REVIEW BY THE OFFICE OF NUCLEAR MATERIAL SAFETY AND SAFEGUARDS OF THE U.S. DEPARTMENT OF ENERGY AGREEMENT RESPONSES RELATED TO THE PROPOSED GEOLOGIC REPOSITORY AT YUCCA MOUNTAIN, NEVADA: KEY TECHNICAL ISSUE AGREEMENTS USFIC.4.01, TEF.2.08, TSPAI.3.25, AND GEN.1.01, COMMENT 15

[PROJECT NO. WM–00011]

1.0 INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) issue resolution goal during this interim prelicensing period is to assure 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 NRC 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 October 31, 2003, DOE submitted a report titled Technical Basis Document No. 3: Water Seeping into Drifts (Bechtel SAIC Company, LLC, 2003a). The DOE responses to seven NRC and DOE key technical issue agreement items are contained in appendixes to that report. NRC reviews of the DOE responses to three of these agreements were conducted previously, and staff evaluations and comments were provided to DOE (Reamer, 2004).

Staff reviews of the DOE responses to the remaining four agreement items are described in the following sections. The wording of the agreement items and brief summaries of the information provided by DOE for each agreement are in Section 2. Section 3.0 provides NRC staff evaluations of the extent to which the DOE responses satisfy respective agreements.

2.0 TECHNICAL INFORMATION PROVIDED IN THE DOE AGREEMENT RESPONSES

2.1 Agreement USFIC.4.01

Agreement USFIC.4.01 was reached at a meeting held October 31–November 2, 2000, to discuss the Unsaturated and Saturated Flow Under Isothermal Conditions Key Technical Issue (Reamer, 2000). The wording of this agreement is as follows:

> “The ongoing and planned testing are a reasonable approach for a licensing application with the following comments: (i) consider a mass balance of water for Alcove 8/Niche 3 cross over test, (ii) monitor evaporation during all testing, (iii) provide the documentation of the test plan for the passive cross drift hydrologic test, (iv) provide the NRC with any cross drift seepage predictions that may have been made for the passive cross drift hydrologic test, (v) provide documentation of the results obtained and the analysis for the passive cross drift hydrologic test. This documentation should include the analysis of water samples collected during entries into the cross drift (determination whether the water comes from seepage or condensation), (vi) provide documentation of the results

obtained and the analysis for the Alcove 7 test. This documentation should include the analysis of water samples collected during entries into Alcove 7 (determination whether the water comes from seepage or condensation), (vii) provide the documentation of the test plan for the Niche 5 test, (viii) provide documentation of the results obtained and the analysis for the Niche 5 test, (ix) provide documentation of the results obtained and the analysis for the Systematic Hydrologic Characterization test, (x) provide documentation of the results obtained and the analysis for the Niche 4 test, and (xi) provide documentation of the results obtained from the calcite filling test. Include interpretation of the observed calcite deposits found mostly at the bottom of the lithophysal cavities. DOE stated that: (1) a mass balance of water for the Alcove 8/Niche 3 test has been considered, but is not feasible due to the size of the collection system that would be required. A collection system to obtain a mass balance is being developed for the Niche 5 test (i); (2) evaporation will be monitored for all tests where evaporation is a relevant process (ii); (3) test plans for Niche 5 and the Cross Drift Hydrologic tests are expected to be available to NRC fiscal year 2002 (iii, vii); (4) the Cross Drift seepage predictions will be documented in the Seepage Calibration Model and Seepage Testing Data Analysis Modeling Report (MDL–NBS–HS–000004) expected to be available to NRC by fiscal year 2003 (iv); (5) DOE will document the results for the tests identified above (except calcite filling observations) in the *In-Situ* Field Testing of Processes Analysis Modeling Report (ANL–NBS–HS–000005) expected to be available to NRC in fiscal year 2003 (v), (vi), (viii),(ix),(x); (6) results of the calcite filling observations will be documented in Analysis of Geochemical Data for the Unsaturated Zone (ANL–NBS–HS–000017) and the Unsaturared Zone Flow Models and Submodels (MDL–NBS–HS–000006) expected to be available to NRC fiscal year 2003 (xi)."

<u>Technical Information Provided for Agreement USFIC.4.01</u>

The DOE response to Agreement USFIC.4.01 is provided in Appendix C of the Bechtel SAIC Company, LLC (2003a) technical basis document. The responses to each aspect of the agreement are summarized as follows:

1. A mass balance of water was considered for Alcove 8–Niche 3, but was not performed because the large scale of this test would have required a collection system that was considered infeasible. A collection system to obtain a mass balance was therefore developed for Niche 5, but its effectiveness was limited, so a complete mass balance was not obtained.

2. Evaporation was monitored in Niche 5 and for the systematic hydrologic characterization tests, and this information was used for the quantitative determination of seepage-related parameters. Evaporation was not monitored in Niche 4, the passive cross-drift hydrologic test, Alcove 8–Niche 3, and Alcove 7, but relative humidity measurements were made. Estimates of evaporation can be obtained from the relative humidity measurements, coupled with appropriate assumptions about evaporative surfaces and impacts of ventilation.

3. The test plan for the passive cross-drift hydrologic test is provided by Bechtel SAIC Company, LLC (2001a) and is summarized in the DOE response.

4. Preliminary seepage predictions for the passive cross-drift hydrologic test were also provided in the test plan for the passive cross-drift hydrologic test (Bechtel SAIC Company, LLC, 2001a) and are summarized in the DOE response.

5. The results and analysis of data from the passive cross-drift hydrologic test are provided in *In Situ* Field Testing of Processes (Bechtel SAIC Company, LLC, 2003b) and are summarized in the DOE response.

6. The results from Alcove 7 are also documented in *In Situ* Field Testing of Processes (Bechtel SAIC Company, LLC, 2003b) and are summarized in the DOE response.

7. The test plan for the Niche 5 test is provided in the test plan for Niche 5 seepage testing (Bechtel SAIC Company, LLC, 2001b) and is summarized in the DOE response.

8. The results from the Niche 5 seepage tests are documented in *In Situ* Field Testing of Processes (Bechtel SAIC Company, LLC, 2003b) and Seepage Calibration Model and Seepage Testing Data (Bechtel SAIC Company, LLC, 2003c) and are summarized in the DOE response.

9. The results from the Systematic Hydrologic Characterization test are documented in *In Situ* Field Testing of Processes (Bechtel SAIC Company, LLC, 2003b), and Seepage Calibration Model and Seepage Testing Data (Bechtel SAIC Company, LLC, 2003c) and are summarized in the DOE response.

10. The results from the Niche 4 seepage tests are documented in *In Situ* Field Testing of Processes (Bechtel SAIC Company, LLC, 2003b), and Seepage Calibration Model and Seepage Testing Data (Bechtel SAIC Company, LLC, 2003c) and are summarized in the DOE response.

11. The results obtained from the calcite-filling test are documented in Analysis of Geochemical Data for the Unsaturated Zone (Bechtel SAIC Company, LLC, 2002a) and Unsaturated Zone Flow Models and Submodels (Bechtel SAIC Company, LLC, 2003d) and are summarized in the DOE response.

2.2 Agreement TSPAI.3.25

Agreement TSPAI.3.25 was reached at a meeting held August 6–10, 2001, to discuss the Total System Performance Assessment and Integration Key Technical Issue (Reamer, 2001a). The wording is as follows:

> "DOE should use the Passive Cross Drift Hydrologic test, the Alcove 8–Niche 3 tests, the Niche 5 test, and other test data to either provide additional confidence in or a basis for revising the Total System Performance Assessment seepage abstraction and associated parameter values (e.g., flow focusing factor, van Genuchten alpha for fracture continuum, etc.), or provide a technical basis for not using it (UZ2.3.4). DOE will utilize field test data (e.g., the Passive Cross Drift Hydrologic test, the Alcove 8–Niche 3 tests, the Niche 5 test, and other test data) to either provide additional confidence in or a basis for revising the Total System Performance Assessment seepage abstraction and associated parameter values (e.g., flow focusing factor, van

Genuchten alpha for fracture continuum, etc.), or provide technical basis for not using it. This will be documented in Seepage Calibration Model and Seepage Testing Data AMR (MDL–NBS–HS–000004) expected to be available to NRC in fiscal year 2003."

Technical Information Provided for Agreement TSPAI.3.25

The DOE response to Agreement TSPAI.3.25 is provided in Appendix B of the Bechtel SAIC Company, LLC (2003a) technical basis document. This agreement reflects NRC concerns about the relevance of seepage tests conducted in Niche 2 (also referred to as Niche 3650), which, at the time the agreement was reached, were the predominant supporting basis for the drift seepage model for performance assessment. The DOE response explains that results of newer tests are available and that data from the previous Niche 2 tests are no longer used for determining seepage-relevant parameters.

The first part of the DOE response addresses the direct quantitative use of data from subsurface tests in revising analyses and models for the abstraction of drift seepage. Data from the Enhanced Characterization of the Repository Block Systematic Hydrologic Characterization tests and Niche 5 were used by the seepage calibration model for determining seepage-relevant parameters for the lower lithophysal zone of the Topopah Spring Tuff. For these tests, relative humidity and evaporation-rate data were explicitly considered in the process models. Data from Niches 3 and 4 were used to estimate parameters in the middle nonlithophysal zone of the Topopah Spring Tuff. Evaporation effects were determined not to be significant for these tests because ambient relative humidity was near 100 percent. All of the tests cited in the DOE response are documented in Bechtel SAIC Company, LLC (2003b). The analysis of the data from these tests is discussed in Bechtel SAIC Company, LLC (2003c).

The seepage calibration model was used to estimate the capillary strength parameters ($1/\alpha$) for the lower lithophysal and middle nonlithophysal zones by calibrating the drift-scale seepage models against the field liquid-release test data. To quantify a key aspect of the uncertainty, $1/\alpha$ parameter estimates were obtained from multiple realizations of the permeability field for each test bed. The mean value computed from the multiple $1/\alpha$ estimates was considered representative of the respective test bed. The mean $1/\alpha$ estimates were then compiled to provide an indication of spatial variability. This spatial variability is included in the performance assessment abstraction by stochastically sampling different parameter values for each repository drift location (Bechtel SAIC Company, LLC, 2003e). The $1/\alpha$ capillary strength parameter is conceptualized as an effective property that represents average fracture hydraulic properties. DOE maintains that this effective parameter also incorporates processes that cannot be explicitly implemented in the conceptual model (such as film flow and small-scale roughness in the drift ceiling). Therefore, the estimated van Genuchten $1/\alpha$ values are not expected to be representative of only the largest apertures on the drift wall.

The second part of the DOE response deals with the subsurface tests that provide confidence in the seepage models and abstraction. These tests include the Alcove 8–Niche 3 tests and the passive cross-drift hydrologic tests, which were not otherwise used to determine seepage-relevant parameters. For the Alcove 8–Niche 3 tests, the DOE response indicates seepage observed in Niche 3 was consistently less than 10 percent of the infiltration rate applied to the overlying floor of Alcove 8. DOE asserts that this low fraction of seepage is generally consistent with the seepage process models. For the passive cross-drift hydrologic tests, the limited available data of temperature and relative humidity gradients suggest condensation accounts for most of the liquid water observed in droplets and small puddles following long periods (several months or more) of unventilated conditions.

The last part of the DOE response discusses the seepage-relevant parameters, such as the flow-focusing factor, that could not be estimated directly from the available test data. The DOE response explains that flow-focusing factors to be used in the seepage abstraction for the total-system performance assessment for the license application were derived from models that describe the intermediate-scale heterogeneity, bridging the gap between the site-scale and the drift-scale models.

2.3 Agreements TEF.2.08 and GEN.1.01 (Comment 15)

Agreement TEF.2.08 was reached during the NRC and DOE Technical Exchange and Management Meeting on Thermal Effects on Flow held January 8–9, 2001, in Pleasanton, California (Reamer, 2001b). Discussions at the technical exchange and management meeting were initiated based on aspects of data uncertainty (heterogeneity) described in Section 5.3.2 of NRC (2000) and model uncertainty described in Section 5.3.4. The wording is as follows:

> "Provide the Mountain-Scale Coupled Processes AMR, or another appropriate AMR, documenting the results of the outlined items on page 20 of the OI 7 presentation (considering the NRC suggestion to compare model results to the O.M. Phillips analytical solution documented in *Water Resources Research*, 1996). The DOE will provide the updated Mountain-Scale Coupled Processes Model AMR (MDL–NBS–HS–000007) Rev 01 to the NRC in FY 02, documenting the results of the outlined items on page 20 of DOE's Open Item 7 presentation at this meeting. The DOE will consider the NRC suggestion of comparing the numerical model results to the O.M. Phillips analytical solution documented in WRR (1996)."

The O.M. Phillips analytical solution for preferential flow in fractures breaching a dryout zone is published in Phillips (1996). Page 20 of Open Item 7 in the DOE presentation at the technical exchange and management meeting (Reamer, 2001b) refers to the use of a finely discretized grid with spatially heterogeneous properties for fractures in a three-dimensional dual continuum model to evaluate results obtained from the coarsely-gridded, spatially homogenous, two-dimensional dual continuum thermal seepage model used by DOE. Page 20 of Open Item 7 also refers to the evaluation of the effect of high-permeability features such as fracture zones and faults on thermal seepage.

Agreement GEN.1.01 (Comment 15) was reached during the NRC and DOE Technical Exchange and Management Meeting on Range of Thermal Operating Temperatures, held September 18–19, 2001 (Reamer, 2001c). This agreement item provides a followup comment related to Agreement TEF.2.08. The wording is as follows:

> "The analytical approach in this section moves in the direction of resolving part of Agreement TEF.2.08 that states, 'The DOE will consider the NRC suggestion of comparing the numerical model results to the O.M. Phillips analytical solution.' However, this approach should factor into consideration changes in water properties such as increased boiling temperatures of concentrated solutions. Also, taking [the variable] $\underline{u}$ in this approach to be condensate drainage in the reflux zone instead of net

infiltration would give a transient period of increased seepage for a few hundred years after closure."

> "Basis—Increased boiling temperatures of concentrated solutions will increase the distance a liquid rivulet can flow into the above-boiling region. This would have the effect of increasing seepage into drifts during the thermal period of the HTOM as modeled using the approach developed in the section starting on page 4-58."

> "Evidence from the DST indicates some condensate drainage could have high concentrations of dissolved solids."

<u>Technical Information Provided for Agreements TEF.2.08 and GEN.1.01 (Comment 15)</u>

The DOE combined response to Agreements TEF.2.08 and GEN.1.01 (Comment 15) is provided in Appendix A of Bechtel SAIC Company, LLC (2003a) technical basis document. To support their thermal seepage model, DOE provided results from a two-dimensional model using realizations of spatial heterogeneous fracture permeability based on statistical parameters derived from air permeability measurements obtained from several locations in the Exploratory Studies Facility and the Enhanced Characterization of Repository Block drift. For the effect of high-permeability features, a special case of fracture heterogeneity, DOE stated the design criteria would preclude waste package placement near large faults. In addition, DOE rationalized that results from the two-dimensional model would be conservative for seepage magnitude compared to those from a three-dimensional model.

To address model uncertainty, DOE modified the Phillips (1996) solution by incorporating the early time behavior for preferential flow along a fracture breaching the dryout zone. By incorporating the transient effect of the vaporization barrier on the Phillips (1996) analytical solution, the DOE method better represented the early time behavior of preferential flow breaching the dryout zone. They concluded that the vaporization barrier, which is evaporation at the leading front of the liquid finger, reduced the amount of water seeping into drifts during the thermal period compared to that estimated using the Phillips (1996) solution. The DOE model results illustrated the decreased likelihood of seepage throughout the thermal period. During the peak thermal period, seepage is reduced because of the high rock temperatures and the thick dryout zone that has to be traversed by fingers of liquid water. During later times, seepage is reduced because the supply of water for preferential flow has decreased by shedding liquid water between drift pillars during earlier times, resulting in a smaller volume contributing water to the condensate zone. The detailed analyses in Bechtel SAIC Company, LLC (2003f) were not available for this review. Birkholzer (2003), however, provides a description and sample calculations for the alternative conceptualization of preferential flow along heated fractures.

For the effect of chemistry on the boiling temperature of water mentioned in Agreement GEN.1.01 (Comment 15), DOE stated that no evidence of concentrated solutions was found in the drift-scale heater test. For the use of a percolation flux reflecting condensate drainage mentioned in Agreement GEN.1.01 (Comment 15), DOE used a flow focusing factor of 10 to represent increases in percolation flux caused by structural controls for ambient seepage. DOE did not provide a basis for assuming that this value for the focusing factor encompasses flux rates associated with condensate drainage.

3.0 NRC EVALUATION AND COMMENT

The following sections provide a discussion of the relevance of the agreements to repository performance followed by results of the NRC review of the agreement responses organized by the applicable review methods in the Yucca Mountain Review Plan (NRC, 2003). The Yucca Mountain Review Plan describes five generic review methods for reviewing postclosure total-system performance assessment abstractions: (i) Model Integration, (ii) Data and Model Justification, (iii) Data Uncertainty, (iv) Model Uncertainty, and (v) Model Support. The DOE responses to Agreements TSPAI.3.25 and USFIC.4.01 provide information related to Data and Model Justification, Data Uncertainty, and Model Support. The DOE responses to Agreements TEF.2.08 and GEN.1.01 (Comment 15) provide information relevant to Data Uncertainty and Model Uncertainty.

3.1 Relevance to Repository Performance

All of the agreements reviewed in this report are related to the DOE performance assessment abstraction for the amount of water that may seep into potential repository drifts. The quantity and chemistry of water seeping into waste emplacement drifts can affect corrosion of engineered barriers, waste dissolution, and radionuclide transport from the repository to the accessible environment. Accordingly, seepage of water into repository drifts is considered of high significance to waste isolation (NRC, 2004).

3.2 Data and Model Justification

The DOE responses to Agreements USFIC.4.01 and TSPAI.3.25 and supporting documentation cited in the responses indicate that test data and modeling results are available from several *in-situ* tests to justify the modeling approach used for the seepage abstraction (Bechtel SAIC Company, 2003b, Section 6.6.2; 2003c, Sections 6.2 and 6.11). Data from the Enhanced Characterization of the Repository Block Systematic Hydrologic Characterization tests and from Niche 5 were used in the Seepage Calibration Model for determining seepage-relevant parameters for the lower lithophysal zone of the Topopah Spring Tuff. For these tests, relative humidity and evaporation rate data were explicitly considered in the process models used to obtain calibrated parameter estimates. Data from Niches 3 and 4 were used for parameter estimation in the middle nonlithophysal zone of the Topopah Spring Tuff. Evaporation effects were assumed not to be significant for these tests because ambient relative humidity was near 100 percent; this is a reasonable assumption. The results obtained from forward modeling of the Seepage Calibration Model to match *in-situ* test data (Bechtel SAIC Company, LLC, 2003b) provide a reasonable demonstration that the modeling approach used to develop the seepage abstraction is applicable for a range of hydrologic and ambient relative humidity conditions in the unsaturated zone at Yucca Mountain. In addition to providing support for the conceptual basis of the seepage abstraction, the range of capillary strength parameters estimated from the Seepage Calibration Model provides justification for the range of parameter uncertainty considered in the seepage abstraction (Bechtel SAIC Company, LLC, 2003b, Section 6.6.4). These seepage test data collection and modeling activities adequately address those aspects of Agreements USFIC.4.01 and TSPAI.3.25 related to data and model justification.

3.3 Data Uncertainty

One of the NRC concerns underlying Agreements USFIC.4.01 and TSPAI.3.25 was that the range of permeability developed from air-injection tests in Niche 2 may not adequately describe the permeability variability in the lower lithophysal unit. Another concern was that the basis for incorporating data uncertainty for the $1/\alpha$ moisture-retention parameter was unclear. The DOE responses to these agreements indicate that analyses of several more recent tests were used to develop parameter distributions to account for data uncertainty in the revised seepage abstraction.

Potentially important data uncertainties that can affect drift seepage estimates include those used to estimate mean fracture-network permeability, variability and correlation length of fracture permeability, and the capillary strength of fracture networks intersecting drifts. Data uncertainties for mean fracture-network permeability and capillary strength are addressed by considering ranges of values for each of these parameters. The uncertainty range for mean fracture-network permeability of the seepage model includes 17 different values spanning five orders of magnitude. This range is consistent with the variability of *in-situ* test data and also reflects uncertainty related to the effects of drift excavation (Bechtel SAIC Company, LLC, 2003e, Section 6.3.2). Uncertainty in the capillary strength parameter, $1/\alpha$, is included by using a range of values from 100 to 1,000 Pa (1.45×10^{-2} to 1.45×10^{-1} psi), which is also consistent with the mean and standard deviation of this parameter estimated from the Seepage Calibration Model (Bechtel SAIC Company, LLC, 2003c, Table 16). According to DOE, the capillary strength parameter represents average hydraulic properties, connectivity, density, geometry, and orientation of the fracture network and incorporates the effects of film and rivulet flow and small-scale drift ceiling roughness. NRC believes the capillary strength parameter calibrated from injection tests also incorporates the effects of structural controls and evaporation model assumptions and uncertainties, which tend to be specific to each test. For each parameter combination of mean fracture-network permeability and capillary strength, 20 different stochastic realizations of heterogeneity are considered using basecase values of 1.0 for the $\log_{10}$ standard deviation of permeability, and 0.3 m [1.1 ft] for the fracture-network permeability correlation length. The technical bases for the probability distributions used for mean fracture-network permeability and capillary strength in the seepage abstraction (Bechtel SAIC Company, LLC, 2003e, Sections 6.5 and 6.6) are described sufficiently to permit a detailed review of data uncertainty for these parameters. DOE determined the standard deviation of permeability and the correlation structure do not need to be varied in the seepage abstraction because the basecase estimates for these parameters produced seepage rates that were either comparable to or larger than seepage rates calculated from selected sensitivity cases (Bechtel SAIC Company, LLC, 2003e, Sections 6.6.2 and 6.4.2). NRC continues to review the modeling used by DOE to exclude uncertainty in the standard deviation of permeability and permeability correlation structure from the seepage abstraction. This consideration of data uncertainties in the drift seepage abstraction appears to include those parameters most significant to seepage flux and its spatial distribution into repository drifts, and the uncertainty ranges are reasonably based upon *in-situ* testing that appears to have been adequately conducted. Thus, the information provided by DOE adequately addresses those aspects of Agreements USFIC.4.01 and TSPAI.3.25 related to data uncertainty. Considering the limited number of test injection locations and the wide range of processes and conditions lumped into the capillary strength parameter, NRC believes that continued injection testing at locations representing a wider range of geological and hydrological conditions across the repository would provide useful support for the assumed representative range of the capillary strength parameter used in the seepage analyses.

The DOE response to Agreement TEF.2.08 included a summary of the model and results from a two-dimensional thermal seepage model that incorporated fracture heterogeneity; detailed descriptions of the model and results were not reviewed because Bechtel SAIC Company, LLC (2003f) was not available. Results from the two-dimensional, dual-permeability thermal seepage model showed the capillary and vaporization barriers were effective at eliminating seepage. In addition, DOE stated analyses of high-permeability zones are not needed because of a design criteria for standoff from faults (Bechtel SAIC Company, LLC, 2003a). High-permeability zones at Yucca Mountain will include intensely fractured zones and fault zones. DOE rationalized that results from the two-dimensional model would be conservative for seepage magnitude compared to those from a three-dimensional model. By incorporating fracture heterogeneity and addressing dimensionality and high-permeability zones, DOE provided adequate information for concerns expressed in Agreement TEF.2.08 pertaining to the thermal seepage model.

It was noted during this review that the two-dimensional thermal seepage model, when implemented without the heat load from the high-level waste, estimates less seepage than the ambient seepage model. When no heat load is applied in the thermal seepage model, seepage fractions of 0 and 0.16 are estimated by the thermal seepage model for a percolation rate of 60 and 160 mm/yr [2.4 to 6.3 in/yr] (Figure A-5 from Bechtel SAIC Company, LLC, 2003a). Only results for the middle nonlithophysal unit were provided. Based on the ambient seepage model, Bechtel SAIC Company, LLC (2003e) indicated that ambient seepage fractions for the middle nonlithophysal unit were 2 to 3 times larger than those for the lower lithophysal unit. For the permeability field used to calibrate the ambient seepage model, seepage fractions of approximately 0.17 and 0.46 were estimated by the ambient seepage model for the same percolation rates (Figure D-6 from Bechtel SAIC Company, LLC, 2003a); no lithological unit was specified. These marked differences in estimated seepage fractions illustrate the influence of grid refinement and parameterization of the different models. Because the thermal seepage model in ambient mode (i.e., no heat level) produces markedly lower seepage rates than the ambient seepage model, conclusions from the thermal seepage model using seepage as a metric will be evaluated in more detail during the review of a potential license application.

Grid resolution and parameterization may be the factors causing marked differences in results between the ambient seepage and thermal seepage models (when the effect of the vaporization barrier is removed). A basis was not provided for the discretization of the thermal seepage model grid near the drift; the grid cell resolution was 20 cm [7.9 in] in the radial direction near the drift. The seepage model uses 5-cm [2-in] grid cells adjacent to the drift. Modeling by Pruess (1997, 1998) indicated that grid refinement had a pronounced effect on seepage estimates; finer grid resolution near the drift wall led to higher seepage rates. Pruess (1997, 1998) used grids refined to 2 cm [0.8 in] near the drift ceiling. The DOE thermal seepage model incorporated stochastically generated fracture permeability. Other hydrological properties, including the capillary strength parameter (inverse of the van Genuchten α parameter) that is important for seepage, were taken from mountain-scale calibrated property set presented in Bechtel SAIC Company, LLC (2003h). DOE noted, however, that sensitivity analyses using an unspecified range of values for the van Genuchten α parameter had little effect on the general conclusions of the study. Because the parameter values in the ambient seepage model are intimately linked to the ambient seepage grid, it is not apparent what parameter values should be used in the thermal seepage model and its coarser grid.

The significance of the thermal seepage results depends on how thermal seepage is abstracted into DOE performance assessment analyses. Two options were recommended in Bechtel SAIC Company, LLC (2003e):

- Abstraction model 1 sets seepage during the thermal period to that estimated by the ambient seepage model (i.e., the asymptotic bound for thermal seepage is the ambient seepage).

- Abstraction model 2 sets seepage to zero when the driftwall is at or above the boiling temperature, which was conservatively recommended to be 100 °C [212 °F]. The boiling point temperature for pure water not held in capillary tension is 96 to 97 °C [205 to 207 °F] for the potential repository horizon.

At this time, it is not known which recommendation will be followed in the DOE performance assessment analyses for a potential license application. DOE estimates of thermal seepage are based solely on numerical model results using the continuum representation without the support of field or laboratory measured data relevant to thermal seepage. Limitations of the drift-scale heater test (moisture loss out of the bulkhead and difficulties in monitoring water movement along fractures) severely limits its use in validating the thermal seepage continuum model. The cross-drift thermal test, which continues to be postponed, may have addressed the inadequacies of the drift-scale heater test. For abstraction model 1, condensate drainage during the thermal period may lead to episodic events of seepage that could violate the asymptotic assumption. The ambient seepage asymptotic bound for thermal seepage, however, may be satisfied in an average sense. Without support of field or laboratory measured data and the inconsistency of results between the ambient and thermal seepage models, NRC believes that abstraction model 1 is defensible but abstraction model 2 likely will not be.

In summary, for Agreements USFIC.4.01 and TSPAI.3.25, the information provided adequately addresses data uncertainty in the drift seepage abstraction including those parameters most significant to seepage flux and its spatial distribution into repository drifts based on completed *in-situ* testing. For Agreement TEF.2.08, the information provided by DOE for the thermal seepage model and parameters addresses the data uncertainty concerns specified in the agreement. During the review of a potential license application, NRC will monitor whether: (i) if the design allows for placement of waste packages near high-permeability zones, NRC expects the effect of these zones on seepage will be factored into the DOE analyses of performance, or (ii) if abstraction model 2 is selected for use in DOE performance assessment analyses, NRC expects clarification and justification for the inconsistencies between the ambient seepage and thermal seepage model representations of seepage processes. Based on the information provided in Bechtel SAIC Company, LLC (2003a), NRC believes abstraction model 1 (Bechtel SAIC Company, LLC, 2003e) would require no additional questions if DOE selected this abstraction model for use in performance assessment analyses.

3.4 Model Uncertainty

The DOE response for Agreements TEF.2.08 and GEN.1.01 (Comment 15) provides results from an alternative conceptual model to compare with results from the thermal seepage continuum model. DOE reduced the conservativeness of the Phillips (1996) solution for preferential flow breaching a dryout zone by incorporating a more realistic representation of early time behavior. Vaporization during early times of intermittent finger flow along a fracture in superheated rock is expected to reduce or eliminate the magnitude of water reaching the drift wall. Appendix A of Bechtel SAIC Company, LLC (2003a) provides a summary of the detailed analyses contained in Bechtel SAIC Company, LLC (2003f), which was not available for this review. Birkholzer (2003), however, provides the basis and sample calculations for the alternative conceptualization.

The Birkholzer (2003) solution leads to intermediate estimates of seepage compared to the higher estimates using the Phillips (1996) solution and the lower estimates using the DOE thermal seepage model. NRC agrees that incorporating early time vaporization into the analysis of preferential flow in thermally perturbed fractures above the drift ceiling is justified, and the associated thermohydrological processes are adequately represented.

Agreement GEN.1.01 (Comment 15) specifically calls for the assessment of boiling point temperatures for concentrated solutions and the use of percolation rates reflecting condensate drainage associated with the reflux zone. The boiling point temperature and percolation flux rates are model inputs for the Phillips (1996) and Birkholzer (2003) solutions for preferential flow in heated fractures.

Bechtel SAIC Company, LLC (2003a) maintained that concentrated solutions will not form in water percolating toward the drifts. They concluded that water samples collected from the drift-scale heater test did not have high enough concentrations to affect estimates of the boiling point temperature. Total dissolved solids in the range of 25 to 320 mg/L were determined from data presented in Bechtel SAIC Company, LLC (2002b), neglecting low pH samples that appeared to have been derived by condensation in the sampling apparatus. Boiling point temperatures of solutions in this range of ion concentrations would rise only a small fraction of a degree celsius over that of pure water. It is not clear, however, if sampling of water from the drift-scale heater test captured water flowing in fractures. Sample locations appeared to be in zones of condensation, thus, leaving the possibility that water entered the sampling location in the borehole in the vapor phase and condensed as it was collected in the sampling apparatus. In a laboratory experiment described by Green and Prikryl (1999), concentrated solutions seeped into the scaled drift and corroded drip sensors. In addition, if DOE drift-scale and seepage conceptual and numerical models are realistic, samples from boreholes in the drift-scale heater test could only be condensed water. No water from flowing fractures would enter boreholes. For example, the analysis of flow along rock bolts (Bechtel SAIC Company, LLC, 2003g) indicated that water would not flow into boreholes but would divert by capillarity around the small openings. The analysis assumed open boreholes represented ungrouted rock bolts. Because the effect of saline solutions on boiling point temperatures was considered by DOE, however, this aspect of Agreement GEN.1.01 (Comment 15) is complete. If subsequent analyses indicate a significantly different concentration of ions in solution is possible, NRC may require further analysis of the effects of increased boiling point temperature on thermal seepage.

Bechtel SAIC Company, LLC (2003a) noted that a focusing factor of 10 was used in the model of preferential flow along heated fractures to represent an upper bound for condensate drainage. This factor may account for percolation rates enhanced by water collecting in the reflux zone, thus addressing one part of Agreement GEN.1.01 (Comment 15). In the ambient unsaturated zone, the focusing factor was intended to account for structural control of flow paths. It appears to be used by Birkholzer (2003) to reflect intermittent flow associated with the condensate zone. Birkholzer (2003) notes the laboratory experiments of Kneafsey and Pruess (1998) and Su, et al. (1999) showed intermittent pulses of finger flow occurred in their analog fractures, but the episodic events were small compared to the volume carried. Although Birkholzer (2003) relies on information from Su, et al. (1999), sufficient basis was not provided that conditions in the synthetic fracture of the laboratory experiment of Su, et al. (1999) reflect conditions above a thermally-perturbed drift in fractured tuffs. In particular, the periodicity and size of liquid detachment is highly dependent on the input flux and the local aperture distribution. The size of the events used by Birkholzer (2003) makes it unlikely that the large dryout zone will be breached to the drift wall, although episodic preferential flow through small dryout zones later in the thermal pulse will more likely lead to seepage. DOE did not provide support that the focusing factor of 10 accounted for both structural control and enhanced flow because of the condensate zone.

A more general comment is needed on the use of either the Birkholzer (2003) or Phillips (1996) model for preferential flow along heated fractures. Although DOE fulfilled Agreement TEF.2.08 by considering alternative models for flow above and seepage into drifts, NRC was not able to identify measure data or other support in Bechtel SAIC Company, LLC (2003a) for the DOE position that these alternative models (Birkholzer, 2003 or Phillips, 1996) can be used to represent the upper bound of uncertainty in thermal seepage modeling. NRC expects to evaluate DOE’s technical basis for estimating the upper bound of uncertainty in thermal seepage modeling as part of the potential license application review.

In summary, information provided in Bechtel SAIC Company, LLC (2003a) justifies the use of the Birkholzer (2003) model to incorporate the effect of the vaporization barrier on seepage into drifts during the thermal period. Thus, model uncertainty aspects of Agreement TEF.2.08 are considered complete. Agreement GEN.1.01 (Comment 15) issues of boiling point temperature and condensate drainage flux inputs to the Birkholzer (2003) model were addressed by DOE. If new information or considerations become available, these issues will be reassessed as part of the review of a potential license application.

3.5 Model Support

The DOE responses to Agreements USFIC.4.01 and TSPAI.3.25 include discussion of results from the Alcove 8–Niche 3 test, the passive cross-drift hydrologic test, and the Alcove 7 test. These tests were not otherwise used in the determination of seepage-relevant parameters and, hence, can be used to provide support for seepage model predictions. For the Alcove 8–Niche 3 test, seepage observed in Niche 3 has been consistently less than 10 percent of the infiltration rate applied to the overlying floor of Alcove 8. This low fraction of seepage is generally consistent with the seepage process models. It should be noted, however, that it was not possible to obtain a mass balance of the water in the Alcove 8–Niche 3 test. It is, therefore, not possible to assess what fraction of the water applied to the floor of Alcove 8 reached the ceiling of Niche 3 and what fraction may have been diverted away by structural controls.

Based on observations of water in the passive cross drift hydrologic test, water is entering the drift by pathways other than direct dripping from the ceiling and is possibly redistributing along the drift. The DOE response summarizes a predictive analysis of seepage in the cross drift, defining one seep as water entering a 5-m [16.4-ft] section of the drift and using an assumption consistent with those applied in the performance assessment abstraction for the site recommendation. The predictions indicated there is a 50-percent chance that 1 or more seeps would occur within the unventilated section of the cross drift, a 10-percent chance that 4 or more seeps would occur in the 200-m [660-ft] section between stations 20+00 and 22+00, and a 10-percent chance that 2 or more seeps would occur in the 100-m [330-ft] between stations 24+00 and 25+00. This analysis did not consider evaporation and associated condensation, which appears to be occurring in the unventilated section of the cross drift. The limited data available for temperature and relative humidity gradients in the drift suggest that condensation accounts for most of the liquid water that has been observed in droplets and small puddles following several months of unventilated conditions. Signs of moisture in Alcove 7 included drip spots on the drip collection sheets that may indicate one instance of natural seepage.

Observations from the ongoing Alcove 8–Niche 3 test, the passive cross-drift hydrologic test, and the Alcove 7 test generally support the concept that significant fractions of ambient percolation are diverted around drift openings by capillary retention in fracture networks and that flow focusing results in natural seepage at a relatively few locations. It has not been clearly established, however, that moisture conditions in the sealed-off portion of the cross drift have returned to ambient background conditions following the long period of dryout caused by ventilation. Additionally, passive testing suggests that condensation of water vapor is a potentially important process that could lead to water contacting waste packages, yet this process is not included in the drift seepage abstraction. Thus, although DOE is likely to have enough information on this issue for NRC to accept a potential licence application for review, and Agreements USFIC.4.01 and TSPAI.3.25 can be considered complete, it is hoped that subsequent augmenting data will strengthen the model support basis. Staff suggest that long-term passive tests should be continued to establish a long-term record of observations to validate the seepage abstraction under demonstrably ambient moisture conditions.

The DOE response to Agreement USFIC.4.01 also contains a summary of model support obtained from a geochemical modeling study of calcite minerals in the unsaturated zone. Seepage rates were calculated assuming a volume fraction of 0.9 for calcite in mineral coatings and that every coating was deposited over a period of 10 million years and using values from the literature to estimate the ratio of the volume of water to the volume of calcite. The results of this analysis suggest that not all lithophysal cavities encountered seepage and that seepage flux estimated from mineral deposits is a very small fraction of total percolation flux. Staff note that such geochemical models are subject to large uncertainties regarding initial and boundary conditions. Recognizing these model limitations, staff agree these interpretations of calcite mineralization provide support for the conceptualization of the DOE seepage abstraction.

In summary, the information provided satisfies the Agreements USFIC.4.01 and TSPAI.3.25 in terms of providing model support; however, staff suggest that long-term passive hydrologic tests be carried out until steady-state moisture and saturation conditions are identified in excavated test cavities and the unsaturated zone above in order to establish a long-term record of observations to validate the seepage abstraction under demonstrably ambient conditions.

4.0 SUMMARY

NRC reviewed the DOE key technical issue agreement responses within the Technical Basis Document to determine if sufficient information was provided to close the agreement items. On the basis of this review and notwithstanding new information that could raise new questions or comments concerning the above agreements, DOE has provided the information requested in Agreements USFIC.4.01 and TSPAI.3.25. In addition, on the basis of this review and notwithstanding the questions and comments discussed in Section 3.3, DOE has provided sufficient information to address Agreements TEF.2.08 and GEN.1.01 (Comment 15).

5.0 STATUS OF THE AGREEMENTS

Based on the above review, NRC considers the Agreements USFIC.4.01, TSPAI.3.25, TEF.2.08, and GEN.1.01 (Comment 15) are complete.

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