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REVIEW OF THE UNSATURATED ZONE FLOW AND TRANSPORT PROCESS MODEL REPORT

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ABSTRACT

This letter report documents a review of the Unsaturated Zone Flow and Transport Model Process Model Report, which was prepared by the Civilian Radioactive Waste Management System Management and Operating Contractor for the U.S. Department of Energy (DOE), Yucca Mountain Site Characterization Office. The reviewed report documents the development and technical basis for the DOE treatment of unsaturated zone flow and transport processes in the Total System Performance Assessment for Site Recommendation. The purpose of the review is twofold: (i) to document the status of resolution of the relevant subissues of the U.S. Nuclear Regulatory Commission (NRC) Key Technical Issue (KTI), Unsaturated and Saturated Flow under Isothermal Conditions (USFIC); and (ii) to provide a review of USFIC KTI subissues that makes use of the generic acceptance criteria outlined in the NRC Issue Resolution Status Report (IRSR) for the Total System Performance Assessment and Integration (TSPAI) KTI. The review topics are organized according to the model abstractions identified in the TSPAI IRSR that are relevant to the USFIC KTI: Climate and Infiltration, Flow Paths in the Unsaturated Zone, Quantity and Chemistry of Water Contacting Waste Packages and Waste Forms, and Radionuclide Transport in the Unsaturated Zone. The scope of this review, however, is limited to the relevant USFIC KTI subissues: Climate Change, Hydrologic Effects of Climate Change, Present-Day Shallow Infiltration, Deep Percolation, and Matrix Diffusion. As documented in this report, all these USFIC KTI subissues are presently considered closed or closed-pending. That is, NRC staff have confidence that the proposed DOE approach, together with DOE agreements to provide NRC with additional information (through specified testing, analysis, etc.) acceptably address NRC questions so that no information beyond that provided, or agreed to, will likely be required at the time of initial license application. Additional input from other KTIs (i.e., Thermal Effects on Flow, Structural Deformation and Seismicity, Evolution of the Near-Field Environment, and Radionuclide Transport) is required before it can be determined whether the acceptance criteria for the relevant model abstractions have been met by DOE. It is suggested this review, combined with similar reviews by the other KTI staffs, will provide a basis for Sufficiency Review Comments, and a framework for an integrated IRSR that documents the status of resolution for all KTIs.

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This report was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the U.S. Nuclear Regulatory Commission (NRC) under Contract No. NRC–02–97–009. The activities reported here were performed on behalf of the NRC Office of Nuclear Material Safety and Safeguards, Division of Waste Management. The report is an independent product of the CNWRA and does not necessarily reflect the views or regulatory position of the NRC.

The authors wish to thank David Turner for thorough technical review and useful insights, Cathy Cudd and Barbara Long for editorial expertise, and Budhi Sagar for programmatic review. The administrative and format support provided by Paulette Houston is greatly appreciated also.

QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

This report is a review of existing data and analyses. There are no CNWRA-generated original data contained in this report. No computer codes or software were used for analyses contained in this report. This report is self-contained: there were no CNWRA scientific notebooks used to document or develop this review or its findings.

1 INTRODUCTION

This letter report documents a review by staff at the Center for Nuclear Waste Regulatory Analyses (CNWRA) of the Unsaturated Zone Flow and Transport Model Process Model Report, published by the Civilian Radioactive Waste Management System Management and Operating Contractor (CRWMS M&O) (CRWMS M&O, 2000). The reviewed Process Model Report (PMR) documents the development and technical basis for the U.S. Department of Energy (DOE) incorporation—also referred to as abstraction—of unsaturated zone (UZ) flow and transport processes at Yucca Mountain (YM) in Total System Performance Assessment (TSPA) analyses for the YM Site Recommendation (SR). Also reviewed are the supporting Analysis/Model Reports (AMRs), which provide additional technical bases for the various analyses and submodels used to develop the site-scale UZ flow and transport model for YM.

The purpose of this review is twofold: (i) to document the status of resolution of the relevant subissues of the U.S. Nuclear Regulatory Commission (NRC) Key Technical Issue (KTI), Unsaturated and Saturated Flow under Isothermal Conditions (USFIC); and (ii) to provide a review of USFIC KTI subissues that makes use of the generic acceptance criteria outlined in the NRC Issue Resolution Status Report (IRSR) for the Total System Performance Assessment and Integration (TSPAI) KTI (U.S. Nuclear Regulatory Commission, 2000). The review topics are organized according to the model abstractions identified in the TSPAI IRSR that are relevant to the USFIC KTI: Climate and Infiltration, Flow Paths in the Unsaturated Zone, Quantity and Chemistry of Water Contacting Waste Packages and Waste Forms, and Radionuclide Transport in the Unsaturated Zone. These abstraction topics, often referred to as integrated subissues (ISIs), are reviewed separately in the following chapters of this report. Consistent with the acceptance criteria outlined in the TSPAI IRSR, review of the technical basis for each ISI is divided into five sections that correspond to the following five generic acceptance criteria:

- Model Integration—System description and model integration are adequate
- Data and Model Justification—Data are sufficient for model justification
- Data Uncertainty—Data uncertainty is characterized and propagated through the model abstraction
- Model Uncertainty—Model uncertainty is characterized and propagated through the model abstraction
- Model Support—Model abstraction output is supported by objective comparisons

Most of the ISIs identified in the TSPAI IRSR (U.S. Nuclear Regulatory Commission, 2000) rely on input from more than one KTI. The scope of this review, however, is limited to the following relevant USFIC KTI subissues: Climate Change, Hydrologic Effects of Climate Change, Present-Day Shallow Infiltration, Deep Percolation, and Matrix Diffusion. Additional input from other KTIs (e.g., Thermal Effects on Flow (TEF), Structural Deformation and Seismicity (SDS), Evolution of the Near-Field Environment (ENFE), and Radionuclide Transport) is required before it can be determined whether the acceptance criteria for each abstraction have been met.

1.1 REFERENCES

Civilian Radioactive Waste Management System Management and Operating Contractor. *Unsaturated Zone Flow and Transport Model PMR*. TDR–NBS–HS–000002. Revision 00. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor. 2000.

U.S. Nuclear Regulatory Commission. *Issue Resolution Status Report Key Technical Issue: Total System Performance Assessment and Integration*. Revision 3. Washington, DC: U.S. Nuclear Regulatory Commission. 2000.

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2 CLIMATE AND INFILTRATION

The climate and infiltration ISI addresses the near-surface hydrologic processes, such as precipitation, temperature, climate change, and rates of infiltration. Climate strongly influences the rates of shallow infiltration, which, in turn, is correlated to the amount of water entering the waste emplacement drifts.

This section provides a review of the abstractions of climate and infiltration incorporated by the DOE in its TSPA. The DOE description and technical basis for the climate and infiltration abstractions are documented in the UZ flow and transport PMR (CRWMS M&O, 2000a) and three supporting AMRs: Future Climate Analysis (CRWMS M&O, 2000b), Simulation of Net Infiltration for Modern and Potential Future Climates (CRWMS M&O, 2000c), and Analysis of Infiltration Uncertainty (CRWMS M&O, 2000d). Portions of additional AMRs are reviewed to the extent they contain data or analyses to support the TSPA abstractions.

2.1 IMPORTANCE TO SAFETY

The importance of infiltration to repository performance at YM is recognized by the DOE by identifying "seepage into emplacement drifts" as one of the eight principle factors in the Repository Safety Strategy for the postclosure safety case (CRWMS M&O, 2000e). Because infiltration is the primary source of water in the UZ at YM, it is the first in a series of natural-system processes that must be considered to evaluate the quantity of water that could potentially seep into emplacement drifts.

Climate changes also must be considered in TSPA because long-term changes in precipitation and temperature will significantly affect surface infiltration rates (CRWMS M&O, 1999). Hence, during the 10,000-yr compliance period, climate changes in the YM region are expected to produce (i) changes in precipitation and temperature that will affect the amount of deep percolation at the proposed repository horizon, (ii) increases in water table elevation that will reduce the distance from the repository horizon to the water table, and (iii) changes in saturated zone (SZ) groundwater fluxes and flow paths from beneath the repository to the compliance boundary.

2.2 RELATIONSHIP TO UNSATURATED AND SATURATED FLOW UNDER ISOTHERMAL CONDITIONS KEY TECHNICAL ISSUE

This review of the Climate and Infiltration abstraction incorporates subject matter that has been previously reviewed within the framework of three USFIC KTI subissues:

- Climate Change—What is the likely range of future climates at Yucca Mountain?
- Hydrologic Effects of Climate Change—What are the likely hydrologic effects of climate change?
- Present-day Shallow Infiltration[1]—What are the estimated amount and spatial distribution of present-day and future shallow infiltration?

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[1]Note that the Climate and Infiltration abstraction also includes review of infiltration during future climate conditions, whereas the relevant subissue for the USFIC KTI was focused only on estimated present-day infiltration rates.

2.3 TECHNICAL BASIS

Precipitation estimates for future climates used by DOE for the Viability Assessment were previously reviewed by NRC and found to meet the applicable USFIC KTI acceptance criteria (U.S. Nuclear Regulatory Commission, 1999). Since then, however, the climate abstraction has been revised to reflect an improved technical basis for estimates of precipitation, temperature, and onset times for future climate states (CRWMS M&O, 2000a,b). NRC staff have also previously reviewed the DOE shallow infiltration process model for YM that was used in the Viability Assessment (U.S. Department of Energy, 1998) and found the approach and estimates of present-day infiltration to be acceptable (U.S. Nuclear Regulatory Commission, 1999). Since then, however, the shallow infiltration model has been updated to incorporate new boundary conditions from the climate model, and to include effects of runoff and climate-induced changes in vegetation (CRWMS M&O, 2000a,c). The result is that present estimates of water percolation flux above the proposed repository are significantly less than those used in the Viability Assessment. It is therefore necessary to review those portions of the DOE shallow infiltration model that differ from the version used to support the Viability Assessment. A review of the revised DOE approaches for including Climate and Infiltration in TSPA abstractions is provided in the following subsections. The review is organized according to the five generic acceptance criteria identified in the TSPAI IRSR (U.S. Nuclear Regulatory Commission, 2000).

2.3.1 System Description and Model Integration

The approach and technical basis for the abstraction of climate in TSPA is documented by DOE in an AMR, Future Climate Analysis (CRWMS M&O, 2000b), herein referred to as the climate AMR. Key assumptions are that (i) climate is cyclical, (ii) climate change cycles can be timed accurately with an orbital clock (i.e., Milankovitch forcing) calibrated with the Devil's Hole chronology, and (iii) past climate cycles repeat themselves in sequential order.

Based on those assumptions, a 10,000-yr climate history, beginning from about 400,000 yr before present, was selected as the most probable analog for the next 10,000 yr. During this period, three different climate states have been identified: (i) present-day climate for the first 600 yr; (ii) a monsoon climate that is warmer and wetter than present day for the following 1,400 yr; and (iii) a glacial transition climate that is cooler and wetter than present for the balance of the 10,000-yr period (CRWMS M&O, 2000a,b). Changes in precipitation rates and temperature from one climate state to the next are explicitly considered as boundary conditions for the shallow infiltration process model (reviewed in section 2.3.2). For the shallow infiltration abstraction, DOE also has added consideration of changes in vegetation during future climates (CRWMS M&O, 2000c).

The scope of the DOE shallow-infiltration process model is limited to surficial hydrological processes, with estimates of net infiltration limited to depth of the root zone only. As described in the UZ flow and transport PMR (CRWMS M&O, 2000a), the infiltration model covers a domain of 123.7 km^2 with 30 × 30 m computational cells. Processes considered are precipitation, infiltration, evapotranspiration, and surface water run-on. These processes are incorporated into a watershed-scale, volume-balanced model using a snowpack submodel, an evaporation and net radiation submodel, one-dimensional (1D) (vertical) root-zone infiltration submodels, and a two-dimensional (2D) (horizontal) surface-water, flow-routing submodel. Potential evapotranspiration is determined by an energy balance dependent on net radiation, air temperature, ground heat flux, a saturation-specific humidity curve, and wind. Water that exceeds the infiltration capacity of a soil column is routed to lower elevation nodes for subsequent infiltration. For each climate state, time varying precipitation and temperature boundary conditions were stochastically derived from measurements

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at analog sites, as discussed previously. These boundary conditions are spatially distributed based on empirical correlations to elevation.

Increases in vegetation density and changes in vegetation type were assumed for the wetter and colder future climates. However, the infiltration AMR indicates these changes in vegetation are considered only for the upper-bound climate scenarios (CRWMS M&O, 2000c, section 6.9.4). For the upper-bound monsoon climate, the root-zone weighting parameters were adjusted to approximate a 40-percent vegetation cover (compared to 20 percent for modern climate), and the maximum thickness of the bedrock root-zone layer was increased from 2 m to 2.5 m. For the upper-bound, glacial-transition climate, the root-zone weighting parameters were adjusted to approximate a 60-percent vegetation cover, and the maximum thickness of the bedrock root-zone layer was increased to 3 m. These increases to vegetation cover and root-zone depth increase evapotranspiration and, hence, decrease net infiltration. It is reasonable, however, to assume that the large increases in precipitation assumed for the upper-bound future climate scenarios would support increased vegetation cover and vegetation types with greater root-zone depth.

Output from the DOE infiltration model is used to define spatially distributed, time-averaged estimates of net infiltration, which provide the necessary steady-state flux boundary conditions for the site-scale UZ flow model. Nine boundary conditions for the UZ flow model are developed: low-, medium-, and high-infiltration scenarios for each of the three climate states. Integration of the infiltration model with the site-scale UZ flow model requires spatial averaging because the UZ flow model grid is coarser than that of the infiltration model. Temporal averaging also is used to convert the time-varying infiltration model output into an equivalent steady-state flux. The DOE justifies spatial averaging and use of a steady-state flux boundary because the sparsely fractured, highly sorptive Paintbrush nonwelded tuff (PTn) layer, beneath the surface at YM, is postulated to attenuate episodic surface infiltration pulses and spatially smooth localized zones of high infiltration.

The UZ PMR and supporting AMRs provide a sufficient description of the conceptual models for climate changes and shallow infiltration at YM. Important design features, physical phenomena, and couplings are adequately incorporated or bounded. Assumptions are clearly stated and used consistently.

2.3.2 Data are Sufficient for Model Justification

Detailed descriptions of these data sets and how they can be used to justify the abstraction approach are provided in the climate AMR (CRWMS M&O, 2000b). Three data sets are crucial to development of the DOE approach: (i) Devil's Hole calcite deposits, (ii) Owens Lake microfossil records, and (iii) meteorologic records from climate analog sites.

Devil's Hole is located about 90 km south of YM in the Paleozoic limestone that composes the regional aquifer. Calcite has precipitated on the walls of Devil's Hole during the last 500,000 or more years, leaving a record of $\delta^{18}O$ that provides insight into the temperature at which the precipitation in the recharge area forms. Because the calcites in Devil's Hole can be dated, they provide a chronology of climate that reflects a cyclic change from interglacial to glacial climates. A relation between Devil's Hole data and orbital precession is evident where maximal values of precession mark the ends of the Devil's Hole interglacials and other warm periods (CRWMS M&O, 2000b). Developed into a formal relationship, this provided a rationale for timing future climate change based on the Devil's Hole chronology of climate change in the YM region. While the Devil's Hole data set provides a reasonable basis for forecasting the cyclical timing of climate change, it does not provide sufficient insight into the climatological conditions that existed in the YM region for each climate state.

To reconstruct the climate history, microfossil records of diatoms and ostracodes from cores drilled at Owens Lake were used. Owens Lake is located on the eastern side of the Sierra Nevada Mountains, east of Los Angeles, California. The known environmental tolerances of ostracode and diatom species provide a way to interpret the relative total dissolved solids (TDS) of the Owens paleolake and the relative temperature of its water. The TDS and water-temperature information are then used to qualitatively infer a range of likely climate conditions—precipitation and temperature—during the Owens Lake stage 11 (interglacial period about 400,000 yr ago) to stage 10 (glacial period) transition. In this manner, monsoon and glacial-transition climate states were identified as the sequence of climate states most likely to follow present-day climate in the YM region during the 10,000-yr compliance period.

Once qualitative descriptions of future climate states were obtained from the Owens Lake record, it was necessary to identify analog sites where present-day climate conditions were qualitatively consistent with those inferred for the monsoon and glacial-transition climates. Meteorological stations within these analog areas were selected to obtain precipitation and temperature data to be used as analog input to the infiltration process model. For the monsoon climate, meteorological stations from two analog sites were chosen to represent an upper bound, while the modern climate meteorological record was used as a lower bound. For the glacial-transition climate, lower- and upper-bound analog sites were chosen. Shallow infiltration simulation results using lower- and upper-bound meteorological records as inputs were averaged to create a mean net-infiltration estimate for the future climates. The meteorological input for estimating mean shallow infiltration for the modern climate, however, was a synthetic 100-yr precipitation and temperature record developed from YM and Nevada Test Site weather stations.

Data collected at YM to support infiltration modeling include soil and bedrock hydrological properties, meteorological data, soil and bedrock water-content profiles, soil and bedrock water chemistry and temperature, and streamflow measurements. These data reveal the episodic nature of precipitation events at YM. Short periods of heavy precipitation (including an occasional snowmelt) may produce fleeting surface run-on and stream flow events. The data also indicate that areas with thin soils and highly fractured bedrock permit rapid infiltration of water below the root zone. Meteorological measurements indicate that the average annual potential evapotranspiration rate is approximately six times greater than the average annual precipitation rate for the current climate, resulting in the arid condition of YM between episodic precipitation events (CRWMS M&O, 2000c). These data and observations are generally consistent with the conceptual model for infiltration at YM on which the process model is based, and they show the importance of considering processes such as surface runoff and evapotranspiration. However, available data leave significant uncertainty pertaining to model parameter values, model calibration targets, and model assumptions; a few examples are noted next.

Equivalent bedrock properties were estimated from changes in water content profiles during time as measured by neutron probes installed in boreholes. Because neutron probes measure water content in the rock matrix, equilibration of bedrock matrix and fractures must be assumed. Near the ground surface, however, this equilibration may be unlikely because of preferential or focused flow in fractures networks. For example, Alcove 1 test results, as yet unpublished, indicate that the equivalent permeability of the fractured bedrock is 35 times greater than the bedrock permeability value used in the model. Alcove 1 is the only area where large-scale infiltration measurements have been made at YM.

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To calibrate the model, streamflow measurements have been collected for selected subwatersheds as calibration targets; data from two storm events were used. As part of this calibration, geochemical data were used to constrain estimates of net infiltration. While this approach could lead to a well-calibrated model, it may lack the ability to accurately predict net infiltration because the data are not sufficient to derive a unique best set of model parameters. For example, important calibrated parameters such as root-zone depth and area of watershed contributing to runoff may simply compensate for errors in fixed parameters such as bedrock permeability and soil depth.

The DOE infiltration model does not consider variations in bedrock saturation. However, bedrock dryout zones beneath areas of thin or no soil cover would tend to lessen rates of shallow infiltration. Thus, the predicted high net infiltration rates in areas of thin soil cover may be partly the result of neglecting variability in bedrock saturation. Another factor to consider is that water potential, saturation, and chloride content data from the Exploratory Studies Facility (ESF) and the East-West Cross Drift (ECRB) suggest the runoff/run-on component of shallow infiltration is underpredicted for stream channels over the repository footprint.[2] So, there are data to suggest that the DOE infiltration model may tend to overpredict net infiltration on ridges with thin soils, and underpredict it in stream channels. The overall effect may be that net infiltration is less variable spatially than is predicted by the model.

In summary, available data support the DOE conceptual models of climate and shallow infiltration at YM used in TSPA. Although the DOE model for shallow infiltration includes important processes required for adequate representation of shallow infiltration, the basis for model parameter values may lack supporting data. The missing data needed to fully support the shallow infiltration model can be compensated for by propagating data uncertainty through the model, which is discussed in the next section. Thus, with the caveat that data uncertainty must be propagated through the shallow infiltration abstraction, sufficient data exist to support development of the shallow-infiltration process model for YM. Data appear to have been collected using acceptable techniques. The quality assurance of data collection and documentation is beyond the scope of this review.

2.3.3 Data Uncertainty is Characterized and Propagated through Abstraction

The climate AMR (CRWMS M&O, 2000a) identifies several sources of data uncertainty. First, there is uncertainty in knowing whether changes in $\delta^{18}O$ values are directly correlated with changes in mean annual precipitation and mean annual temperature or if there is a lead or a lag time between changes in regional climate. Second, each Devil's Hole sample integrates a particular thickness of carbonate in a continuous sample series and represents about 1,000 yr. Consequently, the data would not reveal changes in regional climate with durations much less than 1,000 yr. Third, there is uncertainty in the sediment accumulation rate used to infer relative ages of the microfossils obtained from cores in the Owens Lake. There is no simple or objective way of assessing the nature of any of these three sources of uncertainty. A fourth source of uncertainty is the standard deviation associated with age estimates of Devil's Hole calcite samples. While the standard deviation of Devil's Hole ages is itself an estimate of uncertainty, that estimate was not incorporated into the abstraction, in part, because the other sources of uncertainty cannot be estimated, and, hence, their relation to standard deviation is unknown. A final source of uncertainty is the choice of a starting point at 400,000 yr before present assumed equivalent to modern climate for purposes of projecting forward. Though possible, the choice is somewhat arbitrary considering the lack of data from Devil's Hole during the last 8,000 yr.

[2]Flint, L. *Presentation to Geological Society of America*. November 13–17, 2000. Reno, NV: 2000.

To address data uncertainty in the shallow-infiltration process model, DOE developed distributions for values of 12 input parameters (CRWMS M&O, 2000d, table 4-1). These input parameters were stochastically sampled using a Latin hypercube sampling algorithm in a 100-realization Monte Carlo analysis of infiltration for a glacial-transition climate state. The parameters chosen for development of uncertainty distributions were effective bedrock porosity, bedrock root-zone thickness, soil depth, precipitation multiplier, potential evapotranspiration, bulk bedrock saturated hydraulic conductivity, soil saturated hydraulic conductivity , two parameters associated with bare soil evaporation, and effective surface-water flow area. Two additional parameters are related to sublimation and melting of snow cover.

Upper and lower bounds for the 12 parameters were estimated partly by using physical limits and partly by judgment based on existing bounds within the available data. The logic and the data used to deduce reasonable limits, however, are not described clearly in the infiltration uncertainty AMR (CRWMS M&O, 2000d), and the methods used to deduce these parameter distributions are not transparent to NRC staff. In fact, some of the parameter ranges listed in the infiltration uncertainty AMR are physically impossible (e.g., a value of - 10 for the lower bound of the precipitation multiplier); DOE has indicated there are typographic errors that will be corrected in a future revision of the infiltration AMR. DOE also agreed at a recent technical exchange[3] to provide additional justification for the 12 stochastic parameters identified in the infiltration uncertainty AMR (CRWMS M&O, 2000d, table 4-1).

The range and distribution of net-infiltration rates obtained from this Monte Carlo analyses of parameter uncertainty were used as the basis for estimating probability weighting factors of 0.17, 0.48, and 0.35 for low-, medium-, and high-infiltration scenarios, respectively (CRWMS M&O, 2000d, table 6-2). For example, for a TSPA realization with stochastically sampled inputs, there is a 48-percent chance that the UZ flow fields obtained from the medium-infiltration case will be selected. In this manner, data uncertainty is propagated through the TSPA abstraction. It should be noted that values of the probability weighting factors are expected to change as a result of an NRC concern that the upper-bound, net-infiltration estimates for the three climate states does not incorporate parameter uncertainty.

In summary, there are several sources of data uncertainty that have not been incorporated into the climate model abstraction. The effect of these data uncertainties is that the onset times of 600 yr and 2,000 yr forecast for the monsoon and glacial-transition climate states are also uncertain. It should be noted, however, that ignoring the part of the uncertainty that would result in later onset times results in performance predictions that are conservative. Although climate change onset times could come earlier than predicted, it should be recognized that the presently predicted onset times come relatively early in the compliance period. Note that the estimated time of maximum dryout of repository drifts due to waste heat is 600 yr (CRWMS M&O, 2000a, section 3.10.5.2), so any effect of an earlier onset of the monsoon climate would be minimal compared to the effects of thermally driven redistribution of water. Thus, incorporating uncertainty in climate-state onset times would not likely affect performance predictions. So, from a performance-based viewpoint, the current DOE approach is acceptable. The DOE approach to incorporating data uncertainty into the infiltration process model and TSPA abstraction through Monte Carlo analysis is reasonable, although additional documentation is required to provide a technical basis for the ranges and distributions of sampled parameters. Further, as agreed to by DOE and discussed in the following subsection, parameter uncertainty should be reflected in the lower- and upper-bound, net-infiltration scenarios developed by DOE.

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[3]DOE/NRC Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions, Albuquerque, NM, October 31–November 2, 2000.

2.3.4 Model Uncertainty is Characterized and Propagated through Abstraction

Perhaps the most significant model uncertainty lies in knowing what the magnitude of changes will be in precipitation and temperature for each climate state. Another model uncertainty is that the variation of climate on the scale of decades to centuries, which could lead to greater estimates of net infiltration, is not considered by DOE. These uncertainties are addressed in the climate model abstraction by using several analog sites for each climate state. The locations of these analog sites are described in the climate AMR (CRWMS M&O, 2000b, table 2). Upper- and lower-bound values for precipitation and temperature are quantified by selecting meteorological stations at locations in areas with some or all of the common ostracodes and diatoms found in Owens Lake, thus integrating the biology, hydrology, and climate linkages that were expressed in the past at Owens Lake. Mean (expected) values of precipitation and temperature are determined by averaging the upper and lower bounding values obtained from the analog sites. DOE estimates of annualized mean, lower-bound, and upper-bound precipitation and temperature for the three climate states are listed in table 2-1. These annualized values are for comparison only; actual inputs to the infiltration process model are time varying on a daily basis (CRWMS M&O, 2000c).

It can be seen in table 2-1 that the ranges of precipitation between lower- and upper-bounds for all climate states are quite large; hence, a large range of model uncertainty is incorporated into the abstraction. Note also that the increase in precipitation from modern to the monsoon and glacial-transition climates is quite large. These precipitation estimates for future climates are consistent with those previously estimated by DOE for the Viability Assessment (U.S. Department of Energy, 1998) and found acceptable by NRC (U.S. Nuclear Regulatory Commission, 1999), but have a more rigorous technical basis linking the approach to Devil's Hole calcite and Owens Lake microfossil data.

Infiltration process model uncertainty results from the combined model parameter uncertainty, uncertainty in boundary conditions defined by the climate abstraction, and general uncertainty in the validity of various conceptual model assumptions. It is thus important that the ranges of infiltration estimates—the low, medium, and high cases—for each postulated climate state are sufficient to reasonably bound this combined uncertainty. The approach described in the UZ PMR (CRWMS M&O, 2000a), however, falls short of this goal because the estimated low-, medium-, and high-infiltration scenarios are based only on the consideration of climate uncertainty. That is, the low-, medium-, and high-infiltration estimates for each climate scenario are determined by setting model parameters to their expected values and simply running the model with the lower-bound, mean, and upper-bound climate boundary conditions (see table 2-1). The DOE approach yields a set of nine infiltration scenarios used as constant-flux boundary inputs to the site-scale UZ flow model (CRWMS M&O, 2000a). The nine UZ flow model net-infiltration scenarios are summarized in table 2-2.

Note that net-infiltration flux to the UZ flow model is spatially variable; the values in table 2-2 are averaged over the UZ flow model domain used for comparison only.

A specific concern with the DOE approach is that model parameter uncertainty is not propagated into the range of net-infiltration estimates, which should reflect both model and data uncertainties. Additionally, the current estimates for the high net-infiltration scenarios are significantly lower than those considered acceptable by NRC staff for the Viability Assessment (U.S. Department of Energy, 1998). This concern was

Table 2-1. Annualized precipitation and temperature estimates used in the climate abstraction for the three climate states (CRWMS M&O, 2000a, section 3.5.1.8)

Climate	Mean Annual Precipitation and Temperature		
	Lower Bound	Mean	Upper Bound
Modern (Note: temperature not provided for modern)	186.8 mm/yr	190.6 mm/yr	268.4 mm/yr
Monsoon	190.6 mm/yr 17.3 °C	302.7 mm/yr 17.2 °C	414.8 mm/yr 17.0 °C
Glacial Transition	202.2 mm/yr 10.2 °C	317.8 mm/yr 9.8 °C	433.5 mm/yr 9.4 °C

Table 2-2. Area-averaged mean annual infiltration estimates for the unsaturated zone site-scale flow model area states(CRWMS M&O, 2000a, table 3.5-4)

Climate	Low Infiltration Case (mm/yr)	Medium Infiltration Case (mm/yr)	High Infiltration Case (mm/yr)
Modern	1.3	4.6	11.1
Monsoon	4.6	12.2	19.8
Glacial Transition	2.5	17.8	33.0

related to DOE at a DOE/NRC technical exchange on UZ flow.[4] The DOE plan to address this NRC concern includes three elements: (i) developing an upper-bound infiltration case based on the 90th percentile from the Monte Carlo analysis of the glacial-transition climate documented in the infiltration uncertainty AMR (CRWMS M&O, 2000d), (ii) developing upper-bound infiltration cases for the monsoon and modern climates by proportional scaling based on the ratio between upper-bound and mean cases for the glacial-transition climate, and (iii) calculating new probability weighting factors into the TSPA analyses using the same methodology developed in the infiltration uncertainty AMR (CRWMS M&O, 2000d).

At a later technical exchange,[5] DOE staff conveyed preliminary estimates for the revised high-infiltration scenarios for the glacial-transition and monsoon climates as 53 and 30 mm/yr; the estimate for modern climate is not expected to change. Probability weighting factors also need to be recalculated, DOE staff explained, because selecting the high-infiltration scenario from the end of the Monte Carlo distribution translates to a decreased probability that this scenario would occur. It was stated that the revised probability weighting factor for the high-infiltration scenario will be about 20 percent. Although this factor

[4]DOE/NRC Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions, Berkeley, CA, August 16–17, 2000.

[5]DOE/NRC Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions, Albuquerque, NM, October 31–November 2, 2000.

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is revised to a lower value, TSPA simulations would still sample a reasonably large proportion of high-infiltration scenarios. NRC and CNWRA staffs agreed that this concern regarding infiltration model uncertainty is resolved, pending incorporation of these proposed changes into the TSPA calculations used to support the license application.

2.3.5 Model Abstraction Output is Supported by Objective Comparisons

Predictions of future climate abstraction are derived from meteorological conditions recorded at analog sites that are consistent with observations in the Owens Lake record. In the climate AMR, it is reasoned that climate conditions at Owens Lake are similar to those at the top of YM and are subject to the same climate cycles. Regional changes to climate are driven by shifts in the jet stream pattern. Thus, an objective comparison exists between modern climate conditions at YM and Owens Lake. Although it is not possible to form an objective comparison for future climate conditions that are based on the Owens Lake record and those that may occur at YM, some confidence is gained by the fact that a large range of uncertainty is incorporated into the upper-bound precipitation and temperature estimates for the climate abstraction.

Estimates of precipitation and temperature during past glacial climates in the YM region have been derived from a study of the plant macrofossils found in packrat middens (Thompson et al., 1999). These observations were interpreted to indicate that, during the last full-glacial climate at YM, mean annual precipitation was about 266–321 mm, and mean annual temperature was about 7.9–8.5 °C. Although there is uncertainty with these estimates, they do provide an independent and objective basis for comparison showing that a precipitation estimate for the last full glacial climate at YM is consistent with the mean estimated for the glacial-transition climate (table 2-1), and it is conservatively bounded by upper-bound estimates.

The infiltration AMR (CRWMS M&O, 2000c) cites a 7–14 mm/yr estimate of recharge to the saturated zone beneath YM, based on measurements of chloride from saturated-zone boreholes (CRWMS M&O, 2000f) and an assumed long-term average annual precipitation rate of 170 mm/year. Using a chloride mass balance (CMB) approach, net infiltration also has been estimated from matrix pore-water samples in the ESF: samples obtained from the North Ramp, Main Drift, and Cross Drift correspond to infiltration rates of 5–14 mm/yr; samples from the South Ramp yielded estimates of 1–2 mm/yr (CRWMS M&O, 2000f). These estimates are broadly consistent with the spatial distributions of infiltration estimated by DOE for modern and future climates (CRWMS M&O, 2000c). It should be noted, however, that these values were revised downward by approximately 50 percent from previous reported values (CRWMS M&O, 1998). The reduction was accomplished by a reinterpretation of the chloride input from precipitation. The previously assumed chloride concentration of precipitation (0.62 mg/l) was revised downward (0.30 mg/l) based on historical interpretation of chlorine-36 data.

It should be noted also that there are uncertainties and potential biases associated with recharge estimates obtained from the CMB method. For example, chloride measurements are obtained from matrix pore water, yet the conceptual model for flow in the UZ at YM is that flow occurs predominantly in fractures; fracture-matrix interactions are not taken into account in the CMB method. Thus, to gain additional confidence in chloride-based infiltration estimates, the site-scale UZ flow and transport model, which includes fracture-matrix interactions, used pore-water chloride concentrations in the ESF and ECRB as calibration targets. Model results indicate a range of net-infiltration rates 3–10 mm/yr (CRWMS M&O,

2000a, figure 3.8-4). Again, this range of infiltration estimates is generally consistent with infiltration model calculations.

Neutron probe profiles collected during a 4-yr period were used to estimate shallow infiltration at approximately 98 locations throughout a range of geomorphic sites. The range of shallow infiltration estimates is 0–80 mm/yr for all geomorphic areas (CRWMS M&O, 2000c); an approximate average of 33 mm/yr is estimated for ridges and slideslopes only, which dominate the repository footprint (CRWMS M&O, 2000c, figure 6-5). The high value of shallow infiltration may reflect the short record of measurements and possible correspondence with wetter than average climatic conditions. Conversely, neutron probe data reflect a minimum estimate because they indicate bedrock matrix water content; flow bypassing in fractures may be missed by the probe.

Given the manifold uncertainties in model boundary conditions, parameter values, and conceptual model assumptions, there is generally good agreement—well within an order of magnitude—between the infiltration model estimates and those obtained from geochemical data, flow and transport modeling, and neutron probe profiles. Yet, precisely because of such uncertainties, it is important for DOE to assess repository performance using a range of infiltration rates that reasonably bound that uncertainty. The agreements reached between DOE and NRC at the technical exchanges (discussed in the preceding subsection) should be sufficient to ensure that the range of uncertainty in the spatial and temporal distribution of infiltration at YM is adequately incorporated into TSPA calculations.

2.4 STATUS AND PATH FORWARD

USFIC KTI subissues, Climate Change and Hydrologic Effects of Climate Change, are presently considered closed at the staff level. NRC staff have confidence that the current DOE approach and available information acceptably address staff questions so that no information beyond what is currently available will likely be required for regulatory decisionmaking at the time of any initial license application.

The USFIC KTI subissues pertaining to shallow infiltration at YM during modern and potential future climates are considered closed-pending by NRC staff. The proposed DOE approach, together with the DOE agreement to provide the NRC with additional information, acceptably addresses NRC questions so that no information beyond that already provided, or agreed to, will likely be required at the time of initial license application. As discussed in the preceding technical basis, the additional information to be provided by DOE includes

- technical justification for distributions of the 12 parameters listed in table 4-1 of the infiltration uncertainty AMR (CRWMS M&O, 2000d)
- revised infiltration estimates and probability weighting factor for the high-infiltration scenario, to include revised documentation

In addition to meeting the acceptance criteria of the relevant USFIC KTI subissues (U.S. Nuclear Regulatory Commission, 1999), the preceding review also indicates that relevant TSPAI IRSR acceptance criteria for the Climate and Infiltration abstraction (U.S. Nuclear Regulatory Commission, 2000) are met by the proposed DOE approach, pending compliance with the DOE/NRC agreements.

2.5 REFERENCES

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U.S. Nuclear Regulatory Commission. *Issue Resolution Status Report Key Technical Issue: Total System Performance Assessment and Integration*. Revision 3. Washington, DC: U.S. Nuclear Regulatory Commission. 2000.

3 FLOW PATHS IN THE UNSATURATED ZONE

The flow paths in the UZ ISI address effects of subsurface geology and hydrologic processes on the distribution and velocity of flow between the shallow subsurface and the water table at YM.

This chapter provides a review of the abstractions of flow paths in the UZ incorporated by the DOE in its TSPA. The DOE description and technical basis for abstractions of flow paths in the UZ are documented in the UZ flow and transport PMR (CRWMS M&O, 2000a) and numerous AMRs, which also are reviewed to the extent that they contain data or analyses used to support the proposed TSPA abstraction of flow paths in the UZ.

3.1 IMPORTANCE TO SAFETY

The importance of considering flow paths in the UZ at YM can be directly related to two of the principle factors in the current postclosure safety case identified by DOE in the Repository Safety Strategy (CRWMS M&O, 2000b): seepage into emplacement drifts and radionuclide delay through the UZ. Above the proposed repository horizon, it is necessary to adequately understand how the spatial distribution of hydrologic properties in the UZ can affect the spatial and temporal distribution of flow intersecting repository drifts. For example, flow of a given volume of water uniformly distributed in space and time is less likely to drip into an underground opening than if the same volume of water were channeled or focused into a small area above a drift or if the water arrived as a transient pulse. It is thus important that TSPA abstractions adequately address the potential for focused flow or transient high flow rates.

Below the repository horizon it is necessary to understand how the spatial distribution of hydrologic properties may affect the flow paths from the proposed repository horizon to the water table. For example, flow diverted into fast pathways along faults will have short travel times to the water table, and less mineral surface area will be available for sorption of radionuclides. Conversely, flow through sparsely fractured, vitric, nonwelded tuffs will occur mainly in rock matrix with much slower transport velocity and greater exposure of the surface area of mineral grains for radionuclide sorption.

3.2 RELATIONSHIP TO UNSATURATED AND SATURATED FLOW UNDER ISOTHERMAL CONDITIONS KEY TECHNICAL ISSUE

This review of the Flow Paths in the Unsaturated Zone abstraction incorporates subject matter that has been previously reviewed within the framework of the following USFIC KTI subissue:

- Deep Percolation—What is the estimated amount and spatial distribution of percolation through the proposed repository horizon? What are the likely transport pathways from the proposed repository horizon to the regional water table?

3.3 TECHNICAL BASIS

The DOE abstraction approach for flow paths in the UZ for the Viability Assessment was previously reviewed by NRC (U.S. Nuclear Regulatory Commission, 1999). The present review is organized in the following subsections according to the five review methods and associated acceptance criteria identified in the TSPAI IRSR (U.S. Nuclear Regulatory Commission, 2000) for the Flow Paths in the Unsaturated Zone abstraction.

3.3.1 System Description and Model Integration

A detailed, three-dimensional (3D), dual-continuum, mountain-scale numerical process model is used to incorporate the effects of UZ flow into the TSPA analyses. Outputs from the previously discussed nine infiltration process model scenarios are used to develop steady-state flux boundaries for nine discrete flow model realizations corresponding to the low, medium, and high net-infiltration scenarios for each of the three climate states.

A numerical model grid, provides a representation of the complex geology and stratigraphy. The model grid represents the UZ at YM using 32 layers with differing hydrologic properties. These layer dip to the east and are offset by numerous faults that are explicitly considered in the model. As a result, the proposed repository volume transects three different model layers of the Topopah Spring welded tuff (TSw) unit: about 10 percent is in the middle nonlithophysal layer, 78 percent in the lower lithophysal layer, and 12 percent in the lower nonlithophysal layer (CRWMS M&O, 2000c).

Model grids within the Calico Hills nonwelded (CHn) layers are assigned hydrologic properties for either vitric or zeolitically altered rock types. The intralayer variability of hydrologic properties for these layers is necessary to reproduce observations of perched water bodies found primarily in the northern part of the proposed repository area where low-permeability zeolitic rock units predominate. The presence of the perched water bodies creates potential for the lateral flow of water to nearby high-permeability faults. Three-dimensional simulations of flow and radionuclide transport in the northern part indicate that flow in faults increases with depth below the repository horizon so that, over the UZ model domain, more than 40 percent of the deep percolation reaches the water table though faults (CRWMS M&O, 2000a). The percentage of flow from the repository horizon that reaches the water table through faults is not clear in the PMR/AMRs. However, radionuclide transport studies using UZ flow fields from the mean modern infiltration scenario clearly show that rapid flow in fault zones contributes substantially to the predicted arrival this non-sorbing species at the water table (e.g., CRWMS M&O, 2000d, section 6.12).

Output from the site-scale UZ flow model is integrated into TSPA analyses in two ways. First, model predictions of flow reaching the proposed repository horizon in fractures are used to develop maps of percolation flux that, when combined with output from the seepage process model, provide estimates of the fraction of water that seeps into repository drifts and the fraction of waste canisters that receives drips. Second, calculated flow vectors in both fracture and matrix continua are used to delineate nine sets of UZ flow fields from the repository to the SZ, corresponding to the nine infiltration boundary inputs. These steady-state UZ flow fields provide input to the radionuclide transport model, which is executed directly in TSPA simulations.

The UZ PMR and supporting AMRs provide sufficient descriptions of the conceptual model for UZ flow, the UZ model formulation, and methods of integrating the UZ flow model into TSPA analyses. Important design features, physical phenomena, and couplings are adequately incorporated or bounded. Assumptions are clearly stated and used consistently throughout the abstraction of flow paths in the UZ.

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3.3.2 Data are Sufficient for Model Justification

An extensive database is available for rock matrix properties at YM. These properties include moisture retention characteristics, permeability, porosity, and rock density, which are all measured in the laboratory on samples and cores collected from bedrock transects, surface-based boreholes, and alcove, drift, and niche boreholes in the ESF (e.g., Flint, 1998).

Pneumatic pressure signals between boreholes, core saturation data from laboratory measurements, and *in situ* moisture potential profiles from boreholes were used to calibrate the UZ flow model (CRWMS M&O, 2000e). Observations of perched water also are used for UZ flow model calibration. Perched water bodies exist in the north below the potential repository horizon and in the south in the vicinity of Ghost Dance fault. Perched water bodies have been encountered in boreholes at both the vitrophyre between the TSw and CHn units and at the vitric-zeolitic interface (CHnv–CHnz) within the CHn unit. Data from pumping tests were collected to evaluate the spatial extent of the perched water bodies, and water samples were collected for age dating.

Subsurface studies in the underground ESF include data from four alcoves in the North Ramp: Alcove 1 provides access to the upper Tiva Canyon welded unit (TCw), Alcove 2 to the Bow Ridge fault, Alcove 3 to the upper PTn contact, and Alcove 4 to the lower PTn contact. These alcoves were largely used to collect cores, measure air permeability, and sample gases. Alcoves 6 and 7, along the Main Drift, were designed to measure the properties of the Ghost Dance fault. Alcoves 4 and 6 were used to conduct fracture-matrix and fault-matrix interaction tests. Alcove 1 was instrumented with seepage collectors and wall sensors for a large-scale infiltration and seepage test.

Bomb-pulse chlorine-36 data have verified the existence of fast flow from the land surface to the potential repository horizon. A majority of the bomb-pulse signal locations in the ESF and ECRB can be linked with locations where faults cross the PTn, although several have no clear association with faults. It should be noted that investigators at Lawrence Livermore National Laboratory and Los Alamos National Laboratory appear to have collected conflicting data regarding the presence of bomb-pulse chlorine-36 in the ESF. The U.S. Nuclear Waste Technical Review Board has suggested that high priority be given to resolving this conflict.[1] Until the conflict is resolved, however, it is a conservative approach to continue conceptual model development assuming the earlier findings that bomb-pulse chlorine-36 has penetrated to repository depths.

Geochemical data such as total chloride, nonbomb-pulse chlorine-36, and calcite fillings in fractures are used to build confidence in the conceptual and numerical models of flow and transport processes occurring in the mountain and to constrain the predictions of local and global percolation fluxes. This type model validation is discussed further in section 3.3.5.

The available data on geology, hydrology, and geochemistry at YM have been collected using acceptable techniques. Further, the calibrated UZ flow model is generally consistent with the available site-specific data and has been fine tuned to reproduce observations of perched water below the repository horizon.

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[1]U.S. Nuclear Waste Technical Review Board. Letter (June 16) to Dr. Ivan Itkin, Director, Office of Civilian Radioactive Waste Management, U.S. Department of Energy. 2000. A copy can be obtained from www.nwtrb.gov/corr/jlc076.pdf.

3.3.3 Data Uncertainty is Characterized and Propagated through Abstraction

Uncertainties generally exist in the estimated rock and fracture hydrologic properties due to sparse data and limitations of the estimation procedures used. This is particularly true for the fracture and fault properties, such as moisture retention parameters and porosity. Because these properties cannot be readily measured, they were indirectly estimated from other measurements such as air permeability and fracture spacing. Site data are used for initial estimates of most matrix and fracture properties (CRWMS M&O, 2000f). Matrix porosity, fracture porosity, residual saturation, and satiated saturation were fixed prior to calibration, while the remaining properties were further adjusted during the model calibration process. Thus, many of the parameter values used in the flow model are more a product of calibration than of site data analysis (CRWMS M&O, 2000e).

Data to support the values of assigned hydrologic properties of faults are also lacking. Because data from borehole USW UZ-7a, used to characterize Ghost Dance fault, represent the most complete data set from within a fault zone at YM, they are applied to all faults in the UZ model (CRWMS M&O, 2000a). Although this leaves considerable uncertainty that is not propagated through TSPA, it appears that the current assignment of fault properties would tend to be conservative with regard to performance predictions. For example, above the proposed repository, the evidence presently suggests predominantly vertical flow with little lateral diversion toward faults. Thus, fault properties are not expected to play a dominant role in the distribution of water reaching the repository. Below the proposed repository, where perched water is predicted to occur above or within the CHn layer, the UZ model predicts significant lateral diversion of water toward faults where flow to the water table is relatively rapid. The model predicts nearly 40 percent of flow within the entire UZ model domain reaching the water table via fast flow in faults (CRWMS M&O, 2000a). If a similar percentage is applicable to the proposed repository footprint, it would be reasonable to conclude the TSPA model abstraction does not benefit from undue credit for matrix flow below the proposed repository. To further reduce this source of uncertainty, it was agreed at a recent DOE/NRC technical exchange that DOE will provide an analysis of geochemical data used to support model predictions of the flow field below the repository, particularly in the vitric Calico Hills, Prow Pass, and Bullfrog hydrostratigraphic units.[2]

Another potentially important source of data uncertainty is the measurements of *in situ* rock matrix saturations and water potentials used as calibration targets. Saturation data used in the calibration were obtained from rock cores collected *in situ* but analyzed *ex situ*. Corresponding field-based measurements of water content and water potential indicate that laboratory-derived estimates of the water retention relations underpredict saturations. Preliminary monitoring results from the ECRB indicate the rock mass in the proposed repository horizon is wetter (i.e., water potentials are higher) and that moisture is more uniformly distributed than was expected based on earlier rock-core analyses.[3] Also, measurements of water potential taken in surface-based boreholes have gradually reequilibrated to ambient conditions that are much wetter than the data used to calibrate the 3D UZ model. Of concern is that if the more recent measurements are validated, the calibrated UZ site-scale model should be consistent with these findings. Previous difficulties in matching saturations and water potentials may be alleviated by use of the ambient data in the calibration.

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[2]DOE/NRC Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions, Berkeley, CA, August 16–17, 2000.

[3]Craig, R. *Monthly Progress Report for March.* Letter to W. Kozai, Yucca Mountain Site Characterization Office. U.S. Geological Survey, Yucca Mountain Project Branch. 1999.

Due to the complexity of the model and the large number of hydraulic parameters (matrix, fracture, or matrix/fracture parameter values) whose values could change during calibration to match the ambient, wetter conditions, it is not clear what the effect will be on the calibrated property data sets and predicted distributions of flow between fractures and matrix. DOE stated at a recent technical exchange[4] that the updated saturations and water potentials are being used for ongoing and future calibrations; thus, this uncertainty is expected to be reduced in future model iterations.

Input data from the Geologic Framework Model (GFM3.1) (CRWMS M&O, 2000g) are used to develop the UZ flow model grid. The UZ model numerical grids attempt to closely match the GFM3.1 layers. However, because borehole data used to construct GFM3.1 are limited, there is uncertainty in the assumptions regarding lateral continuity and thickness trends of layers at YM. While layers in GFM3.1 represent a valid interpretation, the impact of more lateral discontinuity resulting from the inclusion of small faults on flow could be significant, especially in areas where little or no information has been collected. Areas of sparse data are generally outside the proposed repository area, however, so the effect of this data uncertainty is mitigated. Numerous fault zones and associated layer offsets within the proposed repository area are explicitly included in the UZ model grid. Hence, while considerable uncertainty exists in the accuracy of UZ model grids at any particular location, the model grid sufficiently allows for consideration of important effects on flow of faults and layer discontinuities at the scale and location of the proposed repository.

In summary, several data uncertainties are not explicitly propagated through the TSPA abstraction process. In each case, however, the current DOE approach is reasonably bounding, or the uncertainty is not expected to be of significant importance to performance predictions.

3.3.4 Model Uncertainty is Characterized and Propagated through Abstraction

To account for combined data and model uncertainty, 18 flow fields were originally defined for the basecase TSPA-SR calculations (CRWMS M&O, 2000a). These consisted of three infiltration cases (lower, mean, and upper) within each of the three climate states (present-day, monsoon, and glacial transition), along with two different perched-water conceptual models. The two perched-water models include (i) a permeability-barrier model with reduced permeability in both fracture and matrix elements in the vicinity of the perched water and (ii) an unfractured zeolite model that eliminated fractures in all zeolitic units. Preliminary calculations by DOE showed the difference between the two perched-water models was not significant (CRWMS M&O, 2000a, figure 3.7-17), with the first model being slightly more conservative in predicting early arrival of contaminants. Hence, only the nine flow fields based on the first perched-water model are carried forward to the TSPA-SR.

Other sources of model uncertainty are associated with the many assumptions and simplifications that must be made to model such a complex environment. For example, the assumption of homogenous layers implies that the model grid-block scale is larger than the scale of variability in hydrologic properties (heterogeneity). It is thus assumed that all grid blocks within any layer capture a comparable range of heterogeneity and, therefore, have the same average properties. DOE contends that the calibration process upscales the core-based measurements to the grid scale, thus accounting for intralayer heterogeneity at the subgrid scale. Based on the sparse data available, heterogeneity is not indicated in the PTn at scales larger

[4]DOE/NRC Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions, Berkeley, CA, August 16–17, 2000.

than the grid scale near the repository. Except for the CHn unit, the only heterogeneities considered in the model occur at layer interfaces and where layers are offset by faults. Within the CHn, layers are divided into either vitric or zeolitic rock types—which have significantly different hydrologic properties—based on borehole data and observations of perched water.

CNWRA investigators are presently evaluating potential effects of lateral heterogeneity in the PTn layer on the distribution of flow into the TSw. Work by Ofoegbu et al.[5] indicated heterogeneity in the PTn properties, caused by either depositional or secondary overprinting processes (e.g., small fault, slumping), could lead to increases in localized fluxes at the repository horizon. Currently, however, no evidence exists that such effects dominate flow patterns at YM. The present DOE model predicts considerable lateral variability in the percolation flux reaching the proposed repository horizon (CRWMS M&O, 2000a, figures 3.7-11 and 3.7-12), mainly due to the predicted spatial variability in net surface infiltration.

A potential concern related to the model grid scale is that the vertical length of model grid blocks at layer interfaces is typically much greater than the capillary-rise length scale (approximately the inverse of the van Genuchten alpha parameter). As a result, the numerical model may not be able to represent adequately lateral capillary diversion at layer interfaces. This concern pertains to the PTn–TSw interface, where capillary retention in the PTn matrix may be greater than that of the TSw fracture network. Preliminary modeling by Lawrence Berkeley National Laboratory (LBNL) staff using refined vertical grid discretization has simulated lateral capillary diversion in the PTn.[6] However, there is little objective evidence that this phenomenon is occurring at the site (e.g., high matrix saturation or perched water above the PTn–TSw interface has not been observed). In fact, elevated matrix saturations occur in the uppermost welded unit of the TSw. The difference noted between the highly discretized LBNL preliminary model and observations may be that the model does not incorporate intralayer heterogeneity in the PTn and TSw that could act to interrupt lateral diversion or does not represent adequately the gradational contact between the PTn and the TSw. Alternatively, the difference may be caused by the lack of direct flow connections in the model between the PTn matrix and the underlying TSw fractures. Thus, with present conditions, it is not expected that capillary lateral diversion in the lowermost PTn layer would occur for scales larger than the model grid-block scale. If large-scale lateral diversion was to occur, possibly during future periods of greater infiltration, the likely effect would be to focus the flow into faulted zones. Such an effect could be a benefit to performance if DOE could identify faulted zones at depth and avoid placement of waste packages in those areas. Both DOE and CNWRA researchers continue to investigate the potential for and possible effects of lateral capillary diversion in the PTn. The permeability barrier at the TCw–PTn contact also is being analyzed to assess the potential for lateral diversion above the PTn where core data from surface-based boreholes indicate significantly elevated matrix saturations, including local saturation, in the lowermost TCw layer. At present, however, it does not appear that failure to consider this process will result in overly optimistic performance predictions.

The appropriateness of the model grid scale is also a concern at the potential repository horizon where model predictions of the distribution of deep percolation flux are used as input to the drift-scale seepage process model. These percolation fluxes represent averages for entire grid blocks, which have scales of hundreds of meters, whereas percolation flux in any single grid block is likely to occur within only a small

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[5]Ofoegbu, G.I., S. Painter, R. Chen, R.W. Fedors, and D.A. Ferrill. Geomechanical and thermal effects on moisture flow at the proposed yucca mountain nuclear waste repository. *Nuclear Technology*. In press. 2001.

[6]Bodvarsson, G.S. *Presentation at the DOE/NRC Technical Exchange and Management Meeting on Radionuclide Transport*, October 31–November 2, 2000. Berkeley, CA. 2000.

fraction of the grid-block area. This potential bias could be taken into account, however, by appropriate use of the flow focusing factor in the seepage model, reviewed in section 4.3 of this report.

Another important model uncertainty lies in the use of a steady-state infiltration boundary, which rests on the assumption that the PTn layer acts to completely attenuate the infrequent pulses of infiltration predicted by the infiltration model. Indeed, DOE researchers have conducted modeling to demonstrate the validity of this assumption (e.g., CRWMS M&O, 1998, section 2.4.2.8). Although these transient-flux models support the steady-state assumption, those presented to date have not used infiltration pulses that average more than 5 mm/yr during the long-term; yet infiltration during future climates may exceed 30 mm/yr over the proposed repository (CRWMS M&O, 2000a, figure 3.7-11). Preliminary results of modeling conducted at CNWRA indicate that, although the PTn layer greatly attenuates episodic infiltration, transient percolation flux may occur at repository depth for infiltration pulses that occur every 5 yr and average 10 mm/yr for the long term. This concern was related at a recent DOE/NRC technical exchange,[7] and DOE agreed to provide additional documentation for the steady-state infiltration assumption. NRC staff agreed this concern could be allayed if such documentation is provided.

3.3.5 Model Abstraction Output is Supported by Objective Comparisons

The low-, medium-, and high-infiltration scenarios for the UZ flow model are calibrated using 1D and 2D inverse methods to match observations of pneumatic signals between boreholes, core saturation data from laboratory measurements, and *in-situ* moisture potential profiles (CRWMS M&O, 2000e). Additional fine tuning of the model was performed to match observations of perched water associated with the CHn layer. Thus, the flow model scenarios are reasonably consistent with those observations. However, supporting data for the predicted flow vectors within, adjacent to, and below the perched water were not presented in the PMR of AMRs. DOE agreed during a recent UZ flow technical exchange[8] to provide documentation of the analysis of available data to validate the predicted 3D UZ model flow fields below the repository footprint, particularly below the perched water or through the vitric CHn, Prow Pass, and Bullfrog hydrostratigraphic units.

Additional model validation was obtained by DOE from two modeling exercises to show that the UZ flow model is broadly consistent with the observed distribution of calcite minerals in Well WT-24 and with chloride concentrations in the subsurface. Geochemical modeling of calcite precipitation was conducted to provide validation of deep percolation rates simulated in the UZ flow model (CRWMS M&O, 2000h). The result was, that for a range of infiltration rates 2–20 mm/yr, simulated calcite distributions agree reasonably well with measured data from Well WT-24 cuttings. The DOE modelers assume the amount of calcite precipitation generally increases as percolation increases. The simulated calcite abundances also are sensitive to the assumed water and gas chemistry, vapor movement, reaction kinetics, and mineralogy. The analysis provides some constraints on hydrological parameters and percolation flux and on additional evidence for validation of the flow and transport model. This analysis cannot give a definite value or a narrow range of values, however, because of the dependence of calcite deposition on the other factors.

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[7]DOE/NRC Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions, Berkeley, CA, August 16–17, 2000.

[8]Ibid.

Another simulation was conducted to compare the basecase UZ flow model with observed chloride data from the ESF and ECRB. Chloride concentrations from the steady-state transport simulation were compared with measured pore-water chloride concentration data (CRWMS M&O, 2000h). The results indicate that measured chloride concentrations show a smaller range than predicted by the modern infiltration rates during steady-state conditions (CRWMS M&O, 2000a, figure 3.8-3). However, because many measured chloride concentrations are fit closely by the model results, it appears the mean infiltration rate is approximately correct. Differences between measured and modeled chloride concentration in the high- and low-infiltration regions suggest the time-averaged infiltration rates may be more uniform than predicted by the UZ flow model. Conversely, L. Flint[9] correlated the systematic measurements of water potential in the ECRB, chloride concentration of matrix pore water to shallow infiltration estimates. It was found percolation estimates from water potential data and from the CMB method both matched the magnitude and heterogeneity of the highly discretized shallow infiltration model results, except under washes where the model underpredicted percolation estimates from the ECRB data. The shallow infiltration model uses grids on length scale equal to 30 m, while the minimum length of the 3D UZ model grids is 100 m. Thus, it is not clear whether the systematic data collected in the ESF and ECRB support the 3D UZ model.

The site-scale UZ flow model of YM is broadly consistent with the DOE interpretations of empirical observations. Due to model complexity, however, alternate interpretations of these observations are possible and model parameters can be adjusted to match a wide range of possible results. Thus, the importance of propagating data and model and data uncertainty through the abstraction, as discussed in the preceding sections, is apparent.

3.4 STATUS AND PATH FORWARD

The Deep Percolation subissue of the USFIC KTI, which pertains to the Flow Paths in the UZ abstraction, is presently considered closed-pending. That is, NRC staff have confidence that the DOE proposed approach, together with the DOE agreements to provide the NRC with additional information (through specified testing, analysis, and the like) acceptably address NRC questions so that no information beyond that provided, or agreed to, will likely be required at time of initial license application. Additional documentation for this status of the Deep Percolation subissue is provided in chapter 4 of this report.

DOE agreements to provide additional information and analyses pertaining to flow paths in the UZ include the following:

- Complete ongoing and planned testing in the ESF and ECRB identified at the DOE/NRC Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions, August 16–17, 2000, Berkeley, California

- Provide final documentation for the effectiveness of the PTn to dampen episodic flow, including reconciling the differences in chloride-36 studies

- Provide the analysis of geochemical data used to support the flow field below the repository

[9]Flint, L. Measuring flow and transport in unsaturated fractured rocks: A large-scale unsaturated flow experiment. *Presentation to Geological Society of America.* November 13–17, 2000. Reno, NV. 2000.

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The conclusions of this review pertain only to the Deep Percolation subissue of the USFIC KTI. Before a determination can be made whether the TSPAI IRSR acceptance criteria for the Flow Paths in the Unsaturated Zone abstraction (U.S. Nuclear Regulatory Commission, 2000) are met by the proposed DOE approach, additional review is required to determine if subissues of the SDS and TEF KTIs pertaining to UZ flow are satisfied.

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4 QUANTITY AND CHEMISTRY OF WATER CONTACTING WASTE PACKAGES AND WASTE FORMS

The purpose of this review is to ensure that DOE adequately considers in the TSPA analyses potential effects that the quantity and chemistry of water potentially contacting waste packages and waste forms at YM may have on repository performance during the proposed 10,000-yr regulatory compliance period. Of specific interests toward addressing concerns of the USFIC KTI, is the amount and spatial distribution of water seepage into repository drifts during isothermal conditions (i.e., following the period of elevated temperature caused by waste-generated heat due to radioactive decay). The DOE description and technical basis for TSPA abstractions for seepage into drifts are documented in the UZ flow and transport PMR (CRWMS M&O, 2000a). Three supporting AMRs also are particularly relevant to this topic: Abstraction of Drift Seepage (CRWMS M&O, 2000b), Seepage Calibration Model and Seepage Test Data (CRWMS M&O, 2000c), and Seepage Model for PA Including Drift Collapse (CRWMS M&O, 2000d). Other AMRs also are reviewed to the extent they contain data or analyses used to support or develop this TSPA abstraction.

4.1 IMPORTANCE TO SAFETY

The importance of considering the quantity and chemistry of water potentially contacting waste at YM is directly related to three of the principal factors of the current postclosure safety case identified by DOE in the Repository Safety Strategy (CRWMS M&O, 2000e): seepage into emplacement drifts, performance of the drip shield/drift invert system, and performance of the waste package. Because the scope of this review is limited to the USFIC KTI, this review is focused only on the first of these principal factors—seepage into emplacement drifts—referred to hereafter as drift seepage.

Drift seepage is important to repository performance for two reasons. First, in the absence of a disruptive process such as human intrusion or volcanism, water passing through drifts is the only means by which radionuclides from waste could be transported away from the proposed repository to the accessible environment. Second, the quantity and chemistry of water contacting drip shields and waste packages affects the predicted rate of waste-package corrosion.

4.2 RELATIONSHIP TO KEY TECHNICAL ISSUE SUBISSUES

This review of the Quantity and Chemistry of Water Contacting Waste Packages and Waste Forms abstraction incorporates subject matter that has been previously reviewed within the framework of the following USFIC KTI subissue:

- Deep Percolation—What is the estimated amount of diversion of deep percolation away from waste package footprints?

4.3 TECHNICAL BASIS

The DOE abstraction approach for the drift seepage was previously reviewed by NRC for the Viability Assessment (U.S. Nuclear Regulatory Commission, 1999). The present review is organized in the following subsections according to the five generic acceptance criteria identified in the TSPAI IRSR (U.S. Nuclear Regulatory Commission, 2000) for the Quantity and Chemistry of Water Contacting Waste Packages and Waste Forms abstraction.

4.3.1 System Description and Model Integration

DOE acknowledges that accurate prediction of seepage from fractures into underground openings is an extremely difficult endeavor, and many of the physical processes that may affect seepage rates are poorly understood. Hence, DOE does not expect to accurately predict either individual seepage events or the precise spatial distribution along the emplacement-drift axis or the drift ceiling. Rather, the approach taken is aimed at yielding robust, conservative seepage estimates for a wide range of hydrologic conditions (CRWMS M&O, 2000a).

The development of the seepage abstraction begins with the Seepage Calibration Model (CRWMS M&O, 2000c), which incorporates results from air-permeability and liquid-release tests from Niche 3650 of the ESF to develop a methodology for the subsequent development of seepage process models. Making use of those results, the Seepage Model for TSPA (CRWMS M&O, 2000d) was developed to provide seepage estimates for a variety of hydrologic properties and drift shapes. Finally, the seepage abstraction (CRWMS M&O, 2000b) was developed to evaluate seepage into drifts for TSPA simulations.

The Seepage Model for TSPA consisted of probabilistic analyses for seepage flux over a model domain representing a 5.23-m drift segment. These analyses were used to develop two transfer functions for the seepage abstraction. The first transfer function is a relationship between percolation flux and the fraction of waste package locations onto which seepage occurs (seepage fraction). The second transfer function describes a relationship between percolation flux and the seepage flux that enters those drift segments that receive seepage (seepage flux).

To integrate the seepage abstraction with the UZ flow model, the maps of repository percolation flux developed from the flow model are divided into six subregions. Area-averaged fluxes for each subregion are used as input to the seepage abstraction. Potential focusing of flow from the large-scale subregions to the scale of an individual drift segment is accounted for by multiplying the average flux by a stochastic flow-focusing factor, which is intended to account for flow focusing on intermediate scales (tens of meters). It should be noted that the AMR on abstraction of drift seepage (CRWMS M&O, 2000b) does not provide sufficient information how this potentially important factor is calculated, other than stating it is based on the active fracture conceptual model of Liu et al. (1998) and showing the resulting seepage-fraction and seepage-flux transfer functions. Thus, NRC should consider requesting additional documentation from DOE to explain how flow focusing-factors are calculated.

In addition to the focusing factor, other adjustments were made to seepage flow rate estimates to account for changes in drift geometry, presence of rock bolts, and possible parameter correlations (CRWMS M&O, 2000d). One adjustment to the seepage flow rate was made to account for the effects of changes in the drift shape due to rockfall. DOE simulations using the Seepage Model for TSPA suggested a moderate increase of drift seepage as a result of partial drift degradation. Accordingly, seepage flow rates were increased by a factor of 1.55 to account for the effects from partial drift degradation and rock bolts. Seepage flow rates were further increased by 10 percent to account for potential correlation between fracture network permeability and the van Genuchten α parameter (related to capillary retention). These adjustment factors are based on results obtained from alternative scenario modeling (CRWMS M&O, 2000d). For example, seepage estimates from alternative models with correlated permeability and α parameters were 0–10 percent higher than the noncorrelated model; thus, rather than incorporate the correlated seepage model into the abstraction, DOE simply increased the current abstraction estimates by the upper end of this range, 10 percent.

In general, the UZ PMR and supporting AMRs provide a sufficient description of the conceptual model for seepage into drifts, the seepage process model formulation, and the approach to integrating the seepage model into TSPA analyses. A notable exception, however, is that insufficient documentation is provided to explain how the focusing factor for seepage is calculated and incorporated into the seepage abstraction. For predicting the amount of seepage during isothermal conditions, the approach incorporates important design features, physical phenomena, and couplings. Assumptions are clearly stated and used consistently throughout the abstraction. As discussed in the following subsections, however, although the proposed DOE approach appears to incorporate the important processes, the mathematical description of those processes remains a difficult endeavor, and it is not clear that parameter and modeling uncertainty has been adequately bounded. Further, additional review and input from the ENFE and TEF KTIs are required to determine whether the abstraction adequately incorporates or bounds processes and couplings affecting both water chemistry and the amount of seepage during periods of elevated repository temperature.

4.3.2 Data are Sufficient for Model Justification

Data from Niche 3650 seepage tests are used to evaluate the capillary barrier and the seepage threshold (zero seepage below a threshold percolation flux) conceptual models and to provide estimates of fracture-network, moisture-retention properties. These data include air permeability and measurements of injected aqueous dye tracers released as pulses above the ceiling of Niche 3650 (CRWMS M&O, 2000f). The observed distribution of tracers arriving at the ceiling of the niche was sampled to evaluate spatial distributions of flow paths associated with the wetting-front movement through the fractures. These data are used in inverse models to estimate hydrologic properties for fracture networks surrounding drifts.

DOE researchers interpret the seepage test data to indicate that seepage thresholds may be much larger than the percolation fluxes predicted by the UZ flow model (CRWMS M&O, 2000c). NRC and CNWRA staffs have previously commented, however, that conclusions drawn from Niche 3650 seepage tests potentially could be biased by ventilation dryout, the close proximity of the injection boreholes to the Niche ceiling, and by injection rates much greater than ambient percolation flux (e.g., U.S. Nuclear Regulatory Commission, 1999). Several ongoing tests at YM, if conducted carefully, may address NRC and CNWRA concerns. These tests include the Alcove 8-Niche 3 test and the ECRB passive monitoring test. In the Alcove 8-Niche 3 test, tracer-bearing water is to be applied to areas in Alcove 8 of the ECRB, about 10 m directly above Niche 3 of the ESF. This test covers a relatively large scale (compared to previous tests) and is sealed off from ventilation. Of perhaps greater interest is the ongoing passive monitoring test in an approximately 1-km section of the ECRB that has been sealed off from ventilation (except for periodic entry to maintain equipment) and is continuously monitored to evaluate when this zone has returned to ambient conditions.

In a recent DOE/NRC technical exchange,[1] DOE agreed to complete and provide documentation of results from the ongoing seepage studies in the subsurface of YM. NRC staff agreed these additional data, combined with the existing information, is likely to provide sufficient basis to make a decision regarding the adequacy of data used to justify the DOE abstraction of drift seepage in the TSPA.

[1]DOE/NRC Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions, Berkeley, CA, August 16–17, 2000.

4.3.3 Data Uncertainty is Characterized and Propagated through Abstraction

Spatial variability of air permeability data and the inability to directly measure moisture-retention properties of fracture networks produce uncertainty in the parameters k and α used in the Seepage Model for TSPA, where k is fracture network permeability and α is a moisture-retention parameter (called van Genuchten's alpha) related inversely to air-entry pressure. In addition to the uncertainty in the appropriate range of values for these parameters is the uncertainty in their spatial distribution. Accordingly, uncertainty in two additional model parameters is considered: the standard deviation, σ, of the logarithm of fracture network permeability; and the spatial correlation length, λ, for fracture permeability. These two parameters are used to generate random spatial heterogeneity for permeabilities assigned to the seepage model grid cells.

The range of fracture permeability considered for k is from 0.9×10^{-14} to 0.9×10^{-11} m^2. This range is based on data from air permeability tests at Niche 3650, which indicate a mean permeability of 2.2×10^{-12} m^2. The low end of the range is consistent with host permeability measurements measured elsewhere in the ESF not affected by drift excavation; the high end of the range accounts for uncertainty in the degree of enhanced permeability due to excavation effects (CRWMS M&O 2000d, section 6.3.2). This range of k values is also consistent with the range of permeability measurements reported by LeCain (1997) for the TSw middle nonlithophysal layer and, thus, seems reasonably to bound uncertainty in this parameter for the seepage process model. However, it is not yet established whether this range also includes or appropriately bounds variability in the lower lithophysal unit.

To incorporate uncertainty in the α parameter, four values were used: $1/\alpha$ = 30, 100, 300, and 1000 Pa. This range of values is somewhat arbitrary, but as discussed in the AMR, it brackets values used in previous modeling studies (CRWMS M&O, 2000d, section 6.3.4). Spatial variability of α is not considered for TSPA abstraction. That is, for any particular process model realization used to develop the TSPA abstraction, α was assumed constant throughout the entire model domain. DOE researchers did, however, investigate the sensitivity to spatial variability of α by evaluating a limited number of cases with α correlated to permeability. It is interesting to note that the correlated α condition yielded higher seepage by 0–10 percent (CRWMS M&O, 2000d). For this reason, seepage values used for the TSPA abstraction are increased by 10 percent to allow for possible spatial correlation. One factor that should be considered is the value of α at the drift-fracture interface is a function of fracture aperture and, hence, can vary considerably for scales of only a few centimeters. Because dripping is more likely to occur where water encounters an increased fracture aperture, DOE should demonstrate that the values of α used to develop the abstraction are consistent with the largest apertures typical for the grid-block scale. From the information presented by DOE so far, is not clear that the uncertainty in this important parameter has been incorporated adequately in the TSPA abstraction.

Three alternatives, σ = 1.66, 1.93, and 2.5, were used to account for uncertainty in the standard deviation in fracture permeability used to incorporate random heterogeneity. The low value is based on data from Niche 3650 tests (CRWMS M&O, 2000c, table 5); the two higher values span a value of 2.1 estimated in a modeling study by Birkholzer et al. (1999). Note that higher values of σ represent stronger heterogeneity that would produce greater opportunity for local seepage. The values of σ considered seem reasonably to bound uncertainty. For example, the σ value of 2.5 would produce a distribution of permeability values that could vary spatially ten orders of magnitude (i.e., approximately 95 percent of assigned permeability values will be within a range of $\pm 2\sigma$ from the mean log-k value). Niche 3650 air perms ranged from 1.53e-15 to 1.27e-10 m^2—about 5 orders of magnitude (CRWMS M&O, 2000c, table 5).

Uncertainty in the correlation length scale, λ, for heterogeneity in fracture network permeability is not propagated through TSPA abstraction. In the AMR for seepage testing data (CRWMS M&O 2000c, section 6.3.2), DOE investigators suggest that permeability is essentially random without a noticeable spatial correlation. Thus, to develop the TSPA abstraction, heterogeneous fields for the seepage model were developed with λ equal to a grid size of 0.5 m (CRWMS M&O, 2000d). To further support this approach, process-level sensitivity studies were conducted with values of $\lambda = 1$ and 4 m. Results suggest that seepage increases with increased λ; hence, the DOE approach of neglecting spatial correlation of permeability may bias seepage predictions to be too low. Although DOE researchers cite data suggesting no spatial correlation beyond the grid-block scale, those data represent only one small Niche and, owing to the data uncertainty, also have been interpreted to show a correlation scale of nearly 4 m (CRWMS M&O, 2000c). Another potentially important uncertainty is the presence of spatial correlation anisotropy due to the presence of subvertical high permeability fractures. The presence of subvertical high permeability fractures could provide conduits for preferential flow toward drifts with a potentially reduced capacity for lateral capillary diversion that is not considered in the DOE abstraction.

To propagate into TSPA the uncertainty in parameters discussed previously, 576 seepage model scenarios were developed, corresponding to four α values, four average-*k* values, three σ values, three realizations of random heterogeneity, and four percolation fluxes. Results were used to define transfer functions for seepage fraction and seepage flux as functions of percolation flux (CRWMS M&O, 2000b). It should be noted that only three realizations of random heterogeneity may not give a statistically meaningful range of results.

In summary, there are several concerns related to the propagation of data uncertainty into the abstraction of drift seepage for TSPA. These concerns relate to the range and spatial variability of the moisture-retention α parameter; the spatial correlation length for permeability, λ; possible spatial correlation anisotropy; and the limited number of random heterogeneity realizations. Sensitivity studies by DOE show that reasonable assumptions regarding some of these parameters can result in significantly increased seepage flux predictions. To address these concerns, DOE has proposed[2] to use results of ongoing *in-situ* field studies to demonstrate the range of uncertainty propagated through the seepage model abstraction provides a conservative bound on the amount and distribution of water that may contact waste packages and waste forms during isothermal conditions. These proposed validation studies are discussed in section 4.3.5.

4.3.4 Model Uncertainty is Characterized and Propagated through Abstraction

There are many model uncertainties in the Seepage Model for TSPA. To begin, the model consists of uniformly sized grid cells of 0.5 × 0.5 × 0.5 m, which implies an assumption that this volume contains a sufficient number of interconnected fractures to treat the fracture network as a 3D continuum. The validity of this assumption is diminished in areas where spacings between water-bearing fractures are greater than few tens of centimeters. As a result, the model may fail to predict dripping that would occur where a drift is intersected by a water-bearing fracture that is not connected to any other fractures at the drift interface.

Another important model uncertainty is whether the use of the van Genuchten-Mualem model for moisture retention and relative permeability is adequate to model unsaturated flow in a fracture network. For the rather low UZ percolation fluxes predicted for YM, film flow may be the dominant flow regime. Film

[2]DOE/NRC Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions, Berkeley, CA, August 16–17, 2000.

flow is a term used to describe flow on fracture surfaces that does not bridge the fracture aperture. Conditions that affect capillary diversion and dripping may be quite different for film flow than are currently modeled. This is one reason for concern that parameter estimates obtained from the relatively high flow rate injection tests in Niche 3650 may not be applicable to ambient repository conditions. At the recent DOE/NRC technical exchange on UZ flow,[3] DOE agreed to either consider film flow processes in the seepage abstraction or provide justification that the current model approach is adequate to bound this uncertainty.

Modeling assumptions used to estimate the adjustment factor of 1.55 for increased seepage flux due to rock-bolts and changes in drift-geometry represent another source of model uncertainty. The effect of drift collapse on seepage rates should account for the scale of asperities in drift geometry caused by rockfall, but the grid scale of the process-model used to estimate this factor is not sufficiently small to address this concern. Scales comparable to the inverse of the van Genuchten alpha parameter are appropriate, so that seepage is not under-predicted for small scale asperities.

DOE process modeling predicts seepage fractions to be higher when percolation flux is episodic (CRWMS M&O, 2000d, section 6.6.7), but the UZ PMR suggests high-frequency fluctuations of infiltration will not reach the potential repository because the PTn layers attenuate transient flow. As discussed in section 3.3.3 of this report, however, the process models used to support this suggestion use average infiltration rates much lower than those expected for future climates. Thus, the validity of the steady-state flow assumption in seepage process models remains an important source of uncertainty that is not propagated through TSPA abstraction. As previously mentioned, DOE agreed to provide additional justification for the steady-state flow assumption.

4.3.5 Model Abstraction Output is Supported by Objective Comparisons

A rigorous demonstration that the Seepage Model for TSPA abstraction is valid for its intended purpose would require testing model results against relevant data not used in the original development of the model. For the Seepage Model for TSPA, these data should include percolation flux at low flow rates for periods of years, even hundreds of years, in many locations in the repository. Unfortunately, such data are not available. Further, data for adequate validation would need to include the wide range of conditions such as drift degradation and collapse with time; and those are not available either. DOE agreed in the recent DOE/NRC technical exchange on UZ flow[4] to conduct and provide results from additional field studies to provide increased confidence for the abstraction approach. Of particular importance is an ongoing field test in the ECRB in which an approximately 1-km section of the tunnel has been sealed off from ventilation and is being allowed to return to ambient conditions. Results from this passive test may not be adequate to rigorously validate the seepage abstraction, but if no seepage is detected for present-day conditions, the test would provide evidence that the current approach used by DOE is bounding in the sense that current seepage predictions are conservative. DOE also has agreed[5] to consider smaller scale tunnel irregularities in drift collapse or justify that the current approach is adequate.

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[3]DOE/NRC Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions, Berkeley, CA, August 16–17, 2000.

[4]Ibid.

[5]Ibid.

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4.4 STATUS AND PATH FORWARD

The Deep Percolation subissue of the USFIC KTI, which pertains to the flow paths in the UZ abstraction, is presently considered closed-pending. That is, NRC staff have confidence that the DOE proposed approach, together with the DOE agreements to provide NRC with additional information (through specified testing, analysis, and the like) acceptably address NRC questions so that no information beyond that provided, or agreed to, will likely be required at time of initial license application.

DOE agreements to provide additional information and analyses regarding the quantity of water potentially contacting waste packages include the following:

- Complete ongoing and planned testing in the ESF and ECRB identified at the DOE/NRC Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions, Berkeley, California, August 16–17, 2000.

- Include the effect of low-flow regime processes (e.g., film flow) in the DOE seepage fraction and seepage flow, or justify that this effect is not needed.

- When conducting seepage studies, consider smaller scale tunnel irregularities in drift collapse, or justify, they are not needed.

The conclusions of this review pertain only to the Deep Percolation subissue of the USFIC KTI. Before a determination can be made whether relevant TSPAI IRSR acceptance criteria for the Quantity and Chemistry of Water Contacting Waste Packages and Waste Forms abstraction (U.S. Nuclear Regulatory Commission, 2000) are met by the proposed DOE approach, additional review is required to determine if subissues of the ENFE and TEF KTIs are satisfied.

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5 CONCLUSION

Using review methods and acceptance criteria outlined in the TSPAI IRSR, the preceding review provides documentation of the status of resolution of the USFIC KTI subissues related to unsaturated flow at YM. The USFIC KTI subissues reviewed (Climate Change, Hydrologic Effects of Climate Change, Present-Day Shallow Infiltration, and Deep Percolation) are presently considered closed or closed-pending. That is, NRC staff have confidence that the proposed DOE approach, together with DOE agreements to provide the NRC with additional information (through specified testing, analysis, and the like) acceptably address NRC questions so that no information beyond that provided, or agreed to, will likely be required at the time of initial license application.

Additional input from other KTIs is required to determined whether all acceptance criteria for the relevant TSPAI model abstractions have been met by DOE. These KTI inputs include Thermal Effects on Flow, and Seismicity, Evolution of the Near-Field Environment, and Radionuclide Transport. The reviews contained in this report, combined with additional reviews of subissues from those KTIs, will provide useful technical bases for the Sufficiency Review Comments that will be developed by NRC after publication of the DOE-SR. The combined reviews also will provide the framework for an integrated IRSR that documents the status of resolution for all KTIs.