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OCT 12 2007

QA: N/A
Project No. WM-00011

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RESPONSE TO THE U.S. NUCLEAR REGULATORY COMMISSION (NRC) COMMENTS ON ADDITIONAL INFORMATION NEED (AIN) ASSOCIATED WITH KEY TECHNICAL ISSUE (KTI) AGREEMENT STRUCTURAL DEFORMATION AND SEISMICITY (SDS) 3.01 AIN-2

References:
1. Ltr, Davis to Williams, dtd 5/21/07 (Pre-Licensing Evaluation of AIN Associated with KTI Agreements RT 3.05 AIN-1, Comment 8 AIN-1, and SDS 3.01 AIN-2)
2. Ltr, Williams to Director, DHLWRS, dtd 12/22/06 (Response to the AIN Associated with KTI Agreements RT 3.05 AIN-1, Comment 8 AIN-1, and SDS 3.01 AIN-2)

On May 21, 2007 (Reference 1), the NRC provided a pre-licensing evaluation of responses from the U.S. Department of Energy (DOE) to KTI agreements RT 3.05 and SDS 3.01 AIN-2 (Reference 2). The NRC evaluation of Reference 2 provided additional comments regarding SDS 3.01 AIN-2, and kept SDS 3.01 AIN-1 open. This letter addresses the NRC evaluation with the enclosed summary response for SDS 3.01 AIN-2. Information in Reference 2 did not adequately address SDS 3.01 AIN-2. The enclosure to this letter provides a complete response to this AIN.

Based on the information presented in this letter and in the enclosed document, pending NRC review and approval, DOE recommends that KTI agreement SDS 3.01 and its AINs be closed.

There are no new regulatory commitments in this letter or its enclosure.

NMSS07

OCT 12 2007

Please direct any questions concerning this letter and its enclosure to William J. Boyle at (702) 794-5506, or e-mail william_boyle@ymp.gov, or Eric T. Smistad at (702) 794-5073 or e-mail eric_smistad@ymp.gov.

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RAO:WJB-1349

Enclosure:
Response to NRC Comments on KTI Structural Deformation and Seismicity (SDS) 3.01 Additional Information Need (AIN)-2

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ENCLOSURE 1

Response to NRC Comments on KTI Structural Deformation and Seismicity (SDS) 3.01 Additional Information Need (AIN)-2

1. INTRODUCTION

This transmittal provides additional information and clarification to address remaining NRC concerns about SDS 3.01 as expressed in the NRC letter dated May 21, 2007. The letter provides a review of the DOE response, dated December 22, 2006, to SDS 3.01 AIN-2. In the May 21, 2007 review, the NRC states:

> *For SDS 3.01 AIN-2, the staff considers that no significant attempt was made to relate observed infiltration and seepage data in the fault test to observed fracture patterns (i.e. fracture-inform). This stands in contrast to the approach, implemented previously in the Technical Basis Document No. 3: "Water Seeping into Drifts," Appendix H (Bechtel SAIC Company, LLC, 2003a), to fracture-inform the large plot test. Consequently, the information presented by DOE is inadequate to address SDS 3.01 AIN-2, and the NRC staff considers this AIN open.*

Later in the same review, the NRC elaborates:

> *With regard to SDS 3.01 AIN-2, instead of providing a fracture-informed analysis of the Alcove 8-Niche 3 fault tests, DOE provided a description of the fault test set-up, the experimental observations, and a modeling study of the fault test. The model analysis used seepage and water-travel velocity data to obtain calibrated rock properties and the corresponding flow field, which was then used for tracer transport simulations. Fault permeability was 2 to 3 orders of magnitude greater than that of the adjacent fractured rock. Water-travel-velocity data provided information on the porosity of the fault-fracture network. DOE provided no evaluation of the overall effects of the fault on infiltration and seepage in the test volume (e.g., by comparing the model with simulations in which the fault was removed from the system). As a result, the staff has the following remaining technical concerns:*
>
> 1. *The analysis of the fault test in the documents referred to in Williams (2006) involved little or no direct consideration of the available fracture data or lithostratigraphic data for the Alcove 8-Niche 3 field tests, nor did the conceptualization of the model in the documents incorporate features similar to the 3-dimensional depiction of fractures between Alcove 8 and Niche 3 that DOE originally provided in response to SDS 3.01 to indicate that the Alcove 8-Niche 3 tests would be fracture-informed (Brocoum 2001).*

2. *The interpretation of the fault test results did not sufficiently consider structural features such as the intersection of the subvertical fault with subhorizontal fractures throughout the tuff, and the potential role that these subhorizontal fractures had in diverting water from the fault and bypassing Niche 3.*

3. *Further, the interpretation of the fault test results did not directly evaluate connection of the fault to subhorizontal fractures, connection of subhorizontal fractures to vertical fractures, connection of lithophysae to both sets of fractures and, consequently, the potential role that these fracture-connected lithophysae had in trapping infiltrated water.*

4. *Instead of considering unrepresented features and processes such as those mentioned above, DOE increased the modeled effective fracture-matrix interface area in the model to account for those unrepresented features and processes. This approach increased the effectiveness of matrix diffusion, which allowed the model to reproduce the observed fault test results. Application of this approach in predictive modeling at other locations is uncertain..*

Technical staff from the DOE and the NRC discussed these remaining NRC concerns in the May 21, 2007 letter at the Appendix 7 meeting held in Las Vegas on August 22-23, 2007.

This enclosure addresses these remaining concerns of the NRC staff about SDS 3.01. First, a summary discussion is given on the use of the Alcove 8/Niche 3 test data in confirming the conceptual model of matrix diffusion and also in helping to validate the site-scale unsaturated zone (UZ) transport models that support the total system performance assessment (TSPA), using a performance-based and risk-informed approach (Section 2). Details about the relevant testing and modeling results are presented to support these responses (Section 3). This detailed discussion includes the following:

- Results and interpretations from the Alcove 8/Niche 3 fault and large-plot tests and observations from the South Ramp seepage event relative to geologic features and fracture characteristics;

- The relationship between geological features and hydrologic behavior in the UZ flow model and in the Alcove 8/Niche 3 test models;

- The relative merits of discrete fracture and continuum hydrologic models; and

- The use of fracture information in the UZ flow model and the Alcove 8/ Niche 3 test models.

Then, a response to each of the four specific concerns is provided with summary information (Section 4). Finally, conclusions from these technical discussions are given relative to the observations noted by the NRC staff concerning the use of fracture information for the analysis of the Alcove 8/Niche 3 fault test (Section 5).

2. ANALYSIS OF THE ALCOVE 8/NICHE 3 TEST DATA USING A PERFORMANCE-BASED AND RISK-INFORMED APPROACH

The analyses of data from the Alcove 8/Niche 3 fault test and the development of the test bed model are performance-based and risk-informed, in keeping with the requirements of the regulation (10 CFR 63). As described in the plan for the Alcove 8/Niche 3 tests (Ziegler 2002), data from the fault and large-plot tests have not been used to develop parameter values for any process or abstraction models that support the TSPA. Instead, information from the tests was only used to confirm the conceptual model for matrix diffusion, and to support the validation of the site-scale UZ transport models for TSPA. The fault and large-plot tests were conducted in series and phases. Data from the infiltration, seepage, and tracer transport tests were used to develop estimates of hydrologic and transport parameters from analyses using the test bed model. The initial parameter estimates came from the site-scale UZ flow and transport models. These parameters were then used to make pretest predictions for the subsequent phase of the test.

Upon excavation of Alcove 8 and Niche 3, it was discovered that a minor fault connected these two excavations. The test plan was changed to first perform seepage and tracer transport tests in the fault before continuing with the original test planned for the fractured rock mass. Although tracer transport tests were conducted in the fault, these tests were never intended to be used for assigning fault properties in the site-scale UZ flow and radionuclide transport models. The fault present at Alcove 8 and Niche 3 was considered to be too small of a feature to be representative of the major faults that are explicitly included in the site-scale UZ flow and radionuclide transport models. These models include major faults such as the Solitario Canyon Fault, Bow Ridge Fault, Ghost Dance Fault, Drill Hole Wash Fault, Pagany Wash Fault, Sever Wash Fault, and Imbricate Fault. Fault characterization is described in the analysis report *Calibrated Unsaturated Zone Properties* (SNL 2007a, Section 6.3.4). Fault properties for these major faults were defined through inverse modeling of site-scale pneumatic observations and hydrologic conditions in borehole USW UZ-7a, which intercepts the Ghost Dance Fault. All major faults were assigned the same properties because models of flow and transport phenomena in the UZ are relatively insensitive to fault properties (BSC 2005a, Appendix D). This is true because faults and surrounding fractured tuff are modeled as major pathways for radionuclide transport from the repository to the water table. The specific fault properties are not important as long as the faults are assumed to provide continuous, permeable pathways through the UZ, which is how faults are represented in the site-scale UZ flow and radionuclide transport models. Fault permeability can be varied over a wide (greater than an order of magnitude) range without substantially affecting UZ flow and radionuclide transport model predictions.

Transport results from the Alcove 8/Niche 3 fault test have been used for model validation of the UZ radionuclide transport process model, matrix diffusion submodel (SNL 2007b, Section 7.3). The seepage data from both the fault test and the large-plot test were used to calibrate the test bed flow model to obtain estimates of hydrologic properties such as van Genuchten parameters for fractures and the matrix. These calibrated flow properties were in turn used in the test bed transport model to estimate breakthrough of tracers, which were then compared to observed tracer concentrations.

The Alcove 8/Niche 3 fault test provided tracer transport results in the form of breakthrough curves at Niche 3 for both bromide and a fluorinated benzoic acid. Model results for the tracer transport test were found to match the observed tracer concentrations at Niche 3 when the matrix diffusion coefficients for both tracers were increased by a factor of 45. For the Alcove 8/Niche 3 large plot tracer transport test, no detectable tracer concentrations at Niche 3 were observed for the six tracers used (iodide, bromide, fluoride, and three distinct fluorinated benzoic acids) prior to scrubbing of the infiltration surface. Model results for the large plot test found that the tracer concentrations are predicted to be either near or below detection limits for iodide and the benzoic acid tracers, or lie within the uncertainty in background concentrations for bromide and fluoride, if the matrix diffusion coefficients were increased by a factor of 45. Therefore, using enhanced matrix diffusion, the large plot test model results were consistent with the absence of detectable tracers in Niche 3 seepage water.

The model used for unsaturated zone radionuclide transport in TSPA does not use an enhancement factor for matrix diffusion. Furthermore, the Alcove 8/Niche 3 test models used refined gridding that results in greater fracture-matrix diffusive exchange for these test models as compared with the coarser grid used for mountain-scale unsaturated zone radionuclide transport calculations in TSPA. Both of these differences suggest that the current treatment of matrix diffusion for radionuclide transport in TSPA leads to predictions of more rapid transport and higher tracer concentrations than expected based on field observations. This use of the test data to confirm the choice of a conservative matrix diffusion model is appropriate considering the uncertainties in the application of these test results to repository performance, which spans much larger space and time scales than the field tests, and the uncertainties in the interpretations of the test data (see detailed discussion in Sections 3 and 4).

Results from the Alcove 8/Niche 3 tests (i.e., estimates of enhancement to effective matrix diffusion coefficient) are also planned for use in a sensitivity analysis of the TSPA model. Here, a range of fracture-matrix interface area enhancement factors, up to the level as identified in the Alcove 8/Niche 3 fault test, will be incorporated into the sensitivity analysis using the UZ radionuclide transport abstraction model.

Although the primary purpose of the test was to observe transport phenomena and ultimately confirm the choice of a matrix diffusion conceptual model and to help validate the UZ transport model, the Alcove 8/Niche 3 test involved drift seepage in addition to tracer transport processes. Seepage modeling was performed using the zero capillary pressure condition at the ceiling of Niche 3, which is representative in any unpressurized underground opening. However, the Alcove 8/Niche 3 test results were not used for calibrating seepage models used in TSPA. The reason is that several underground tests were performed for drift seepage with much better control over the water arrival at the top of the opening. This was accomplished by injecting water close to the tops of the openings being tested. These tests provided the needed data for calibration and quantitative validation of the drift seepage models without having the additional uncertainty regarding the flow field arriving at the ceiling of Niche 3. The seepage diversion at Niche 3 can be viewed as a qualitative validation for the seepage abstraction model in that the test results indicate diversion of seepage by Niche 3.

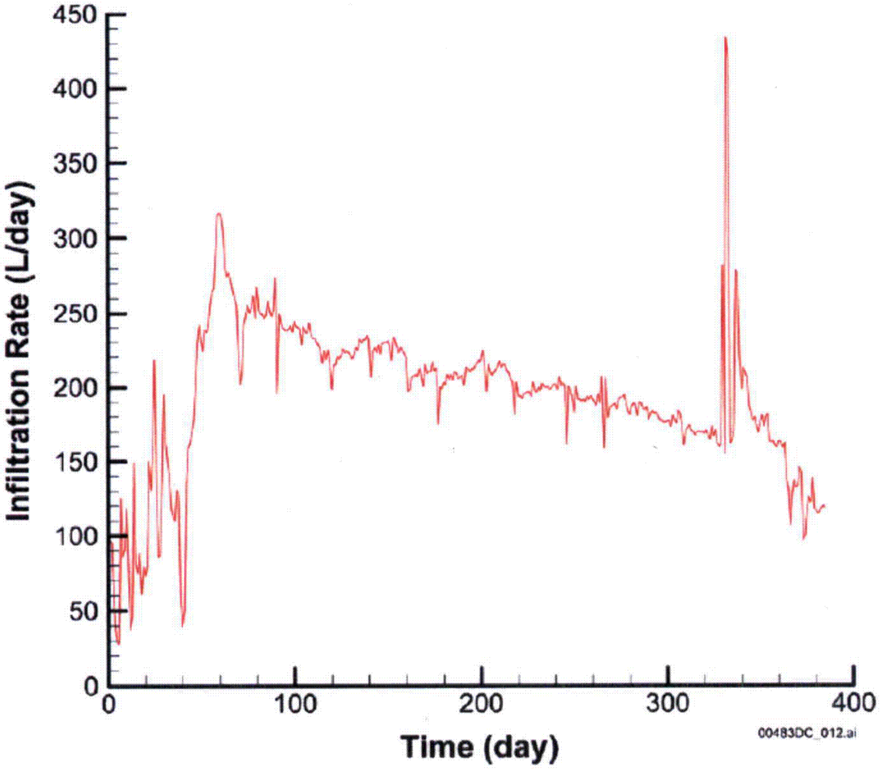
3. DETAILED DISCUSSION OF SUPPORTING INFORMATION

3.1 Interpretations of the Alcove 8/Niche 3 Tests and South Ramp Seepage Observations

The following examination of infiltration and seepage observations from the Alcove 8/Niche 3 fault and large-plot tests and seepage observations from the South Ramp of the Exploratory Studies Facility (ESF) indicates that flow in the UZ is controlled by faults and other pronounced lithostratigraphic features, and that the occurrence of seepage is not necessarily tied to the individual fractures.

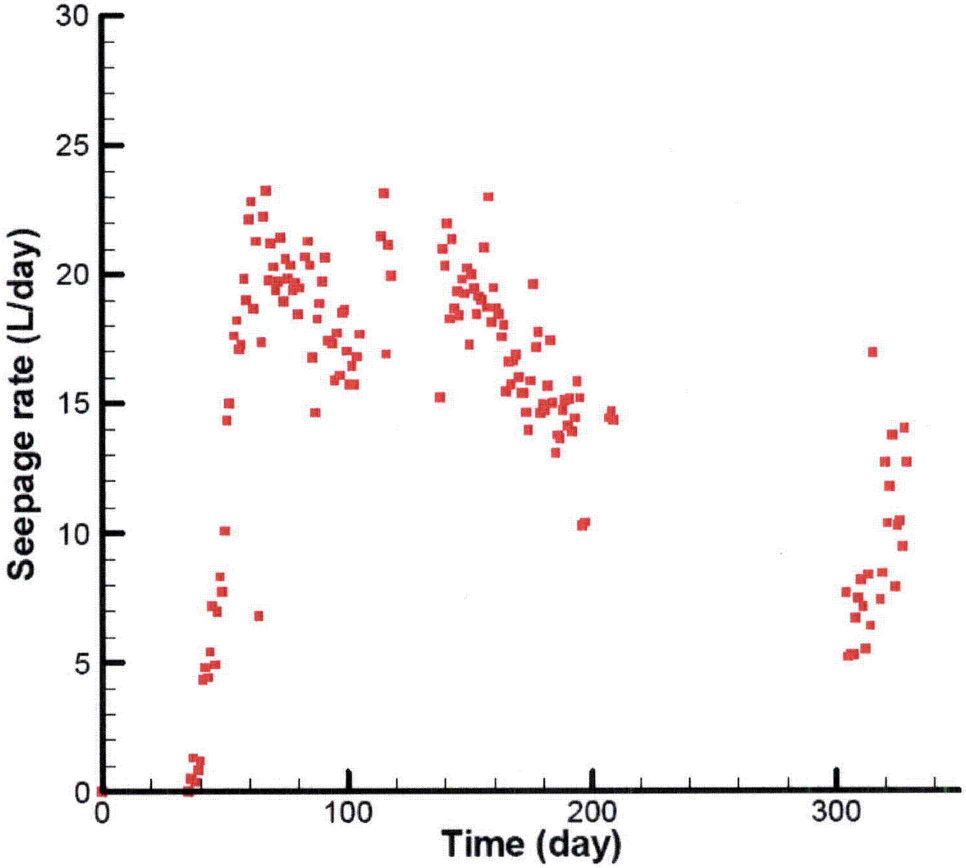
Alcove 8/Niche 3 Fault Test

Flow behavior in the Alcove 8/Niche 3 fault test was clearly dominated by the fault. Dripping into Niche 3 occurred at 10 locations close to the fault trace. No seepage was observed far away from the fault in Niche 3, although the ceiling was noticeably damp. Furthermore, the profiles for infiltration into the floor of Alcove 8 and seepage into Niche 3 appear to both show a rapid rise in rates followed by a slow decline (Figures 1 and 2). The variations in infiltration are believed to be a result of infill materials within the fault just below the infiltration plot that caused the fault and fracture properties at this location to be time dependent. However, given the parallel behavior for infiltration and seepage observed in the test, the flow appears to follow quasi-steady behavior within the test bed such that tracer transport could be reasonably interpreted by a steady-state flow model. There is no reason to suspect that other unrepresented features and processes were responsible for the delayed tracer arrival times and reduced concentrations as compared with the uncalibrated transport model predictions. The tracer concentration profiles were reasonably matched by the transport model with an increase in the fracture-matrix interface area (Figure 3). This is also referred to as enhanced matrix diffusion because the area enhancement primarily results in a higher rate of diffusive mass transfer of solutes between fractures and rock matrix. Given these test results, the fit of the data to the model with enhanced matrix diffusion, and similar observations of enhanced matrix diffusion by other investigators at other locations, the interpretation that matrix diffusion was enhanced for tracer transport in the Alcove 8/Niche 3 fault test is reasonable.



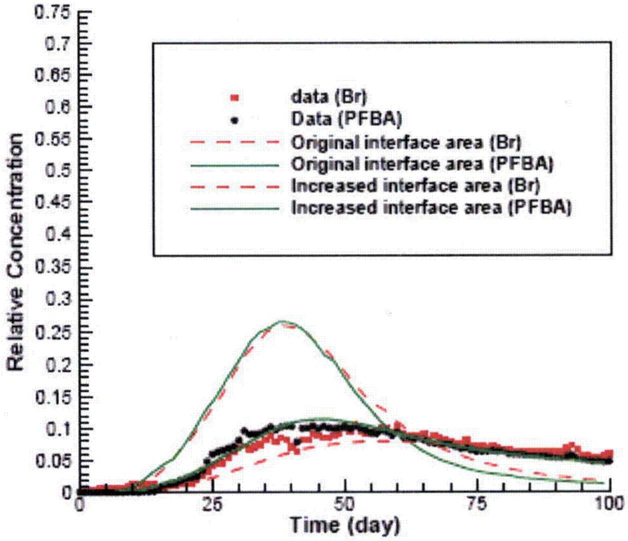
Source: BSC 2004a, Figure 7.6-1

Figure 1. Infiltration Rate as a Function of Time in the Fault Test.



Source: BSC 2004a, Figure 7.6-2

Figure 2. Total Seepage Rate as a Function of Time in the Fault Test.



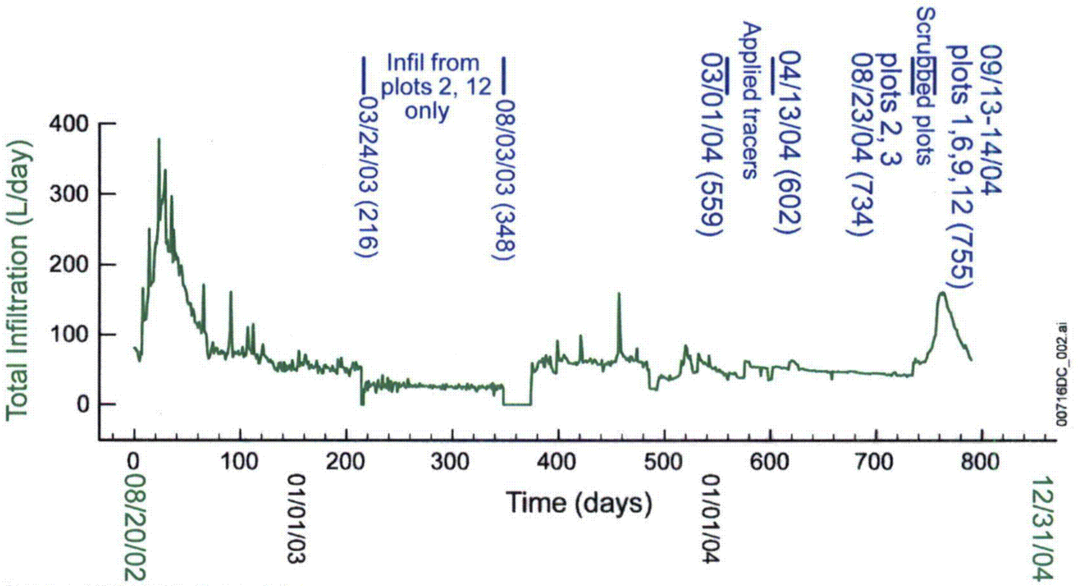
Source: SNL 2007b, Figure 7-22

Figure 3. Comparison between Simulated Breakthrough Curves at Niche 3 for Two Different Fault-Matrix Interface Areas and the Observed Data for the Fault Test.

Alcove 8/Niche 3 Large-Plot Test

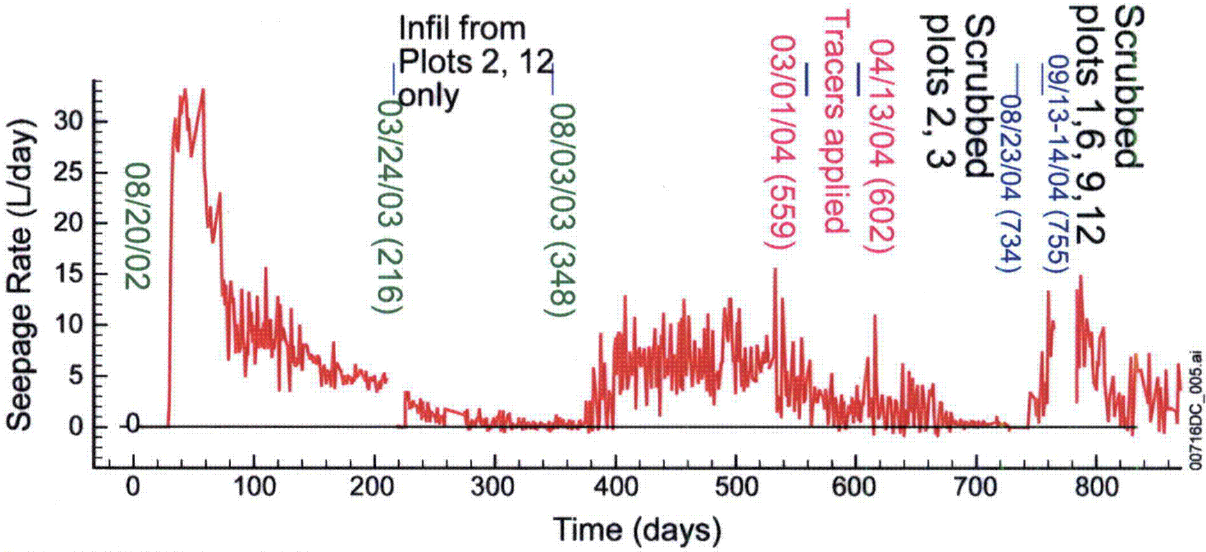
The results of the Alcove 8/Niche 3 large-plot test were more difficult to interpret. In this test, the infiltration rate during the tracer transport tests remained relatively constant while the seepage rates into Niche 3 declined (Figures 4 and 5). Several explanations exist. It is possible that the flow paths that were originally from Alcove 8 to Niche 3 had changed over time to some alternate flow paths away from Niche 3. This could occur as the hydrologic conditions of the test bed changed with time upon the introduction of water into the system. Another explanation is that there were some in-filled materials or dust particles (due to construction of Alcove 8) in fractures. Initially, these particles below the Alcove 8 floor were close to infiltration plots, which is why there was a significant temporal variability in infiltration rate at the early stage of the tests (Figure 4). These moving particles were then pushed downstream by infiltrating water and far away from the infiltration plots. This can explain why the observed infiltration rates were stabilized between 400 to 700 days. When these moving particles were close to Niche 3, they might have had important effects on flow structures near the ceiling of the niches and considerably reduced the seepage rates. These arguments are consistent with a recent laboratory and field study of particle transport in unsaturated fractured rock by Weisbrod et al. (2002). They concluded that particle deposition controls the flow channel's structure and therefore varies the flow rates through the fracture, and large particles may accumulate near the water table due to the air-water-interface trapping mechanism. Note that the similar trapping mechanism exists above the ceiling of Niche 3, as a result of high fracture water saturation above the ceiling due to capillary-barrier effects.

No significant tracer transport arrivals were observed at Niche 3 during the large-plot test. As discussed in *Analysis of Alcove 8/Niche 3 Flow and Transport Tests* (BSC 2006, Section 6.3.2), the absence of detectable tracer concentrations is consistent with the tracer transport predictions if matrix diffusion is enhanced by the same factor used to match the fault test transport results. However, the more complex flow behavior in the large-plot test, as discussed above, leads to greater uncertainty concerning the interpretation of the test results.



Source: BSC 2006, Figure 6.1-4

Figure 4. Total Infiltration Rate as a Function of Time for the Large-Plot Test.

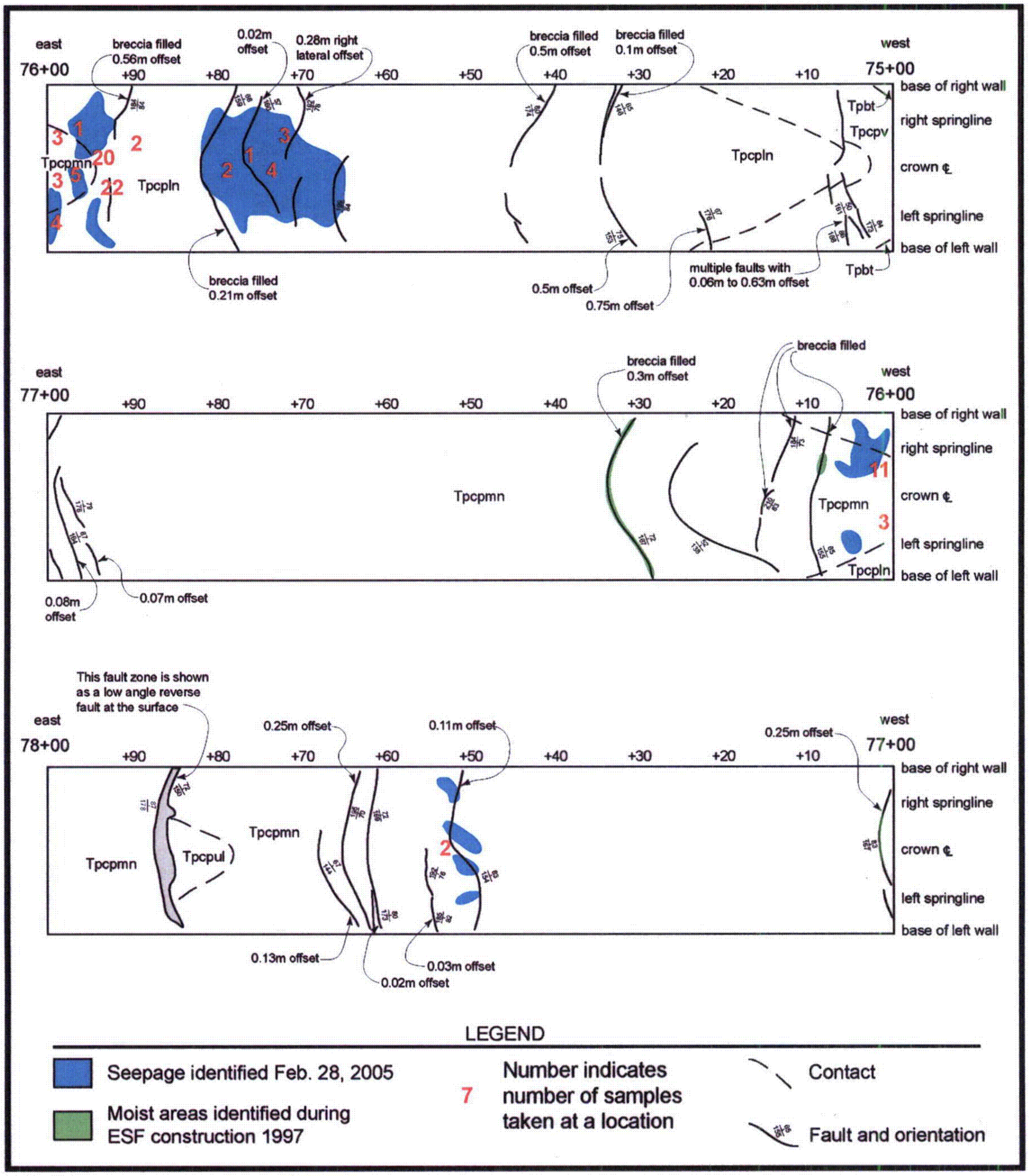


Source: BSC 2006, Figure 6.1-7

Figure 5. Total Seepage Rate as a Function of Time for the Large-Plot Test.

Seepage Observed in the South Ramp of the ESF

Between October 2004 and February 2005, unusually heavy precipitation—12.75 inches, which is about 3.5 times the recent nine-year average of 3.64 inches, taken over the same time period between October and February (BSC 2005b, Section 2.3)—occurred in the Yucca Mountain area. On February 28, 2005, Yucca Mountain Project personnel working in the South Ramp of the ESF observed—in select areas—wet spots on the main drift's crown, ribs, and invert. This field observation is considered the first unambiguous evidence of seepage under ambient conditions. As shown in Figure 6, wet areas were identified between Stations 75+62 and 75+82, Stations 75+92 and 76+07, and Stations 77+48 to 77+53. Water seeps were identified and located by station (Figure 6). A seep at station 77+52 enters the drift at the crown and flows down the left rib following a fault. This seep is near the top of the Topopah Spring Tuff, crystal poor, middle non-lithophysal zone (Tptpmn) lithostratigraphic unit. A series of seeps between stations 76+04 and 75+60 enters the drift from the crown to both springlines. This location covers the contact of the Tptpmn and Topopah Spring Tuff, crystal poor, lower non-lithophysal zone (Tptpln). There are six faults mapped between 76+30 and 75+70. A seventh fault is located at 75+90 and an eighth fault at 75+70. These observations suggest that seepage is linked to lithostratigraphic offsets and fault features, and not to individual fractures.



Source: BSC 2005b, Figure 1

Figure 6. Full Periphery View of the ESF South Ramp from Stations 75+00 to 78+00 Showing Seeps Identified since February 28, 2005. (Normal offset is noted for most faults, however, the fault zone at 77+85 has been interpreted as a low-angle reverse fault at the surface.)

3.2 Relationship between Geology and UZ Flow and Seepage Modeling

In the development and validation of the site-scale UZ flow and drift seepage models, efforts have been made to make use of all available site-specific geologic information, including characteristics and properties faults and fractures. Additional attention was paid to match field observations with a similar set of flow and transport models developed for the Alcove 8/Niche 3 test bed, the result of which was used, in turn, to provide confidence in the UZ transport model.

UZ Flow Model

Field observations of water potentials and perched water indicate that stratigraphic contacts likely control lateral flow in the UZ (BSC 2004b, Sections 7.4.1.2 and 7.4.2), particularly within the Paintbrush nonwelded tuff (PTn) hydrogeologic unit and near the contact of the Topopah Spring welded (TSw) and Calico Hills nonwelded (CHn) hydrogeologic units contact. The hydrologic characteristics of the contacts that lead to such behavior are primarily the fracture permeability and capillary strength variations between layers. Smaller-scale variations in fracture characteristics within the layers have only a secondary effect on hydrologic processes at the mountain scale (Zhou et al. 2003). For the site-scale flow model the stratigraphic layering, stratigraphic dip, zeolitic alteration of the CHn unit, and faults are the primary geologic features affecting flow. The stratigraphic layering and dip are important because changes in hydrologic properties correlate with the stratigraphic layers. Similarly, major changes in hydrologic properties are found for the zeolitized and vitric CHn unit. Major faults potentially provide continuous, permeable pathways to the water table. This is particularly important through the CHn zeolitic zones where the fractured rock mass permeability is reduced by the alteration, leading to perched water formation and large-scale lateral flow into faults. This is why the model explicitly represents hydrogeologic units and major faults with distinct properties.

Seepage Abstraction Model

The seepage abstraction model is based on a continuum approach for describing the interaction of fracture flow with drift openings in the repository host rock. The justification for the continuum approach to seepage modeling is presented in *Seepage Calibration Model and Seepage Testing Data* (BSC 2004c, Section 6.4.1), where a direct comparison is made between results for a discrete fracture network model and a continuum model. The conclusion from this comparison is that a continuum model is suitable for quantifying seepage behavior into drifts in fractured rock. Unlike the larger-scale UZ flow model, the seepage abstraction model does explicitly treat the effects of fine-scale and intermediate-scale heterogeneity in the fracture permeability through measurement of properties that affect flow. The small-scale fracture permeability variations for the 0.1-m grid size in the vicinity of the drift were described using spatially correlated stochastic permeability fields. The reason for the difference in treatment of heterogeneity for the seepage abstraction model as compared with the UZ flow model is that seepage occurs at a much smaller scale than considered in the UZ flow model and that heterogeneity in the vicinity of the drift has a pronounced effect on seepage behavior, whereas at the site scale, seepage is not a process of interest and small-scale heterogeneities have a negligible effect on flow. Therefore, the effects of small-scale fracture permeability heterogeneity are accounted for in the seepage abstraction model.

In addition to fine-scale heterogeneity in the vicinity of the drift, the seepage abstraction model also considers the effects of intermediate-scale fracture permeability heterogeneity within the hydrogeologic units and the potential for flow focusing between the base of the PTn and the repository horizon as a result of this heterogeneity (BSC 2004d, Section 6.6.5). Flow focusing in the fractures is quantified through a two-dimensional, heterogeneous, unsaturated flow model of flow patterns in a fracture continuum between the base of the PTn and the repository horizon. This flow focusing model, with grid resolution on the order of 1 m, spans the gap in spatial resolution between the UZ flow model, with grids on the order of 100 m in horizontal dimension to the seepage abstraction model domain, which is concerned with flow around a 5-m-diameter drift. The effects of heterogeneity in fracturing at the intermediate scale are represented using a spatially correlated, stochastic, fracture permeability field. The degree of flow focusing is sampled in TSPA for the seepage abstraction model to reflect convergence and divergence of the flow field in response to this scale of heterogeneity. Therefore, the effects of intermediate-scale fracture permeability heterogeneity are accounted for in the seepage abstraction model.

Alcove 8/Niche 3 Fault Test and Large-Plot Test Models

The flow patterns in the Alcove 8/Niche 3 fault test are sensitive to different factors. The one stratigraphic contact within the test bed, the tsw33-tsw34 contact, does not present a significant change in fracture properties and does not necessarily control lateral movement within the test bed. Because of the small size of the test bed, heterogeneity and/or anisotropy in fracture properties may play a significant role in lateral flow within the test bed. These properties, however, are difficult to distinguish.

As discussed previously, the flow from Alcove 8 to Niche 3 for the fault test was primarily confined to the fault. This is based on the observations of seepage into Niche 3. Based on these observations, the heterogeneity in the model of the fault test only considered the enhanced permeability of the fault and used a homogeneous permeability to represent the surrounding fractured rock mass for each geological unit. Note that the permeability fields within the fault and the fractured rock in the model were isotropic, therefore, lateral connections between the fault and fractures in the rock mass were present in the model, allowing for lateral flow. The recovery factor for seepage into Niche 3 was about 10 percent of the introduced water (Liu et al. 2004, p. 43). The other 90 percent of the water either flowed from the fault into the surrounding fractured rock, was diverted away from Niche 3 within the fault plane, or was diverted from seeping into Niche 3 as a result of the opening's capillary barrier effect.

The presence of lithophysal cavities were acknowledged in the modeling analysis. For example, from *Radionuclide Transport Models under Ambient Conditions* (SNL 2007b, p. 7-40):

"The overestimation of the water travel velocities may result from the following: (1) some cavities in tsw33 are connected to fractures and could contribute to increasing the storage in the fracture continuum; (2) in reality, the fault is a zone rather than a single fracture."

Also note that a large (calibrated) fracture porosity (0.066) for the unsaturated zone flow model layer, tsw33, was used in the Alcove 8/Niche 3 test models to consider the effects of lithophysal cavities (SNL 2007b, Table 7.6.3; BSC 2006, Table 6.2-1). Therefore, the effects of lithophysae on flow and transport behavior are accounted for in the Alcove 8/Niche 3 test model.

Under natural conditions, flow rates are generally much lower than in the Alcove 8/Niche 3 tests. The high rates of flow in the tests mean that flow encroachment into lithophysal cavities during the Alcove 8/Niche 3 tests is more likely than under natural conditions. Lithophysae are characterized by a low-capillary pressure environment relative to fractures. This difference in capillary properties results in a capillary barrier to flow entering lithophysae from fractures just as for any other underground opening. In the lower-flow-rate environment of the UZ at Yucca Mountain, flow would have a greater tendency to divert around lithophysal cavities as compared with the higher-flow-rate environment in the Alcove 8/Niche 3 test bed. Nevertheless, there are observations of mineral deposits in some lithophysal cavities, indicating that flow was able to enter these cavities. These observations also show that the mineral deposits in lithophysal cavities are almost exclusively found on the base of the cavities, indicating that water never filled the cavities (Wilson and Cline 2001, p. 21).

For the large-plot test, correlations between fracture intensity on the floor of Alcove 8 showed only weak correlation with infiltration rate and fracture permeability in the upper part of the test bed (Zhou et al. 2006, Sections 4.2.2 and 4.2.3). Seepage rates were found to be uncorrelated with fracture intensity in Niche 3 (Zhou et al. 2006, Section 4.2.4). These results suggest that characterizing hydrologic fracture properties based on fracture mapping information is not feasible, which is consistent with previous studies (National Research Council 1996, p. 350).

3.3 Continuum and Discrete Fracture Hydrologic Models

A variety of numerical approaches have been proposed in the literature to deal with flow and transport processes in fractured media at the field scale. When classified according to the manner in which fracture networks are treated in the model structure, the approaches can be divided into continuum approaches, discrete fracture-network approaches, and their variations. Excellent reviews of these approaches, which have been developed and used in different fields (including oil-reservoir engineering, groundwater hydrology, geothermal engineering, and soil physics), can be found in Bear et al. (1993, pp. 267-320 and 396-428) and National Research Council (1996, pp. 307-394).

In continuum approaches, fractures are considered to be sufficiently ubiquitous and distributed in such a manner that they can be described statistically in a meaningful way (Bear et al. 1993, pp. 395-396). The role of individual fractures in fractured media is considered to be similar to that of individual pores in porous media in that individual pores and fractures are not modeled explicitly, but the effects of the pores and fractures are reflected in their continuum properties. Therefore, connected fractures and rock matrix (with pores) can be viewed as two or more overlapping, interacting continua. As indicated in National Research Council (1996, p. 331), the continuum approaches are preferred for most applications that are encountered in practice. This is mainly because of the following advantages of the continuum model over a discrete fracture model:

- Requires fewer parameters
- Known methods to relate field measurements to continuum parameters
- Computationally feasible for large domains

Of course, there is uncertainty in the parameterization for any practical application, but that fact applies to both continuum and discrete fracture methods. The main disadvantage of the continuum approach is the averaging implied by the method such that flow behavior at a specific point is not accurately represented; only the spatially averaged flow behavior can be represented.

A discrete fracture model is based on an assumption that flow and transport behavior can be predicted from knowledge of fracture geometry and data on hydraulic properties of individual fractures (National Research Council 1996, p.332). This approach involves computational generation of a synthetic fracture network (often based on limited field observations) and subsequently modeling of flow and transport in each individual fracture. While discrete fracture-network approaches are useful as tools for concept evaluation or model-based studies, they have several limitations for dealing with real-world unsaturated flow and transport problems. First, the approach requires a description of the fracture network, which requires a description of the fracture-geometric details (frequency, length, aperture, and orientation) over the three-dimensional domain. It should be pointed out that the representative fracture aperture for any given fracture is difficult to estimate from any geometric measurement for the purposes of hydrologic modeling. Accurate characterization of the hydraulic aperture of a fracture requires a direct measurement of permeability for the fracture. Such measurements of individual fractures are not standard. In short, there are no standard methods to characterize the hydrologic parameters of such a network, even if the other fracture-geometric information were available. Realistically, only an approximation of the discrete fracture network could be developed, which tends to negate the main advantage of the discrete fracture model, i.e., to accurately describe the flow field at small scales and specific locations. Only a volume average could be expected to be representative of the flow behavior, even for a discrete fracture model. Second, it is difficult, if not impossible, to separate the conductive fracture geometry from the nonconductive fracture geometry (National Research Council 1996, p. 350). This point of view is strongly supported by Zhou et al. (2006), which shows that no meaningful correlation was observed between local seepage rate from the ceiling of Niche 3 and the local fracture densities. Third, so far, the studies based on discrete fracture-network approaches have rarely considered unsaturated flow and matrix because of computational complexity (Pruess et al. 1999, p. 308).

Specification of particular fracture characteristics is only necessary where such features are distinct from the average hydrologic characteristics of the surrounding rock mass and span a significant fraction of the flow path. Examples of such features are the major faults in the site-scale UZ flow model and the minor fault in the Alcove 8/Niche 3 test bed model. Such specification is possible in continuum codes and is used in the site-scale UZ model.

Based on the above reasoning and considerations of the overall flow and transport behavior in the Yucca Mountain UZ and the scale of the problem, the continuum approach has been used for modeling flow and transport in the UZ of Yucca Mountain (BSC 2004e, Section 6.3.2). For the Alcove 8/Niche 3 fault test model, a combination of the discrete-fracture approach and the continuum approach was employed for capturing the field-scale flow and transport behavior. Specifically, the fault was explicitly modeled in a continuum code as a specific heterogeneous feature of the test bed surrounded by the general fractured rock. It is important to note that this treatment allows for connections between the fault and surrounding fractures that were conceptualized as a fracture continuum.

Based on similar considerations, the drift seepage models also use the continuum approach. See the DOE response to Unsaturated and Saturated Flow under Isothermal Conditions (USFIC) 4.06 (Ziegler 2003, Appendix D) for details of that use.

3.4 Use of Fracture Information to Parameterize Hydrologic Models

The main fracture-related information used to parameterize, and therefore fully inform, the hydrologic properties of the fracture continuum for the UZ flow model includes the following:

- Air permeability measurements for fracture permeability, capillary strength, and pore-size distribution parameter
- Gas-phase tracer concentrations for fracture porosity
- Matrix water saturations and water potentials for indirect calibration of fracture capillary strength and active fracture parameter

- Fracture frequency for fracture-matrix spacing, fracture area per unit volume, porosity, capillary strength, and pore-size distribution parameter

- Fracture trace length for fracture area per unit volume

The easily observable fracture properties such as orientation and mineralization can affect the continuum fracture flow properties, but these geologic characteristics are built into the fracture hydrologic properties through the characterization described above. Fracture orientation may lead to anisotropic permeability in the fracture continuum, however, any measures of anisotropy in fracture permeability have been ambiguous, in part because the effect is not strong (BSC 2004b, Section 7.2.2.5). Therefore, fracture permeability within each hydrogeolgic unit is represented as isotropic. The layering of hydrogeologic units along with variations in fracture permeability between the layers, however, results in large-scale anisotropy of the global-average fracture permeability.

For the seepage abstraction model, air permeability information was used to not only characterize average fracture permeability, but also the heterogeneity in fracture permeability in terms of a frequency distribution and correlation length.

For the Alcove 8/Niche 3 test model, the infiltration, water arrival times, and seepage information from the Alcove 8/Niche 3 test were used to calibrate, and therefore fully fracture inform, the fracture and fault permeabilities, fracture porosity, fault aperture, and fracture and fault capillary strength values. Air permeability measurements for fracture networks are available for limited regions near Niche 3 in the test site (BSC 2004f, Table 6-2). These data were not directly used in the model development, but are fairly close to the calibrated property results. The fracture information was developed independently for the two hydrogeologic units present in the test bed, the unsaturated zone flow model layers tsw33 and tsw34. The fracture frequency for the dual-continuum grid was determined from the fracture map at the Alcove 8 floor for the tsw33 and from the fracture map at the ceiling of Niche 3 for the tsw34. Therefore, the principal fracture flow properties were calibrated to information that is site specific because of the fractures at that site.

Other fracture information, such as the three-dimensional depiction of fractures between Alcove 8 and Niche 3, was not used because such information is not useful for parameterizing a continuum fracture model. In particular, for the Alcove 8/Niche 3 fault test, the dominance of the fault in terms of infiltration in Alcove 8 and seepage into Niche 3 suggests that detailed characterization of the surrounding rock mass is not necessary. Heterogeneity of the fault could be more significant because this could lead to greater lateral movement of flow from the fault to the rock mass or within the fault plane. However, detailed information to characterize heterogeneity of the fault was not available. The fact that subhorizontal fractures intercept the fault was included in the continuum model through the use of an isotropic permeability for both the fault and the fractures, as discussed above. Lateral flow from the fault into the surrounding rock mass did occur in the model, as well as flow through the fault to Niche 3.

4. RESPONSE TO THE FOUR SPECIFIC CONCERNS OF THE NRC STAFF

Each of the four concerns in the May 21, 2007 NRC letter (shown in italics) is explicitly addressed below.

1. *The analysis of the fault test in the documents referred to in Williams (2006) involved little or no direct consideration of the available fracture data or lithostratigraphic data for the Alcove 8-Niche 3 field tests, nor did the conceptualization of the model in the documents incorporate features similar to the 3-dimensional depiction of fractures between Alcove 8 and Niche 3 that DOE originally provided in response to SDS 3.01 to indicate that the Alcove 8-Niche 3 tests would be fracture-informed (Brocoum 2001).*

Response:

For the flow and transport analyses of the test data from the Alcove 8/Niche 3 fault test, the direct use of a discrete fracture model or explicit representation of fractures in the fractured rock mass adjacent to the fault is not warranted. Similarly, the adequacy of the current modeling approach using dual continua to represent fractures and the matrix in the UZ for seepage analyses is demonstrated in the DOE response to USFIC 4.06 (Ziegler 2003, Appendix D), which was accepted by the NRC. It is recognized that fracture data from the ESF and Enhanced Characterization of the Repository Block (ECRB) have been used in a more detailed manner in other Project work such as the drift degradation analysis (BSC 2004g). This arises from the different needs associated with the understanding of different processes. Fracture geometric information plays a more direct and more significant role in the understanding of drift degradation processes (BSC 2004g), whereas in the quantification of the site-scale UZ flow and transport, the effects of fractures are less direct and can be incorporated through the use of hydrologic and transport properties.

To capture the effects of fractures on site-scale UZ flow and drift seepage, the fractures are directly represented in the continuum models through the use of measured properties, such as permeability, whose values are affected by the presence and nature of the fractures. Hydrologic processes that are affected by the fractures are included in the models by using the appropriate fracture hydrologic properties. For site-scale flow and transport models, there is no need to include other information about the fractures.

For analyses of the Alcove 8/Niche 3 seepage and transport test data, the dual continuum approach is borne out because there is no correlation between seepage and fractures in Niche 3 and only a weak correlation between infiltration and fractures in Alcove 8. The analyses that support the TSPA are directly fracture-informed by incorporating the effect of fractures through measurements of gas-phase permeability, gas-phase tracer movements, fracture frequency, and fracture trace length, as well as matrix water saturation and water potential. For simulating the site-scale UZ flow, the model also explicitly incorporates selected faults in the numeric mesh used, and assigns the faults properties separate from the fractured rock mass through the use of site-scale pneumatic measurements and results from borehole UZ 7a. For seepage analyses, the fracture properties as they affect seepage are incorporated into the seepage models through measurements of properties that control seepage.

Both UZ flow and seepage models have been calibrated and validated against test measurements at Yucca Mountain. Also, the effects of fractures and faults on site-scale unsaturated flow and seepage are directly incorporated through measurement of properties that affect flow, with such properties themselves being dependent on the nature of the fractures and faults.

2. *The interpretation of the fault test results did not sufficiently consider structural features such as the intersection of the subvertical fault with subhorizontal fractures throughout the tuff, and the potential role that these subhorizontal fractures had in diverting water from the fault and bypassing Niche 3.*

Response:

It is important to recognize that there are differences between the test conditions for the Alcove 8/Niche 3 test and the expected repository conditions. Given these differences, care must be used not to mistake a response from a certain test, under conditions that will never be experienced in a repository, for the response that a repository will actually experience in the future. For tests that involve slow physical processes, such as heat conduction and water movement through the unsaturated rock mass, in order to get any measurable response in any meaningful time frame, the test bed is overstressed such that certain aspects of the tests would result in conditions that would not be expected under ambient or normal repository operating conditions. Alcove 8/Niche 3 is such a hydraulically overstressed test, in which the amount of input water per unit time is much larger than infiltration that will occur under ambient conditions or repository conditions. In the Alcove 8/Niche 3 tests, because of the large water input, all fractures that could flow, including horizontal fractures, did flow. However, that does not mean that horizontal fractures need to be explicitly represented in a discrete fracture model, nor does it mean that horizontal fractures need to be explicitly treated as discrete features within a dual continuum model. The effect of the horizontal fractures on UZ flow is incorporated through the use of isotropic permeabilities, and test results match sufficiently well with the dual continuum models used. This is also reinforced by seepage observations from the South Ramp during the winter of 2004-2005, details of which are provided in *Abstraction of Drift Seepage* (SNL 2007d, Section 7.1[a]). Analyses of the observations there indicate that UZ flow was controlled by faults and lithostratigraphic contacts instead of horizontal fractures. Additionally, similar observations were made during the excavation of the ESF about the control of lithostatigraphic contacts and faults instead of horizontal fractures. It should be noted that adjacent to such preferential flow paths as faults or lithostratigraphic contacts, fractures of all orientations become wetter because of more water being present in the preferential flow paths.

Although it is possible to speculate that horizontal fractures were responsible for the bulk of the infiltrating water in Alcove 8 that did not become seepage in Niche 3, there is no evidence that this process occurred. In other Project tests, a large fraction of the infiltrating water does not seep simply because of wetting of the rock mass and capillary effects.

In summary, the validated UZ flow and seepage models do reasonably match various test results, without explicit use of discrete horizontal fractures. Also, there is a lack of observations of preferential horizontal flow, although there are observations of preferential flow in faults and at lithostratigraphic contacts. Therefore, in lieu of convincing field evidence, direct incorporation of discrete horizontal fractures into these models is not warranted at this time.

3. *Further, the interpretation of the fault test results did not directly evaluate connection of the fault to subhorizontal fractures, connection of subhorizontal fractures to vertical fractures, connection of lithophysae to both sets of fractures and, consequently, the potential role that these fracture-connected lithophysae had in trapping infiltrated water.*

Response:

The concern above again seems to be that the site-scale UZ flow and drift seepage models do not explicitly include representations of observable geologic features, in this case, the lithophysae. As with the case of faults and fractures discussed above, even though the lithophysae are not represented explicitly as entities in the numerical model mesh, the effects of the lithophysae on flow properties have been represented. A casual glance at the more lithophysae-rich portions of rock clearly shows that the lithophysae must have an effect on porosity. For this reason, the lithophysal unit is modeled with larger porosity for the Alcove 8/Niche 3 tests. Any effects on permeability are automatically included through gas-phase permeability testing. In the Alcove 8/ Niche 3 tests, the effects of lithophysae on fracture porosity were incorporated through calibration to the water-arrival-time measurements. Lithophysae behave like all large openings in that they present a capillary barrier to water entry. Under the accelerated flow conditions in Alcove 8/Niche 3, a portion of the lithophysae did appear to participate in fracture flow. However, this participation is expected to be much less under lower flow rates representative of ambient or repository conditions. In addition, the effects of fracture porosity on site-scale UZ transport have been shown to be small. Furthermore, lithophysal porosity has no effect on drift seepage under the steady flow conditions characteristic of the UZ below the PTn. Therefore, the incorporation of lithophysal porosity into the site-scale UZ flow and drift seepage models is not warranted.

In summary, discrete, individual lithophysae have not been incorporated into the UZ flow and drift seepage models, because it is not feasible to incorporate the numerous discrete lithophysae into these models. The current approach based on the use of dual permeability continuum models is reasonable, as demonstrated by the fact that the validated models for UZ flow and drift seepage do reasonably match test results, without explicit use of discrete, individual lithophysae.

4. *Instead of considering unrepresented features and processes such as those mentioned above, DOE increased the modeled effective fracture-matrix interface area in the model to account for those unrepresented features and processes. This approach increased the effectiveness of matrix diffusion, which allowed the model to reproduce the observed fault test results. Application of this approach in predictive modeling at other locations is uncertain.*

Response:

This final concern is related to the three above. Once again, although the "unrepresented" features are not represented explicitly in a numeric model mesh, the effects of these features on flow are incorporated. As explained for the three concerns above, to whatever extent these features affect flow, those effects have been measured and accounted for in the flow properties used in the site-scale UZ flow and drift seepage models. The tests conducted at Alcove 8/Niche 3 also contain a transport component. Upon properly accounting for the effects on flow as described above, the test bed model could not quite explain the transport aspects of the test. Even with a representation of fractures through their effects on flow properties, there was a mismatch between measurements and predictions for transport. This result shows that some other aspect of the model must be corrected to explain the transport response. As was done at other sites (Löfgren 2004; Shapiro 2001), the effective diffusion coefficient was increased. This increase did produce a better correlation between measured and predicted transport results, indicating that the adjustment may be reasonable. The reasonableness of the adjustment is reinforced by the fact that the adjustment was applied to lab measurements of matrix diffusion used in combination with the estimated wetted fracture-matrix interface area. This area, calibrated for its effects on unsaturated flow, may very well be underrepresented in terms of the effective area available for matrix diffusion.

Notwithstanding the importance of the Alcove 8/Niche 3 tests, the DOE recognizes that there is some uncertainty in increasing matrix diffusion in the site-scale UZ transport model based on existing test results including those from Alcove 8/Niche 3 and Alcove 1. Therefore, this adjustment in the effective matrix diffusion coefficient has not been implemented in the TSPA compliance case, and will only be used in a TSPA sensitivity analysis.

The validated models for UZ flow and transport are suitable for their intended use, because the results do not under-represent the rate of UZ flow or solute transport in field tests and therefore do not under-represent risk. The explicit use of discrete, individual fractures, small faults, and lithophysae is not feasible for the UZ modeling domain and therefore, would not result in an improvement in the modeling capability. For this reason, the direct incorporation of discrete, individual fractures, small faults, and lithophysae in the UZ flow and transport models is not necessary, and the scaling of the effective matrix diffusion coefficient is a reasonable approach to investigate the sensitivity of these processes to UZ transport.

5. OVERALL CONCLUSIONS

The information of the fracture network as observed at Alcove 8 and Niche 3 was incorporated into the Alcove 8/Niche 3 test bed model using a dual continuum approach. The continuum modeling approach used for analyses of the Alcove 8/Niche 3 test data, the site-scale UZ flow model, and the seepage abstraction model is justified based on the fracture densities and the required length scale of resolution of each of these models. For similar reasons to those discussed in DOE responses to USFIC 4.06, a discrete fracture modeling approach is not needed for the flow and transport analyses of the Alcove 8/Niche 3 test data. Unlike some other Project work such as drift degradation analyses in which detailed fracture geometric information is needed, fractures and faults are captured in the Alcove 8/Niche 3 test bed model, as in the site-scale UZ flow model and the seepage abstraction model, through capturing their effects on flow and transport properties.

The test bed models are all fracture informed in that fracture information (e.g., fracture frequency and air permeability) required to characterize these hydrologic models at the relevant scales has been used. Additional fracture information (e.g., a three-dimensional fracture network description) is either not necessary or is not applicable to continuum hydrologic models. Information characterizing the fault and fractures in the Alcove 8/Niche 3 fault test were used in the test bed model, and the presence of subhorizontal fracture connections with the fault was included through permeability properties. The presence of lithophysae was included through the model calibrations of fracture porosity.

The analyses of data from the Alcove 8/Niche 3 fault test and the development of the test bed model are performance-based and risk-informed, in keeping with the requirements of the regulation (10 CFR 63). Data from these tests provide additional field evidence for confirming the conceptual model of matrix diffusion, which serves to help validate the site-scale UZ transport models. Considering uncertainties in the Large Plot tracer transport test, however, the test data, including the enhancement factor for matrix diffusion, are not planned to be incorporated into the TSPA compliance case. Instead, the enhancement factor to the fracture-matrix interface is planned to be used to test the sensitivity of these processes to UZ transport. This use of the Alcove 8/Niche 3 fault test data is reasonable based on the consistency between flow observations and the test bed flow model, the observed tracer transport behavior, and similar observations of enhanced matrix diffusion at other sites.

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