Niche 3) conducted at higher flow rates that are expected to encompass flow behavior representative of future climates. Alternatively, sensitivity analyses which adequately address NRC’s concerns with DOE’s approach to resolving agreements via risk arguments would be sufficient to complete the agreement.”

5.1 Relevance to Repository Performance

Agreement TSPAI.3.22 relates to uncertainty in the modeled transport pathways in the unsaturated zone that arises from using a model calibrated based on present-day infiltration estimates to predict unsaturated zone flow during periods of higher infiltration expected as a result of climate change. Some degree of confidence is needed that a calibration against present-day infiltration will be valid in a higher infiltration regime.

In a previous response (Ziegler 2002), DOE indicated it considers flow in the unsaturated zone to be of generally low significance to waste isolation (Bechtel SAIC Company, LLC, 2002). This conclusion, however, was based on analyses that assume the presence of intact drip shields, which masks the important role of the unsaturated zone as part of a geologic component of a multiple barrier system. Unsaturated zone flow fields can affect repository performance in two ways: (i) by affecting the rates and spatial distribution of seepage into drifts; and (ii) by affecting the traveltime of radionuclides released from the engineered barrier system. NRC (2004) considered drift seepage to be of relatively high significance to waste isolation because solubility-limited radionuclide release rates are directly proportional to seepage rates. Hydrologic properties of the unsaturated zone below the repository are considered to be of medium significance to waste isolation (NRC, 2004). Although Agreement TSPAI.3.22 is related to both seepage rates and flow below the repository, this agreement item is generally considered to be of low risk significance (Travers, 2003) because small changes to the rock saturations and water potentials matched in the model calibrations are not expected to have a significant effect on modeled flow velocities or modeled distributions of water flowing in matrix and fractures.

5.2 NRC Evaluation and Comment

DOE addresses Agreement TSPAI.3.22 by providing information from field tests conducted at Alcove 8–Niche 3 and at Alcove 1 at high infiltration rates. DOE seeks to show the calibrated hydraulic properties derived from field test results (Bechtel SAIC Company, LLC, 2003f; Liu, et al., 2003) are consistent with the ranges of hydraulic properties derived from calibrations to match borehole saturation data (Bechtel SAIC Company, LLC, 2003b). DOE’s response indicates the criterion for determining consistency is that the differences between corresponding parameter estimates from the high-infiltration field tests should be smaller than the standard deviations of the calibrated parameter distributions determined from the one-dimensional model inversions for current climate conditions.

The Alcove 1 tests indicate that fracture properties estimated from the field test are within the ranges of uncertainties of the calibrated parameter values for the tcw11 hydrogeologic unit. The estimated matrix properties are slightly outside the range of calibrated values for the tcw11 hydrogeologic unit. However, a more rigorous statistical test that accounted for both the uncertainty in the test results and the uncertainty in the drift-scale results would likely increase the uncertainty bands and may result in a passed test. Results from the Alcove 1 tests generally support the contention that the calibrated properties model is consistent with parameter estimates from tests conducted at higher infiltration rates.

Alcove 8–Niche 3 field test results are used to evaluate consistency of the calibrated fracture permeability and capillary strength parameters for the tsw33 and tsw34 hydrogeologic units. DOE's response states that fracture permeability values were not changed in the calibration procedure, because the model is either insensitive to this parameter or it can be well constrained. It is, thus, not possible to demonstrate that field test results fall within the standard deviation of model calibration results as proposed by DOE as the criterion for demonstrating consistency. The fixed fracture permeability values used for the calibrated property set, however, do fall within the ranges of fracture permeabilities estimated from several different tests conducted in Alcove 8–Niche 3.

The mean fracture capillary strength parameters estimated from the Alcove 8–Niche 3 *in-situ* tests lie outside the range of the uncertainty determined from the model calibrations, indicating a failed consistency test. The capillary strength parameter values estimated from the two procedures, however, are within one order of magnitude. Although the uncertainty in the capillary strength values estimated from the infiltration tests was not evaluated, this parameter uncertainty might overlap with the range of values estimated from the model calibration, given that the values are of the same order of magnitude. Another consideration is that the Alcove 8–Niche 3 tests represent a scale of several meters within each hydrogeologic unit, whereas the calibrated model parameter is an effective representation of the entire thickness of each hydrogeologic unit. Therefore, although there is no rigorous statistical interpretation of the test results, it is reasonable to conclude the results are broadly consistent. Because the uncertainties in the fault zone fracture permeability or capillary strength parameters are not reported, it is not possible to apply the consistency test to the fault zone fracture parameters.

Although consistency between results derived from borehole-based calibrated model parameters and parameters estimated from *in-situ* infiltration test data do not conclusively demonstrate there are no statistically significant differences, neither do the results suggest that results of the tests are clearly inconsistent. Furthermore, as DOE notes, there is no theoretical reason why the parameters of the calibrated property model should vary with infiltration rate, and there is no indication from results of the Alcove 8–Niche 3 tests that these properties vary in any significant way with the infiltration rate. Based on the review of the relative importance of rock saturations and water potential measurements on model calibrations (as discussed in preceding reviews of Agreements TSPAI.3.24 and TSPAI.3.26), DOE has provided sufficient information to satisfactorily address this agreement.

6.0 REVIEW OF TECHNICAL BASIS DOCUMENT NO. 2, APPENDIX H: DOE RESPONSE TO AGREEMENTS EVOLUTION OF THE NEAR-FIELD ENVIRONMENT (ENFE).2.03 AND TSPAI.2.02 (COMMENTS 3, 4, 12, and J–23)

Appendix H of Bechtel SAIC Company, LLC (2004a) provides the combined DOE response to Agreements ENFE.2.03 and TSPAI.2.02 (Comments 3, 4, 12, and J–23) (Ziegler, 2004a). Agreement ENFE.2.03 was reached at a meeting held January 9–12, 2001, to discuss the ENFE KTI (Reamer, 2001c). The wording of this agreement is as follows:

ENFE.2.03

“Provide the technical basis for FEP 1.2.06.00 (Hydrothermal Activity), addressing points (a) through (e) of NRC Subissue 2 slide handed out at the January 2001 ENFE technical exchange. The DOE will provide additional technical bases for the screening of FEP 1.2.06.00 (Hydrothermal Activity) in a future revision of the Features, Events, and Processes in UZ Flow and Transport AMR (ANL–NBS–MD–000001), expected to be available in FY 02. Within these technical bases, the DOE will address NRC comments [points (a) through (e)] presented on the NRC Subissue 2 slide handed out at the January 2001 ENFE technical exchange or provide justification that it is not needed.”

Points (a) through (e) mentioned in Agreement ENFE.2.03 are worded as follows:

“(a) Document the results (conductive cooling model of Timber Mountain Caldera magma body) presented by Brian Marshall at Summit 2000 Geological Society of America conference or provide an independent model that explains elevated temperatures in the unsaturated zone from about 12 Ma to 2 Ma; and

(b) In any analysis provided, address the effects of boundary conditions on the calculated results and, for the conductive cooling model, losses due to convection should be addressed; and

(c) Support the Marshall model by additional data (U-Th-He with error bars to overlay the theoretical cooling curve or thermochronology fission track data and analysis), including data that constrain the time of peak temperature. Support Marshall model or any other model with data from analogous systems (i.e., are there younger calderas where temperature profiles in boreholes have been measured that would support conductive heating of the unsaturated zone for kilometers away from the eruption site?); or

(d) Complete the exclusion of the FEP by demonstrating that the consequences of hydrothermal activity on repository performance doesn’t significantly affect the magnitude and time of the resulting expected annual dose.

(e) In addition to items (a), (b), and (c) or (d), DOE should address the timing and mode of formation of secondary mineralization for the Type B faults which record elevated temperatures (calcite twinning). Explain or interpret the apparent saturated conditions of mineralization in Class B faults. If DOE would like to argue that the twinning thickness is due to frictional heating and does not reflect temperature of fluids during formation, then DOE will need to provide a technical basis for their assertion."

Agreement TSPAI.2.02 was reached at a meeting held August 6–10, 2001, to discuss the TSPAI KTI (Reamer, 2001b). The wordings of Comments 3, 4, 12, and J–23 are as follows:

TSPAI.2.02 (Comment 3)

"2.2.10.03.00 (Natural Geothermal Effects). It is stated that natural geothermal effects are included because the current geothermal gradient is addressed in the saturated zone flow and transport model [Analysis/Model Report ANL–NBS–MD–000002, Revision 1]. This discussion, however, does not address the potential for spatial and temporal variations in that gradient."

TSPAI.2.02 (Comment 4)

"1.2.06.00.00 (Hydrothermal Activity). Saturated Zone: In [Analysis/Model Report ANL–NBS–MD–000002, Revision 1], this item is excluded on the basis of low consequence. For saturated zone transport, the argument is that the adopted K_d distributions account for possible lithologic changes and thermal effects, with reference to [Analysis/Model Report ANL–NBS–MD–000011, Revision 0]. However, the latter document does not provide a clear technical basis that the K_ds were derived in such a fashion. In addition, though the screening argument is based on low consequence, there is a reference at the conclusion of the supplemental discussion to the low probability of hydrothermal activity [Analysis/Model Report ANL–NBS–MD–000002, Revision 1]."

"Unsaturated Zone: This item is excluded in the unsaturated zone on the basis of low consequence and low probability [Analysis/Model Report ANL–NBS–MD–000001, Revision 1]. DOE has not yet provided sufficient technical bases for models explaining elevated temperatures in the unsaturated zone from approximately 12–2 million years ago or adequately addressed the timing and mode of formation of Type B faults, which record elevated temperatures."

TSPAI.2.02 (Comment 12)

"2.2.10.13.00 [Density-Driven Groundwater Flow (Thermal)]. The analysis and model report [ANL–NBS–MD–000002, Revision 1] addresses this item in two parts: repository-induced effects (excluded, low consequence) and natural geothermal effects (included). Exclusion of repository effects on flow based on the DOE analyses is accepted. Natural effects are included only to the extent that the natural geothermal gradient is applied in the saturated zone flow and transport model. However, changes in thermal gradients are excluded on the basis of low consequence, with reference to 1.2.06.00.00 (Hydrothermal Activity) and 1.2.10.02.00 (Hydrologic Response to Igneous Activity) [Analysis/Model Report ANL–NBS–MD–000002, Revision 1]. A clear technical basis is not provided for these items that all possible changes in thermal gradients will be localized. The screening argument for 1.2.06.00.00 (Hydrothermal Activity) focuses on geochemical effects (see separate entry), whereas 1.2.10.02.00 (Hydrologic Response to Igneous Activity) is focused on highly localized igneous intrusions. How these arguments apply to 2.2.10.13.00 [Density-Driven Groundwater Flow (Thermal)] is not entirely clear."

TSPAI.2.02 (Comment J–23)

"1.2.06.00.00 (Hydrothermal Activity). Excluded on the basis of low consequence for basaltic magmatism and low probability for silicic magmatism [Analysis/Model Report ANL–NBS–MD–000001, Revision 1]. A consistent approach for the screening arguments is needed. The screening argument is considered incomplete because (i) past hydrothermal activity in the Yucca Mountain region is not clearly related to basaltic igneous activity and (ii) probability screening arguments in [Analysis/Model Report ANL–NBS–MD–000001, Revision 1] are incomplete with respect to silicic magmatism. In addition, DOE cites unpublished studies by the U.S. Geological Survey and the University of Nevada Las Vegas that reportedly demonstrates hydrothermal activity was a site characteristic until about 2 million years ago. Additional unpublished work by Dublyanski and others, however, does not support this conclusion. None of the unpublished work, however, has supported the conclusion that the likelihood of hydrothermal activity at Yucca Mountain during the next 10,000 years is clearly less than <1:10,000. Absent a clear linkage to the consequences of basaltic igneous activity, or a demonstrated technical basis for probability values below 1 in 10,000 in 10,000 years, DOE has an incomplete technical basis to screen 1.2.06.00.00 (Hydrothermal Activity) from further consideration."

6.1 Relevance to Repository Performance

Agreements ENFE.2.03 and TSPAI.2.02 (Comments 3, 4, 12, and J–23) reflect an NRC concern that the exclusion of hydrothermal upwelling and natural geothermal effects from performance assessment calculations was based on screening arguments that did not fully consider evidence of past elevated temperatures in the unsaturated zone at Yucca Mountain. For example, abundant two-phase fluid inclusions in secondary calcite minerals suggest temperatures in the unsaturated zone at Yucca Mountain might have been hotter for longer periods of time than can be explained by results from thermal modeling of rock temperatures since the primary deposition of hot volcanic ash-flow tuffs. Scientists employed by the State of Nevada have proposed that the two-phase fluid inclusion data provide evidence of high-temperature water which indicates that seismically or geothermally activated perturbations of the saturated zone flow system have inundated the unsaturated zone at Yucca Mountain in the recent geologic past (e.g., Szymanski and Harper, 2002; Szymanski, et al. 2002; Dublyanski, et al., 2002). Potentially significant effects of such periodic flooding on waste isolation include changes to groundwater flow and transport behavior and changes to the in-drift geochemical environment that could affect waste package corrosion rates. These agreement items request DOE to improve the technical basis for the exclusion from consideration of hydrothermal upwelling in performance assessments of the potential repository at Yucca Mountain. Agreement ENFE.2.03 was identified (Travers, 2003) as low-risk significance. Although Agreement TSPAI.2.02 was identified as high-risk significance (Travers, 2003), the individual comments within TSPAI.2.02 were not separately categorized within the significance framework.

6.2 NRC Evaluation and Comment

DOE's response to Agreements ENFE.2.03 and TSPAI.2.02 (Comments 3, 4, 12, and J–23) provides a summary of data and modeling used to assess the thermal history of Yucca Mountain.

Studies of two-phase fluid inclusions at Yucca Mountain using petrography, microthermometry, and U-Pb dating indicate that temperatures have remained cooler than about 35 EC [95 EF] for the past 2–5 million years, with evidence for elevated temperatures prior to 2–5 million years. Data used in this assessment include oxygen and strontium isotopes in secondary calcite minerals that Marshal and Whelan (2000) interpreted to indicate significantly elevated temperatures occurred at Yucca Mountain from 12 to 6 million years before present. They initially attributed the elevated temperatures to the thermal perturbation at 12 million years caused by the emplacement of large volumes of magma beneath the Timber Mountain caldera, which is located at least 4–9 km [2.5–5.6 mi] north of Yucca Mountain.

Additional thermal modeling by Marshall and Whelan (2001) suggests that the long-lived, near-surface thermal perturbations at Yucca Mountain could not be reproduced by their thermal models, which predicted much faster cooling than inferred from oxygen and strontium isotope analyses in secondary minerals (Whelan, et al., 2003). Although modeled temperatures could increase up to 120 EC [248 EF] within the Timber Mountain caldera for several million years, modeled temperatures rapidly decreased to near ambient conditions within 4 km [2.5 mi] of the caldera boundary. DOE’s response notes that similar thermal gradient effects are observed at the 0.7-million year Long Valley caldera, California, where the only observed thermal anomalies occur within the caldera boundary.

Similar to the isotopic data, temperature histories inferred from two-phase fluid inclusions in calcite minerals also suggest that temperatures at Yucca Mountain were hotter for longer periods of time than is indicated by the thermal modeling. Age constraints on the temperature estimates from the fluid-inclusion and oxygen-isotope data were obtained using uranium-lead and uranium series dating methods (Whelan, et al., 2003). These age constraints suggest that the isotopic and fluid-inclusion data show a consistent, slow cooling trend from approximately 80–90 EC [176–196 EF] down to approximately 35–55 EC [95–130 EF] during the period from 10–6 million years. This portion of the cooling trend could not be matched by the thermal modeling results. At 5 million years, the estimated temperatures are in the range 30–40 EC [86–104 EF] and decline to values of approximately 20–25 EC [68–77 EF] during the past 0.5 million years. This latter portion of the cooling trend is consistent with thermal model results.

Other relevant evidence for elevated temperatures at Yucca Mountain includes an evaluation of secondary calcite minerals in Class B faults by Gray, et al. (2000, 1999), who interpreted thick calcite twins to indicate the calcite within these faults was deformed at elevated temperatures above approximately 170 EC [338 EF], based on analyses by Ferrill, et al. (2004). Explanations proposed in DOE’s response for the different estimated temperatures are that either the thick calcite twins formed at lower temperatures or the twinned and untwinned calcites formed at different times. No ages were determined for the twinned calcites.

Textural evidence from the Class B faults also suggests the secondary calcite found there was precipitated under saturated or near-saturated conditions (Gray, et al., 1998). Class B fault cores consist of angular rock fragments and as much as 65 percent or more calcite matrix. The tuff clasts are generally intact and show little evidence that they were pulverized after initial fracturing. Tuff fragments in these fault zones are commonly angular and elongate, creating tabular- or rectangular-shaped clasts. The dispersion of rock fragments is perhaps best described as an exploded jigsaw puzzle breccia (Sibson, 1986) or jigsaw breccia (Seront, et al., 1998). Some clasts can be restored graphically to fit into one another by simple rigid body translation, rotation, or both. Unlike the secondary minerals observed in the lithophysal cavities, calcite in the Class B fault zones shows poikilotopic texture, in which the tuff wall rock clasts are completely supported with a coarse to microcrystalline calcite matrix. Often the calcite matrix forms large patches of crystallographically continuous calcite, similar to poikilotopic cements observed elsewhere in carbonate rocks (e.g., Folk, 1974; Scholle and Ulmer-Scholle, 2003). These observations suggest the secondary mineralization at Yucca Mountain was polygenetic (e.g., Gray, et al., 2000), involving a variety of hydrogeologic conditions.

Because the thick calcite twins have been found only in Class B faults and not in other types of faults, fractures, or lithophysal cavities, the presence of twinned secondary calcite in the Class B faults does not support a conceptual model of widespread hydrothermal upwelling throughout the unsaturated zone at Yucca Mountain. Perhaps, the Class B faults indicate the presence of localized geothermal systems that advect thermal fluids from depth. Localized geothermal systems also would be consistent with DOE's scenario of subsurface outflow of thermal fluids from the cooling Timber Mountain caldera system. (This scenario is discussed later in this report section.)

Based on available evidence, the conceptual model proposed by DOE is that secondary minerals at Yucca Mountain were deposited by waters of meteoric origin and that fluid inclusions with homogenization temperatures greater than about 35 EC [95 EF] are generally older than 6 million years and reflect processes no longer active at Yucca Mountain. This conceptual model lacked an explanation for the enhanced heating that allowed high temperatures to persist during the period from 10 to 6 million years. DOE's agreement response proposes the following scenarios that could have resulted in enhanced heating of the Yucca Mountain area:

- Sustained magmatism after the cessation of volcanic activity;
- Magmatic intrusion outside the caldera margins and closer to the Yucca Mountain area;
- Lateral subsurface outflow of hydrothermal fluids from the Timber Mountain area in the direction of Yucca Mountain; or,
- Presence of additional overburden that has been eroded away subsequently above the Yucca Mountain area that would have resulted in a deeper location for the earlier part of the thermal history.

There is little evidence to support DOE's scenario of sustained magmatism and, thus, sustained heating of crustal rocks within the Timber Mountain caldera after 11 million years. Tuffs of the Timber Mountain and Paintbrush Groups represent an eruption of more than 4,500 km^3 [1,080 mi^3] of magma (Sawyer, et al., 1994). Relatively small-volume eruptions {order of 100 km^3 [25 mi^3]} associated with resurgent dome formation at Timber Mountain do not appear to have sufficient thermal mass to affect cooling models significantly. Regional magmatism earlier than 11 million years to the north and west of Timber Mountain is too distant to reasonably affect thermal models for Yucca Mountain. DOE does not cite any information to support the scenario of a hidden magmatic intrusion occurring south of the Timber Mountain or Claim Canyon caldera boundaries. Features characteristic of a significant subsurface intrusion, such as large, coherent gravity or magnetic anomalies, are not found in available data (Ponce, et al., 2001; Ponce and Blakely, 2001). Although large thicknesses of eroded overburden may have buried Yucca Mountain deeper than previously thought, DOE does not provide a technical basis to account for the thickness of potentially missing deposits needed for this scenario. In addition, DOE does not discuss how much additional burial would be needed in this scenario to account for paleotemperatures measured in 6 to 11 million year minerals at Yucca Mountain.

Subsurface outflow of hydrothermal fluids from the Timber Mountain caldera system, however, appears a credible scenario to account for elevated paleotemperatures preserved in 6 to11 million year minerals at Yucca Mountain. Although DOE does not present a model for advective hydrothermal flow from the cooling Timber Mountain caldera, such flows are commonly observed in geothermal systems that occur above and adjacent to large-volume magma bodies (e.g., Goff, et al., 1988). In comparison, small-volume magma bodies representative of basaltic volcanism in the Yucca Mountain area since 11 million years are not associated with such hydrothermal flows.

Absent a recurrence of caldera-scale magmatism, hydrothermal fluids with similar characteristics are not expected to occur. Because caldera-scale magmatism has not occurred in the Yucca Mountain area since 9 to 11 million years, DOE considers the likelihood of renewed caldera-scale magmatism to be negligible (Bechtel SAIC Company, LLC, 2003g). Regional tectonic and magmatic conditions that led to the development of the >11 Ma Timber Mountain caldera system are significantly different from those conditions during the last several million years (e.g., Sawyer, et al., 1994). Large changes in the geometry of Pacific-North American plate interaction since 11 Ma (e.g., Severinghaus and Atwater, 1990) have altered the regional tectonic patterns that likely led to caldera development. Relatively large-volume silicic volcanism also has migrated northwest from the Yucca Mountain region (e.g., Sawyer, et al., 1994). These relationships support the conclusion (Bechtel SAIC Company, LLC, 2003g) that renewed caldera-scale magmatism in the Yucca Mountain region does not appear to be a credible event for performance calculations.

Although studies of secondary minerals at Yucca Mountain by several organizations continue to this date, the NRC staff consider the conceptual model proposed by DOE for secondary mineral deposition at Yucca Mountain is generally consistent with available lines of evidence, notwithstanding remaining uncertainties in the age, timing, and origin of the thermal perturbations that produced elevated temperatures evidenced by fluid inclusions, and the age, origin, and thermal evolution of other occurrences of secondary minerals at Yucca Mountain, including the calcite in Class B faults. In addition, staff note there are some differences in the interpretation of geochemical data used to support DOE's conceptual model. For example, the University of Nevada Las Vegas geochemists (as reported in Wilson, et al., 2003), disagree with the U.S. Geological Survey application of stable isotope data in developing an age progression of secondary mineralization based on carbon/oxygen isotope ratios. Those age progression data form an integral part of the conceptual model of steady-state mineral growth for millions of years (e.g., Marshall and Whelan, 2000).

Nevertheless, based on the foregoing considerations, the NRC staff believe DOE's features, events, and processes screening arguments for the exclusion of hydrothermal upwelling and natural geothermal effects from performance assessment calculations, as documented by Bechtel SAIC Company, LLC (2004d), are sufficient to satisfy Agreements ENFE.2.03 and TSPAI.2.02 (Comments 3, 4, 12, and J–23). Staff recognize that new data or analyses related to the interpretation of thermal histories from secondary minerals and other lines of evidence continue to be evaluated. Pertinent new information could raise new questions or comments related to this issue.

7.0 REVIEW OF TECHNICAL BASIS DOCUMENT NO. 2, APPENDIX I: DOE RESPONSE TO AGREEMENTS UNSATURATED AND SATURATED FLOW UNDER ISOTHERMAL CONDITIONS (USFIC).4.04, TSPAI.2.02 (COMMENT J–20), AND GEN.1.01 (COMMENTS 24 and 69)

Appendix I of Bechtel SAIC Company, LLC (2004a) provides the combined DOE response to Agreements USFIC.4.04, TSPAI.2.02 (Comment J–20), and GEN.1.01 (Comments 24 and 69) (Ziegler, 2004b). Agreement USFIC.4.04 was reached at a meeting held October 31–November 2, 2000, to discuss the USFIC KTI (Reamer, 2000b). The wording of this agreement is as follows:

USFIC.4.04

"Provide final documentation for the effectiveness of the PTn to dampen episodic flow, including reconciling the differences in [chlorine]-36 studies."

Agreement TSPAI.2.02 was reached at a meeting held August 6–10, 2001, to discuss the TSPAI KTI (Reamer, 2001b). The wording of Comment J–20 is as follows:

TSPAI.2.02 (Comment J–20)

"2.2.07.05.00 (Flow and Transport in the Unsaturated Zone from Episodic Infiltration). Excluded based on low consequence. Screening argument asserts that episodic infiltration is expected to be attenuated by flow in the paintbrush nonwelded tuff layer such that unsaturated zone flow beneath this layer is effectively steady-state. Analyses to support this assertion, however, have only considered episodic infiltration with an average of 5 mm/yr [0.197 in/yr] infiltration flux. Area-average infiltration flux over the proposed repository horizon at Yucca Mountain is expected to exceed 20 mm/yr [0.787 in/yr] during future wetter climate conditions."

Agreement GEN.1.01 was reached at a meeting held September 18–19, 2001, to discuss the range of thermal operating temperatures (Reamer, 2001a). The wordings of Comments 24 and 69 are as follows:

GEN.1.01 (Comment 24)

"No data [are available] to support the conclusion that sublayers in the PTn might act as laterally continuous capillary barriers."

GEN.1.01 (Comment 69)

"The alternative modeling of flow through the PTn as discussed on p. 3-25 [of the Supplemental Science and Performance Assessment document] is based on the capillary pressure data of a single borehole. It seems that the conclusions use the implicit assumption that this single borehole (point) data is valid across the entire PTn layer. Spatial variability of this capillary pressure distribution could lead to very different modeling results. In particular, unless the spatial distribution of capillary pressures is not supported, the strong lateral flow component and resulting damping function of the PTn is not supported. On the contrary, lateral flow could be limited in scale, and result in localized flow focusing.

The conclusion in section 3.3.3.5 on p. 3-27, that the TSPA abstraction is conservative, is not supported. It is only conservative with respect to the presented simulation including lateral PTn flow over the entire layer. It could be non-conservative if lateral flow were found to be spatially limited, thus leading to a flow focusing within the PTn layer."

7.1 Relevance to Repository Performance

USFIC.4.04, TSPAI.2.02 (Comment J–20), and GEN.1.01 (Comments 24 and 69) all pertain to effects of the Paintbrush nonwelded tuff hydrogeologic unit on unsaturated zone flow. Compared to welded tuffs, the larger matrix porosity and generally lower fracture density of the Paintbrush nonwelded tuff unit are the basis for DOE's assumption that highly episodic infiltration is attenuated to an effectively steady-state condition below the Paintbrush nonwelded tuff. The steady-state flow condition is much simpler to model, and the attenuation of short-duration, large percolation fluxes reduces the possibility that percolation reaching the potential repository horizon will occur at rates that exceed the threshold for drift seepage. NRC (2004) identified seepage into drifts as being of high significance to waste isolation. DOE's site-scale unsaturated zone model also predicts significant lateral flow within the Paintbrush nonwelded tuff unit. Such lateral flow could have the effect of diverting water away from the potential repository horizon, thereby reducing the amount of percolation in excess of seepage thresholds and also reducing the amount of water available for transport of radionuclides. Agreement USFIC.4.04 addresses one issue associated with seepage and was identified as medium-risk significance (Travers, 2003) while both Agreements GEN.1.01 and TSPAI.2.02 were identified as high-significance (Travers, 2003), the individual comments within these agreements were not separately categorized with the significance framework.

7.2 NRC Evaluation and Comment

Agreements USFIC.4.04 and TSPAI.2.02 (Comment J–20)

Agreements USFIC.4.04 and TSPAI.2.02 (Comment J–20) request DOE to justify the assumption that the Paintbrush nonwelded hydrogeologic unit acts to attenuate episodic infiltration. DOE had previously provided transient infiltration modeling results to justify this steady-state assumption, but that modeling considered average net infiltration rates of only 5 mm/yr [0.2 in/yr], whereas expected infiltration rates during future climate conditions at Yucca Mountain are expected to be significantly greater. DOE's response (Bechtel SAIC Company, LLC, 2004a, Appendix I) provides summaries of the previous analyses of episodic flow, as well as a new one-dimensional episodic flow analysis that assumes an annualized net infiltration rate {20 mm/yr [0.8 in/yr]}, which is approximately representative of the area-averaged net infiltration rate estimated for the glacial-transition climate state. All episodic flow models presented in DOE's response employ a generally conservative assumption that the total net infiltration occurs as a single 1-week event every 50 years.

The newer episodic flow model with the higher infiltration addresses the original NRC concern that the previous models did not consider a high enough infiltration rate. A continuing concern, however, is that, compared to the previous analyses, the location used for the higher rate model of episodic infiltration is based on the hydrostratigraphy at the northern extreme of the potential repository footprint where the 165-m [541-ft] total thickness of the Paintbrush nonwelded tuff unit (CRWMS M&O, 2000) is generally unrepresentative of the vast majority of the repository footprint area. The Paintbrush nonwelded tuff unit is much thinner just a short distance to the south and is approximately in the range of 50–100 m [164–328 ft] thick for the majority of the most recent potential repository footprint described by DOE. The previous models were based on a location farther south that could be considered representative of the majority of the repository area. It is not clear from available information why DOE investigators changed to a location with a much thicker Paintbrush nonwelded tuff unit for the higher infiltration rate model. Additionally, DOE's response does not include sufficient detail regarding the input parameters and model grid used in the episodic flow analyses; the reference cited in the response for this information (Wang, 2003) was not publically available at the time of this review. Staff, therefore, conclude the models used by DOE to justify the steady-state flux boundary condition presently lack justification and have not been sufficiently documented to permit a detailed review.

Agreement USFIC.4.04 also requests DOE to reconcile differences in Cl-36 studies. Earlier studies (e.g., Fabryka-Martin, et al., 1997) reported evidence of bomb-pulse Cl-36 at several locations in the Exploratory Studies Facility, mostly in or near fault zones. Two subsequent validation studies (e.g., Paces, et al., 2003), however, found no clear evidence of bomb-pulse Cl-36 in the Exploratory Studies Facility. DOE's response suggests the difference in results between the original and subsequent validation studies is most likely because of differences in protocols for preparing rock samples for leaching of chloride. That is, rock samples in the validation studies were crushed to a finer chip size, which likely led to enhanced leaching of very old chloride from the rock matrix, thereby reducing Cl-36/Cl ratios so that it was impossible to discern bomb-pulse Cl-36 from background concentrations. This conclusion suggests that the findings from the original Cl-36 studies (Fabryka-Martin, et al., 1997) should stand. This plausible rationale summarized in Appendix I (Bechtel SAIC Company, LLC, 2004a) provides a basis for reconciling differences between lab results from the Cl-36 studies. Staff note, however, that complete documentation of the validation studies by Bechtel SAIC Company, LLC (2003h) was in draft form at the time of this review and that the additional information cited in the final paragraph of Appendix I (Bechtel SAIC Company, LLC, 2004a) is not available.

DOE's response summarizes previous modeling of Cl-36 transport times (Bechtel SAIC Company, LLC, 2001b) that indicates approximately 1 percent of a conservative tracer applied to the land surface at Yucca Mountain can reach the potential repository horizon within 50 years, and the locations of earliest tracer arrival are generally associated with fault zones included in the model. Although these results do not directly corroborate specific Cl-36 detections, they do indicate DOE's unsaturated zone flow model includes physically plausible mechanisms by which Cl-36 from the bomb-pulse period could have reached potential repository depths. It is, thus, appropriate to expect some relatively fast flow pathways (i.e., traveltimes less than 50 years from surface to repository depth) that are generally, but not exclusively, associated with fault zones. Thus, on the basis of this review and the incorporation of a fast pathway approach for estimating unsaturated zone flow in DOE's model, DOE has provided sufficient information regarding reconciliation of the Cl-36 studies to satisfactorily address Agreement USFIC.4.04.

In summary, DOE provided documentation of analyses that show attenuation of transient flow for a limited set of conditions. DOE's response also addresses staff questions regarding reconciliation of the Cl-36 studies. DOE has provided sufficient information to satisfactorily address Agreement USFIC 4.04. The information provided by DOE, however, does not provide sufficient justification for excluding the effects of transient infiltration below the Paintbrush tuff hydrogeologic unit throughout all portions of the model domain relevant to potential repository performance. Staff, therefore, conclude that DOE has not provided sufficient information to satisfactorily address Agreement TSPAI.2.02 (Comment J–20). DOE should provide additional analyses of the damping of transient flow by the Paintbrush tuff unit. These analyses should be based on net infiltration scenarios that are reasonably representative of the higher infiltration rates expected for future wetter climates and also on a thickness of the Paintbrush tuff representative of the area above the majority of the potential repository footprint. Alternatively, DOE could include the effects of transient flow in performance assessment seepage abstractions or provide other lines of evidence to show that transient flow below the Paintbrush tuff layer would not be detrimental to repository performance.

Agreement GEN.1.01 (Comments 24 and 69)

Comments 24 and 69 of Agreement GEN.1.01 pertain to the extent of lateral diversion within sublayers of the Paintbrush nonwelded tuff unit. The NRC staff were concerned the treatment of Paintbrush nonwelded tuff subunits as laterally continuous capillary barriers with smooth layer interfaces could result in unrealistic predictions of lateral diversion within the Paintbrush nonwelded tuff unit (e.g., Wu, et al., 2002). DOE's response (Bechtel SAIC Company, LLC, 2004a, Appendix I) shows the current DOE site-scale unsaturated zone flow model indeed estimates significant downdip lateral flow in the Paintbrush nonwelded tuff. This modeled lateral flow across distances exceeding 500 m [1,640 ft] results in a significant redistribution of water at the base of the Paintbrush nonwelded tuff, with as much as 40 percent of the total percolation flux being diverted into fault zones within the unsaturated zone model domain. Field evidence and observations suggest that naturally occurring heterogeneities and irregular layer interfaces, which are not considered in DOE's model, could act to limit the extent of lateral diversion (e.g., Fedors, et al., 2002; Flint, et al., 2003; Dinwiddie, et al., 2004). The NRC staff believe this field evidence provides evidence that lateral diversion within the Paintbrush nonwelded tuff unit is unlikely to be greater than a few tens of meters and that DOE's unsaturated zone flow model significantly overestimates the scale of lateral flow within the Paintbrush nonwelded tuff unit.

Because of the foregoing NRC concern with DOE's unsaturated zone flow model, staff must consider whether possible overestimation of lateral diversion in the Paintbrush nonwelded tuff unit can significantly affect repository performance assessments. An analysis documented in Bechtel SAIC Company, LLC (2003i, Table 6.6-11, Figures 6.6-11 and 6.6-12) specifically compares differences in percolation fluxes at the base of the Paintbrush nonwelded tuff unit for unsaturated zone models with and without significant lateral flow in the Paintbrush nonwelded tuff. This DOE analysis clearly shows that the modeled spatial distribution of fluxes are different for the two conceptualizations although the resulting statistical distribution of percolation fluxes above waste package locations is not significantly affected. The main difference is that the model with significant lateral flow in the Paintbrush nonwelded tuff unit results in fewer model grid locations within the repository footprint that receive zero or little flux and perhaps three or four locations that receive significantly higher flux [e.g., compare Figures 6.6-11 and 6.6-12 of Bechtel SAIC Company, LLC (2003i)]. For all three mean climate scenarios, the average flux rates were not significantly different for the two model conceptualizations of flow in the Paintbrush nonwelded tuff unit (Bechtel SAIC Company, LLC, 2003i, Table 6.6-11). Additionally, although the model with lateral flow in the Paintbrush nonwelded tuff results in significant diversion of water toward fault zones within the unsaturated zone model area, there appears to be relatively little water diverted into fault zones within the repository footprint area (Bechtel SAIC Company, LLC, 2003i, Table 6.6-11). Also, it appears the quantity of water diverted downdip and off the repository footprint area is roughly offset by a similar quantity of water that runs onto the footprint from the updip area west of the footprint but east of the Solitario Canyon fault. Thus, DOE's unsaturated zone model that results in significant lateral flow in the Paintbrush nonwelded tuff unit is not expected to result in significant changes to predictions of seepage or radionuclide transport at more than a few of the more than 11,000 drift locations considered in the performance assessment.

In summary, although the NRC staff believe large-scale lateral flow in the Paintbrush nonwelded tuff unit is unlikely to occur, it appears this model uncertainty should not significantly affect repository performance predictions based on the repository footprint delineated in Bechtel SAIC Company, LLC (2003i, Figure 6.6-10). Comments 24 and 69 of Agreement GEN.1.01 are, therefore, considered sufficiently addressed by available information. Staff note, however, that any changes to the potential repository footprint area, such as the inclusion of the zone referred to as the contingency area (Bechtel SAIC Company, LLC, 2003i, Figure 6.6-5), will necessitate a reevaluation by the NRC staff of the significance to waste isolation of overestimating lateral flow in the Paintbrush nonwelded tuff unit.

8.0 SUMMARY OF THE AGREEMENTS

The NRC staff has reviewed DOE's KTI agreement responses provided in Appendixes A–I of Technical Basis Document No. 2 (Bechtel SAIC Company, LLC, 2004a) to determine if sufficient information on these technical agreement items will be available for review of a potential license application. On the basis of this review, and notwithstanding new information that could raise new questions or comments concerning the preceding agreements, DOE has provided sufficient information to satisfactorily address Agreements ENFE.2.03, RT.1.01, RT.3.02, USFIC.4.04, TSPAI.3.22, TSPAI.3.24, TSPAI.3.26, TSPAI.2.02 (Comments 3, 4, 12, and J–23), and GEN.1.01 (Comments 24, 69, and 106).

However, DOE's response to Agreement TSPAI.2.02 (Comment J–20). DOE's response to Agreement TSPAI.2.02 (Comment J–20) does not provide sufficient justification for DOE's assumption of steady-state flow below the Paintbrush tuff hydrogeologic unit.

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