APPENDIX K

INTEGRATION BETWEEN THREE-DIMENSIONAL UNSATURATED ZONE FLOW, MULTISCALE THERMAL-HYDROLOGIC, AND DRIFT SEEPAGE MODELS (RESPONSE TO TSPAI 3.11 AND GEN 1.01 (COMMENT 82))

Note Regarding the Status of Supporting Technical Information

This document was prepared using the most current information available at the time of its development. This Technical Basis Document and its appendices providing Key Technical Issue Agreement responses that were prepared using preliminary or draft information reflect the status of the Yucca Mountain Project's scientific and design bases at the time of submittal. In some cases this involved the use of draft Analysis and Model Reports (AMRs) and other draft references whose contents may change with time. Information that evolves through subsequent revisions of the AMRs and other references will be reflected in the License Application (LA) as the approved analyses of record at the time of LA submittal. Consequently, the Project will not routinely update either this Technical Basis Document or its Key Technical Issue Agreement appendices to reflect changes in the supporting references prior to submittal of the LA.

APPENDIX K

INTEGRATION BETWEEN THREE-DIMENSIONAL UNSATURATED ZONE FLOW, MULTISCALE THERMAL-HYDROLOGIC, AND DRIFT SEEPAGE MODELS (RESPONSE TO TSPAI 3.11 AND GEN 1.01 (COMMENT 82))

This appendix provides a response for Key Technical Issue (KTI) agreement Total System Performance Assessment and Integration (TSPAI) 3.11 and General Agreement (GEN) 1.01 (Comment 82). These agreements are related to integration between the three-dimensional unsaturated zone flow model, the multiscale thermal-hydrologic model, and the drift seepage models.

K.1 KEY TECHNICAL ISSUE AGREEMENTS

K.1.1 TSPAI 3.11 and GEN 1.01 (Comment 82)

TSPAI 3.11 was reached during the U.S. Nuclear Regulatory Commission (NRC)/U.S. Department of Energy (DOE) Technical Exchange and Management Meeting on TSPAI held August 6 to 10, 2001, in Las Vegas, Nevada (Reamer 2001a), which was convened to discuss four TSPAI KTI subissues: (1) system description and demonstration of multiple barriers; (2) scenario analysis within the total system performance assessment (TSPA) methodology; (3) model abstraction within the TSPA methodology; and (4) demonstration of the overall performance objective. During the course of the meeting, agreement TSPAI 3.11 was reached in the area of Subissue 3.

Agreement GEN 1.01 was reached during the NRC/DOE Technical Exchange and Management Meeting on Range of Thermal Operating Temperatures, held September 18 to 19, 2001 (Reamer 2001b). At that meeting, NRC provided additional comments, resulting in GEN 1.01 (Comment 82), which pertains to uncertainties regarding evaporation effects and drift degradation.

The wording of the agreements is as follows:

TSPAI 3.11[1]

> DOE should account for appropriate integration between the 3D UZ flow model, the MSTH model, and the drift seepage model. In particular, DOE should ensure that relevant spatial distributions are propagated appropriately between the UZ flow model, the thermohydrology model, and the seepage model (ENG3.1.6). DOE will compare the infiltration flux used for the infiltration bins with the 3D Unsaturated Zone flow model and the multi-scale thermohydrologic (MSTH) model results. The technical basis for any approximations in the spatial distribution of flow rates involved in this abstraction will be provided in Abstraction of NFE Drift Thermodynamic Environment and Percolation Flow AMR (ANL-EBS-HS-000003) or other suitable document. In particular, DOE

[1] ENG3.1.6 in this agreement refers to item 3.6 of NRC integrated subissue ENG3 on quantity and chemistry of water contacting waste packages and waste forms (NRC 2002, Table 1.1-2). This item addresses the NRC's concern regarding the spatial integration of percolation flux and seepage.

will ensure that the MSTH model output to the seepage abstraction (or any other model that may provide percolation flux to the seepage abstraction) does not lead to underestimation of seepage. This AMR is expected to be available to NRC in FY 2003.

GEN 1.01 (Comment 82)[2]

More comments on the abstraction of uncertainty:

Page 4-6: Uncertainties regarding evaporation effects were addressed by selecting conservative parameter sets in the seepage abstraction. This type of procedure to address uncertainty is problematic at best and typically a source of great error. To address uncertainty in this manner, suggests one knows what the impact of the uncertainty being addressed is. If the seepage experiments are significantly in error due to this type of bias, addressing uncertainty in this manner is unlikely to capture the impact.

[Page 4-8, Remaining unquantified uncertainties (specifically regarding spatial variability of seepage-relevant rock properties, local percolation flux distribution, and the impact of design decisions regarding ventilation, thermal loading, repository extent, and drift orientation) were addressed through appropriately broadened uncertainty distributions and conservative modeling in the abstraction.]

Page 4-38: In addition, the calculated seepage increases are small enough that they are well within the ranges of variability and uncertainty in seepage, as determined in the seepage abstraction for TSPA-SR. The increases may be within the original range of uncertainty and variability, but the changes would influence the mean result, therefore a quantitative comparison is warranted.

DOE Initial Response to GEN 1.01 (Comment 82)

This issue has been recognized as "to be verified" in AMR Seepage Calibration Model & Testing Data. DOE will address the issue consistent with KTI agreement TSPAI 3.11.

K.1.2 Related Key Technical Issue Agreements

KTI agreements Thermal Effects on Flow (TEF) 2.04, TEF 2.05, and TSPAI 3.27 are related to KTI agreement TSPAI 3.11. TEF 2.04 requires the issuance of the report documenting the multiscale thermal-hydrologic model (BSC 2004a), and TEF 2.05 requires the inclusion of the cold trap analyses in that report (BSC 2004a). TSPAI 3.27 provides an overview of water flow rates used in the unsaturated zone model above and below the repository, in the multiscale thermal-hydrologic model, in the seepage abstraction, and in the in-drift flow path models.

[2] The page numbers indicate pages of *FY 01 Supplemental Science and Performance Analyses, Volume 1: Scientific Bases and Analyses* (BSC 2001a).

K.2 RELEVANCE TO REPOSITORY PERFORMANCE

The three-dimensional unsaturated zone flow model, the multiscale thermal-hydrologic model, and the drift seepage models are abstracted for the total system performance assessment (TSPA). In particular, ambient seepage, thermally driven seepage, and unsaturated zone flow discussed in TSPAI 3.11 are relevant to the repository performance because the abstraction of seepage and the associated parameter values are directly used in TSPA calculations and in the evaluation of the capillary barrier. In addition, flow and transport through the unsaturated zone play an important part in the assessment of total system performance, because the unsaturated zone is one of the key features of the natural barriers upon which the repository relies.

K.3 RESPONSE

Agreement TSPAI 3.11 pertains to the appropriate integration of spatial distribution of fluxes between the three-dimensional unsaturated zone flow model, the multiscale thermal-hydrologic model, and the drift seepage models (i.e., seepage abstraction model and supporting process models). The three-dimensional unsaturated zone flow model (Section K.4.1.1) is a process model that describes flow in the unsaturated zone of Yucca Mountain extending from beneath the surficial soils to the top of the groundwater table. Because of the large size of the model domain, the model utilizes relatively large gridblocks, on the order of 100 m, compared to submeter gridblock sizes used in drift-scale models. The model consists of numerous layers representing different stratigraphic units with layer-averaged thermal-hydrologic properties (e.g., Bodvarsson et al. 1999; Wu et al. 1999; Wu et al. 2002; BSC 2003a; BSC 2004b).

The multiscale thermal-hydrologic model (Section K.4.1.2) is composed of three drift-scale and one mountain-scale submodels. The drift-scale submodels are: (a) the one-dimensional, smeared-heat-source, drift-scale thermal-conduction (SDT) model; (b) the two-dimensional, line-average-source, drift-scale thermal-hydrologic (LDTH) model; and (c) the three-dimensional, discrete-heat-source, drift-scale thermal-conduction (DDT) model. The mountain-scale submodel is a smeared heat source, thermal conduction-only model (SMT). The multiscale thermal-hydrologic model derives its conceptual basis, as well as its stratigraphic units and their properties, from the three-dimensional unsaturated zone flow model (BSC 2004a).

The drift-scale seepage models (Section K.4.1.3) include (a) the seepage calibration model (Section K.4.1.3.1; BSC 2004c), (b) the seepage model for performance assessment (Sections K.4.1.3.2 and K.4.1.3.3; BSC 2004d), (c) the thermal-hydrologic seepage model (Section K.4.1.3.3; BSC 2003b), (d) the thermal-hydrologic-chemical seepage model (Section K.4.1.3.3; BSC 2003c), and (e) the abstraction of drift seepage (BSC 2004e).

The spatial distributions of percolation flux at the mountain scale were integrated across the three models three-dimensional unsaturated zone flow model, multiscale thermal hydrologic model, and drift-scale seepage models) by utilizing the percolation fluxes at the PTn–TSw interface predicted by the three-dimensional unsaturated zone flow model during the three climatic regimes (present-day, monsoon, and glacial-transition) (Sections K.4.2.1.1 and K.4.2.2). The fluxes are used to (1) constrain the range of percolation fluxes applied at the upper boundary of the seepage model for performance assessment (Section K.4.2.2.2), (2) provide background percolation flux for the seepage calibration model (Section K.4.2.2.1), and (3) provide percolation fluxes for the multiscale thermal-hydrologic models (Section K.4.2.1.1). This consideration assumes that there is little mountain-scale flux redistribution (lateral flow) between the PTn–TSw interface and the repository horizon. Therefore, at the mountain scale, the spatial distribution of percolation flux is considered appropriately integrated between the three models.

At the time KTI agreement TSPAI 3.11 was reached, the multiscale thermal-hydrologic model calculations that supported TSPA for site recommendation (TSPA-SR) directly used the infiltration maps as upper boundary flux, with the underlying assumption that there is no significant lateral attenuation of infiltration in any unit above the repository (i.e., percolation above the repository occurs strictly as one-dimensional vertical downward flow). The revised version of the multiscale thermal-hydrologic model is modified so that the upper-boundary, liquid-phase flux is set as the distribution of percolation flux below the base of the PTn unit. The percolation flux map is generated by the three-dimensional, unsaturated zone models and accounts for the influence of lateral diversion in the PTn unit. Thus, it is not necessary to compare the infiltration flux used for the infiltration bins with the three-dimensional unsaturated zone flow model and the multiscale thermal-hydrologic model results (Section K.4.2.1.1).

There is a significant scale-difference between (1) the three-dimensional unsaturated zone flow model and (2) the drift-scale seepage models and drift-scale components of the multiscale thermal-hydrologic model. This scale difference and the resulting flux redistribution (flow focusing) at scales smaller than the gridblocks of the three-dimensional unsaturated zone flow model are described in both the drift-scale seepage abstraction model and the multiscale thermal-hydrologic model document. However, the treatments of flow focusing in the abstraction of drift seepage and multiscale thermal-hydrologic models are different (Section K.4.2.1.2).

The seepage abstraction feeding the TSPA treats flow focusing using a probabilistic flow-focusing factor, which is considered independent of the percolation flux or the location within the repository horizon. The distribution of the flow-focusing factor is derived from two-dimensional and three-dimensional intermediate-scale, high-resolution flow models that considered heterogeneity within the hydrologic units between the PTn and TSw.

The multiscale thermal-hydrologic model analyzes the potential for flow focusing using additional runs with extreme values of upper-boundary percolation fluxes. This flow-focusing analysis performed with multiscale thermal-hydrologic subcomponent models is not included in the results provided to the TSPA model because of the following two reasons. First, peak waste-package temperature and waste-package relative humidity are relatively insensitive to the flow focusing effect. Second, the influence of percolation-flux uncertainty is already captured by the inclusion of the lower-bound, mean, and upper-bound infiltration-flux cases in the multiscale thermal-hydrologic model results provided to TSPA (Section K.4.2.1.2).

This response also addresses GEN 1.01 (Comment 82), which is concerned with uncertainties regarding evaporation effects and drift degradation. *Seepage Calibration Model and Seepage Testing Data* (BSC 2004c) incorporates the evaporation model. *Abstraction of Drift Seepage* (BSC 2004e) provides seepage conditions under the maximum drift degradation (complete drift collapse) and accounts for uncertainty in drift degradation analyses by 20% increase to the calculated seepage rate.

The information in this report is responsive to agreements TSPAI 3.11 and GEN 1.01 (Comment 82) made between the DOE and NRC. The report contains the information that the DOE considers necessary for NRC review for closure of these agreements.

K.4 BASIS FOR THE RESPONSE

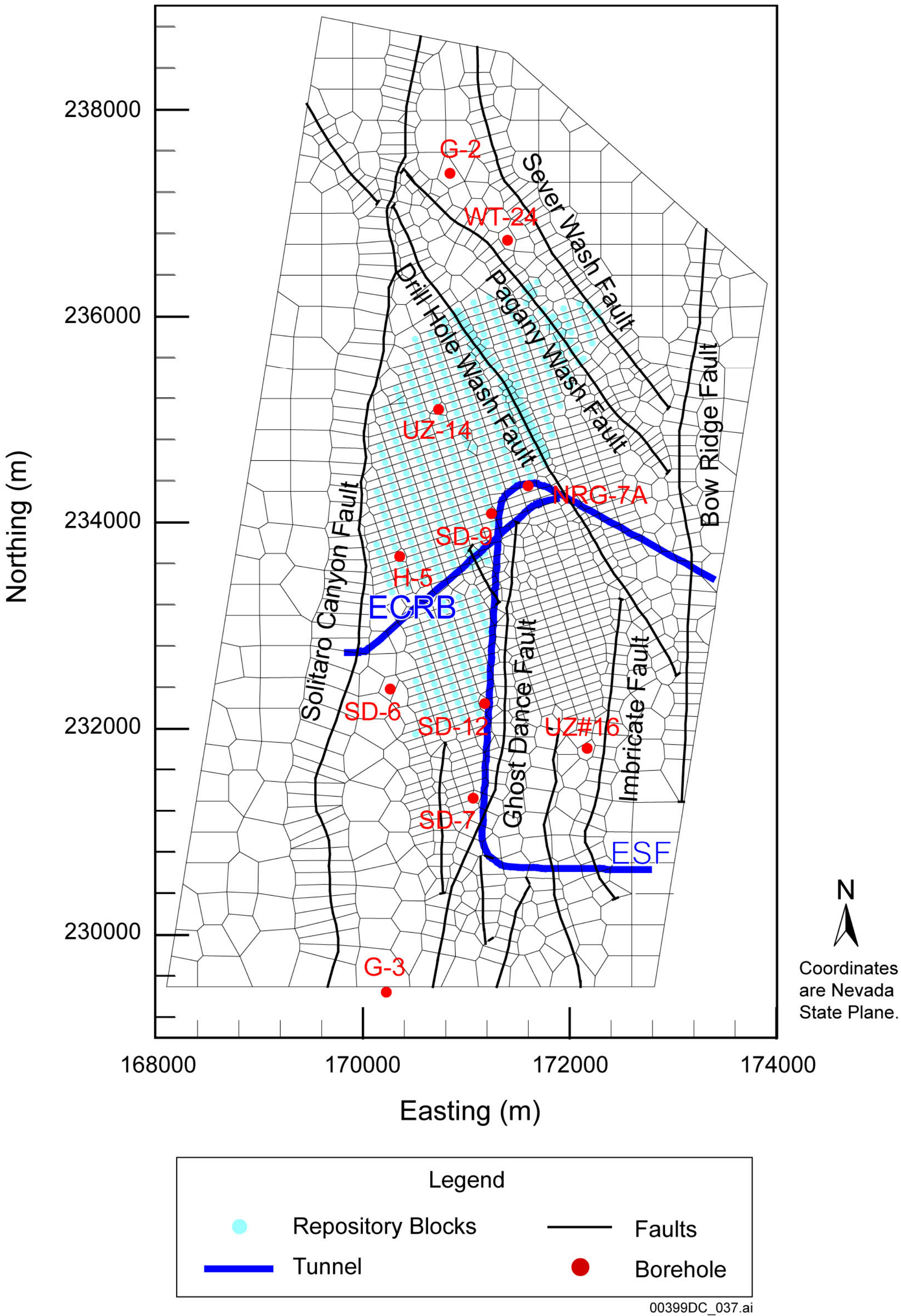
Agreement TSPAI 3.11 is concerned with integration of spatial distribution of fluxes between the three-dimensional unsaturated zone flow model, the multiscale thermal-hydrologic model, and the drift-scale seepage models. The important components of these models are briefly described below (Section K.4.1), followed by discussions of the treatment of percolation flux and its spatial distribution in these models (Section K.4.2).

K.4.1 Model Descriptions

K.4.1.1 Three-Dimensional Unsaturated Zone Model

The three-dimensional unsaturated zone model (e.g., Bodvarsson et al. 1999; Wu et al. 1999; Wu et al. 2002; BSC 2003a; BSC 2004b) integrates the pertinent data from the unsaturated zone at Yucca Mountain.

The model includes 36 unsaturated zone model layers, each of which is considered homogeneous with respect to thermal and hydrologic properties, while the heterogeneity is captured by the 36 layers. The three-dimensional unsaturated zone model domain and the numerical grid for this study are shown in plan view in Figure K-1.



Source: BSC 2003a, Figure 6.1-1.

Figure K-1. Plan View of the Three-Dimensional Unsaturated Zone Model

Precipitation water entering the unsaturated zone from the surficial soils as net infiltration is an important factor in the overall hydrologic and thermal-hydrologic conditions within the unsaturated zone at Yucca Mountain. The net infiltration is the ultimate source of percolation flux through the unsaturated zone. The three-dimensional unsaturated zone model uses net infiltration rates as surface water–recharge boundary conditions. The net infiltration rates are determined from *Future Climate Analysis* (USGS 2001a) and *Simulation of Net Infiltration for Modern and Potential Future Climates* (USGS 2001b). The climatic regimes considered include present-day, monsoon, and glacial transition. These climatic regimes are each represented with a drier lower-bound, a wetter upper-bound, and an intermediate mean climate scenario. The lower- and upper-bound scenarios are developed to account for uncertainty and variability in the characteristics of precipitation and air temperature for each estimated climate stage. The mean climate scenario is developed to represent average conditions within each climate regime. The results of the net infiltration analysis are interfaced with the three-dimensional unsaturated zone flow model through a set of nine infiltration maps (three infiltration scenarios in each of the three climates) (BSC 2004f). The mean infiltration rate maps for the three climatic regimes are shown in Figures K-2, K-3, and K-4. The infiltration rates averaged over the unsaturated zone model domain are given in Table K-1.

The hydrologic properties are determined through an inverse modeling approach constrained by site hydrologic data (Bandurraga and Bodvarsson 1999). Calibrated hydrologic properties based on one-, two-, and three-dimensional calibrations were obtained for each of the lower-bound, mean, and upper-bound infiltration scenarios for the modern climate. The resulting property sets are used for their respective scenario for each of the present and future climates (BSC 2004f).

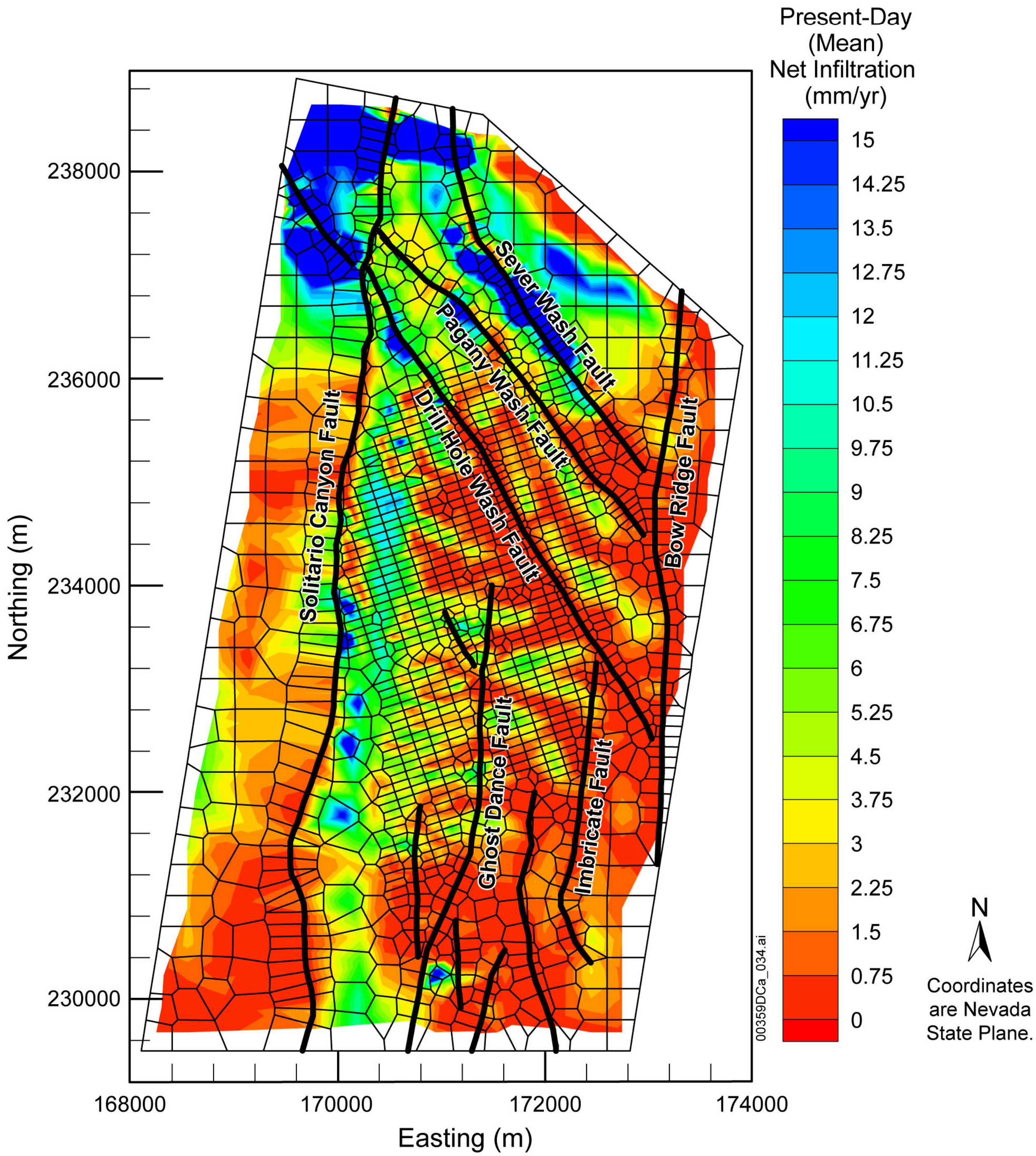
Table K-1. Infiltration Rates Averaged over the Unsaturated Zone Model Domain

Scenario	Lower-Bound Infiltration (mm/yr)	Mean Infiltration (mm/yr)	Upper-Bound Infiltration (mm/yr)
Present-Day/Modern	1.25	4.43	10.74
Monsoon	4.43	11.83	19.23
Glacial Transition	2.35	17.02	31.69

Source: BSC 2003a, Table 6.1-26.

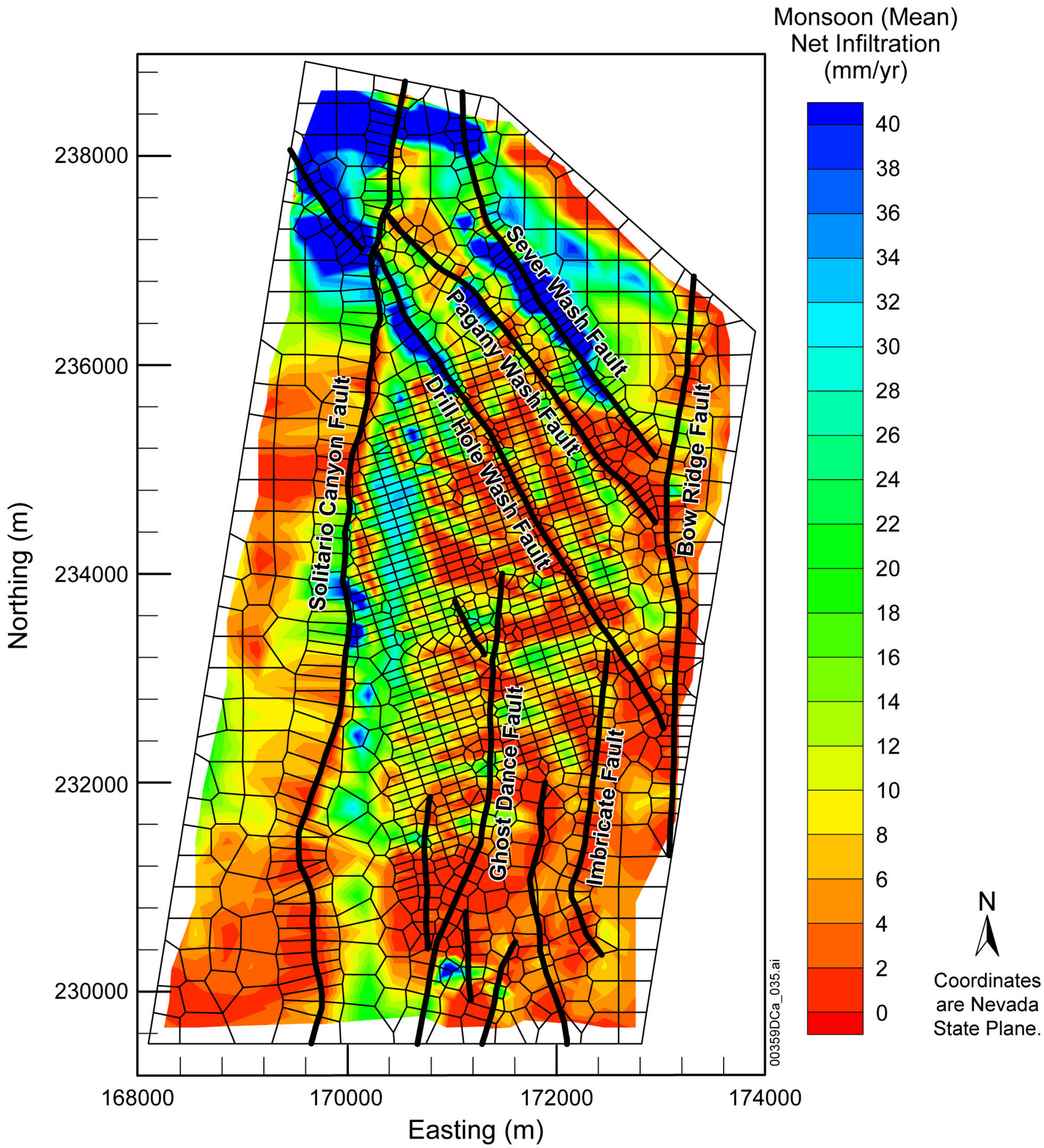
NOTE: Values are averaged from DTN: GS000308311221.005.

The three-dimensional unsaturated zone flow model produces a set of nine flow fields (three infiltration scenarios in each of the three climates).



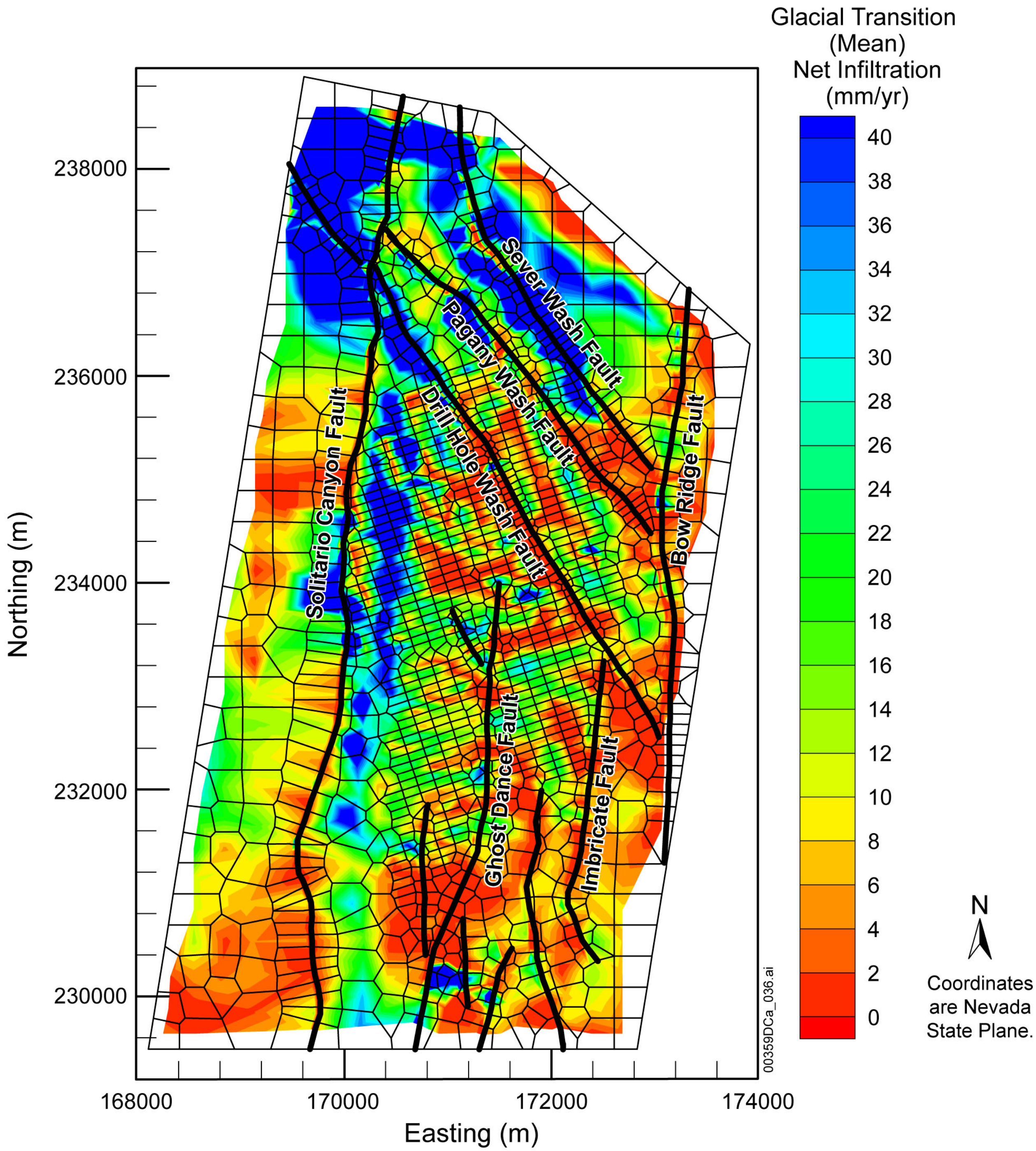
Source: BSC 2004f, Figure 6.1-2.

Figure K-2. Plan View of Net Infiltration Distributed over the Three-Dimensional Unsaturated Model Grid for the Present-Day (Base-Case) Mean Infiltration Scenario



Source: BSC 2004f, Figure 6.1-3.

Figure K-3. Plan View of Net Infiltration Distributed over the Three-Dimensional Unsaturated Zone Model Grid for the Monsoon Mean Infiltration Scenario



Source: BSC 2004f, Figure 6.1-4.

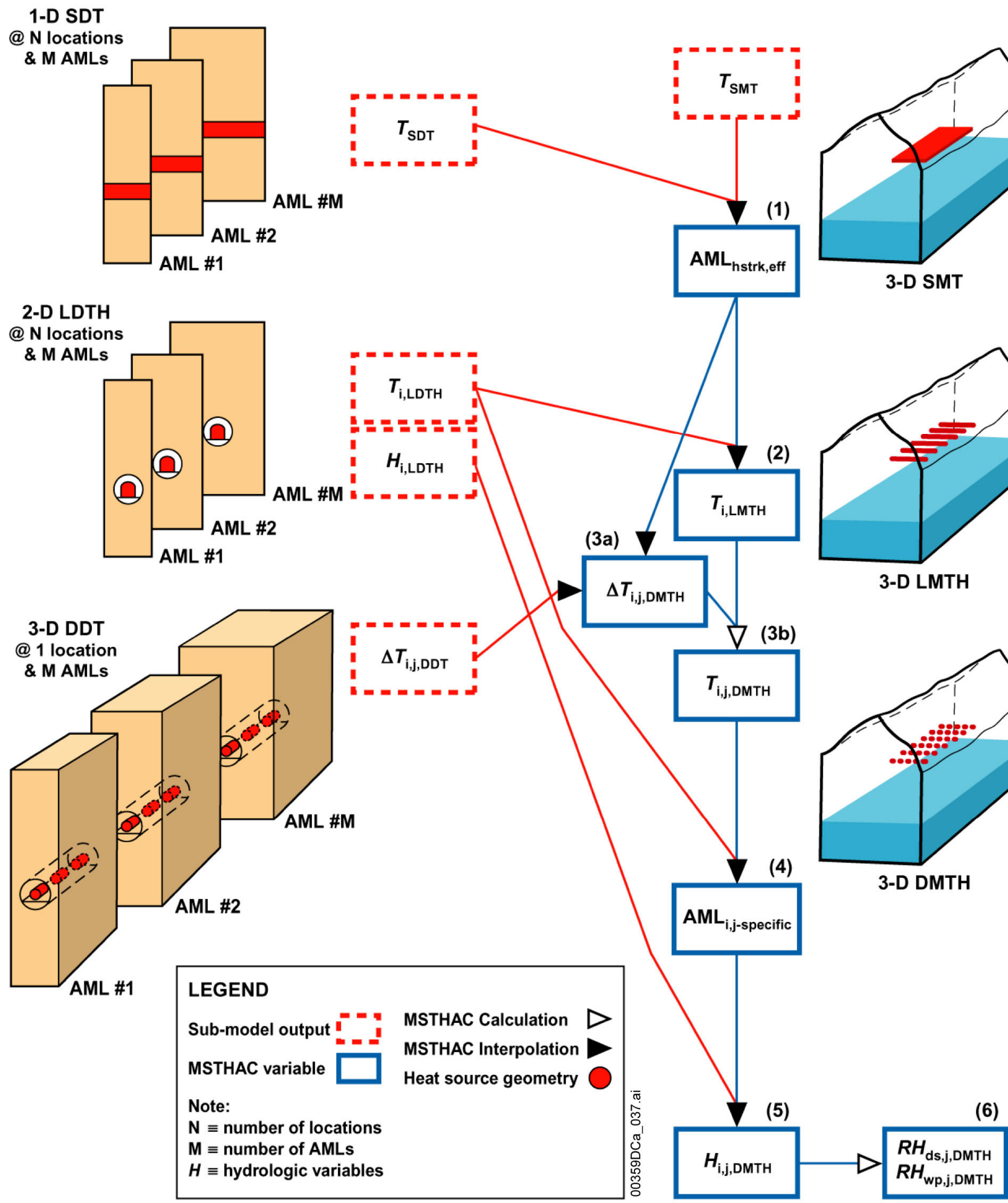
Figure K-4. Plan View of Net Infiltration Distributed over the Three-Dimensional Unsaturated Zone Model Grid for the Glacial Transition Mean Infiltration Scenario

K.4.1.2 Multiscale Thermal-Hydrologic Model

The purpose of the multiscale thermal-hydrologic model is to predict the evolution of thermal-hydrologic conditions in the repository emplacement drifts and in the adjoining host rock for the repository at Yucca Mountain. The multiscale thermal-hydrologic model calculates the following thermal-hydrologic variables: (1) temperature, (2) relative humidity, (3) liquid-phase saturation, (4) evaporation rate, (5) air-mass fraction, (6) gas-phase pressure, (7) capillary pressure, and (8) liquid- and gas-phase fluxes. The multiscale modeling approach is a modeling tool that simultaneously accounts for processes occurring at a scale of a few tens of centimeters around individual waste packages and emplacement drifts and also at the scale of the mountain; it is an alternative method to the numerically cumbersome monolithic thermal-hydrologic approach of modeling both drift-scale and mountain-scale processes simultaneously. By taking advantage of the linear nature of heat conduction, it superimposes the results of three-dimensional mountain scale and three-dimensional drift-scale thermal models onto two-dimensional drift-scale thermal-hydrologic models. Detailed three-dimensional heat flow at the mountain scale and drift scale are modeled independently of the more complicated coupled thermal and hydrologic interactions modeled in two dimensions at the drift scale. The conceptual model, three-dimensional model structure, stratigraphic units, and hydrologic properties of these units are derived from the three-dimensional unsaturated zone model. Thermal properties of the units are determined from laboratory measurements (BSC 2002). The multiscale thermal-hydrologic model is composed of four submodels that use the nonisothermal unsaturated–saturated flow and transport (NUFT) simulation code (Nitao 1998). The submodels are:

- Smeared-heat-source drift-scale thermal-conduction model (SDT), one-dimensional
- Line-average-source drift-scale thermal-hydrologic model (LDTH), two-dimensional
- Discrete-heat-source drift-scale thermal-conduction model (DDT), three-dimensional
- Smeared-source mountain-scale thermal-only submodel (SMT), three-dimensional.

Subcomponent variables of the multiscale thermal-hydrologic model include three-dimensional line-averaged-heat-source, mountain-scale, thermal-hydrologic model (LMTH), which is an intermediate result, and a three-dimensional discrete-heat-source, mountain-scale, thermal-hydrologic model (DMTH), the final result of the multiscale thermal-hydrologic model (MSTHM). Figure K-5 shows a six-stage flow chart diagram of the MSTHM. The six stages illustrate the process of constructing intermediate variables and final MSTHM variables. Though the two-dimensional LDTH submodel is the only MSTHM component that deals directly with hydrology, the other MSTHM components direct the application of the LDTH response curves for use in the total system performance assessment for license application (TSPA-LA) model (e.g., mountain-scale effects such as heat sinks along the outer edges of the repository require the SMT component to select which LDTH model is the correct representation for each location during specific time periods). The flowchart of the multiscale thermal-hydrologic model, including the stages of calculations, is shown in Figure K-5.



Source: BSC 2004a, Figure 1-1.

NOTE: The four submodels of the multiscale thermal-hydrologic model are the smeared-heat-source drift-scale thermal-conduction (SDT), line-average-source drift-scale thermal-hydrologic model (LDTH), discrete-heat-source drift-scale thermal-conduction model (DDT), and smeared-source mountain-scale thermal-only submodel (SMT) submodels. The LMTH model is an intermediate result of the multiscale thermal-hydrologic model; the DMTH model is the final result of the multiscale thermal-hydrologic model. AML = areal mass loading (mass of spent nuclear fuel and high-level waste per unit area of heated repository footprint MTU/acre).

Figure K-5. Multiscale Thermal-Hydrologic Model Processes

The multiscale thermal-hydrologic model output is used by water flow models inside the waste emplacement drift (BSC 2003d), providing the invert intragranular flow rates. The MSTHM provides percolation flux rates and drift-wall temperatures to the seepage abstraction model (BSC 2004a). However, these output values are unchanged by the multiscale thermal-hydrologic model from the input values given by the three-dimensional unsaturated zone flow model (Section K.4.2.1).

K.4.1.3 Seepage Abstraction Model and Supporting Process Models

Drift seepage refers to the flow of liquid water into waste emplacement drifts. The unsaturated rock layers overlying and hosting the repository are a feature of the upper natural barrier that reduces the amount of water entering emplacement drifts by natural subsurface processes. Drift seepage is limited by the capillary barrier forming at the drift wall, which minimizes or even eliminates water flow from the unsaturated fractured rock into the drift. During the first few hundred years after waste emplacement, when above-boiling rock temperatures will develop as a result of heat generated by the decay of the radioactive waste, vaporization of percolation water will be an additional factor preventing seepage. Details on seepage and important factors affecting seepage are described in this technical basis document.

The purpose of the seepage component in TSPA is to calculate the seepage rate (amount of seepage per time) and the seepage fraction (the fraction of waste packages affected by seepage) as a function of time and location in the repository. The calculation is performed using a probabilistic approach that accounts for the spatial and temporal variability and inherent uncertainty of seepage-relevant properties and processes. The results are presented in the form of probability distributions of seepage events. These distributions are used by other TSPA models that determine waste form degradation or radionuclide transport.

Abstraction of Drift Seepage (BSC 2004e) provides the necessary methodology, tools, parameter distributions, lookup tables, and simplifications to the TSPA so that the seepage calculations can be performed by the respective TSPA module. The multiscale thermal-hydrologic model provides the percolation-flux boundary at the top of the repository horizon needed for the TSPA seepage calculations. The seepage abstraction model is primarily based on the following unsaturated zone process models that use consistent model concepts, rock properties, and boundary conditions (i.e., water flow rates):

- Seepage calibration model (BSC 2004c)
- Seepage model for performance assessment (BSC 2004d)
- Thermal-hydrologic seepage model (BSC 2003b).

These process models are briefly described below.

K.4.1.3.1 Seepage Calibration Model

The seepage calibration model provides the conceptual basis for modeling of ambient seepage processes (BSC 2004c, Section 6.3). The conceptual basis of the seepage calibration model is that unsaturated flow near waste emplacement drifts occurs through a heterogeneous continuum of fracture network. Flow in the matrix is not directly represented in the seepage calibration model. The model provides estimates of the seepage-relevant capillary-strength parameter (van Genuchten $1/\alpha$ parameter) through calibration of the model against seepage data obtained from in situ liquid-release tests. In these tests, water was artificially released into test boreholes drilled above drifts (or niches). After flowing through the unsaturated fracture network between the injection borehole and the drift ceiling, part of the injected water seeps into the drifts and is collected by an automated capture system. By calibrating the model-predicted seepage rate against late-time (steady-state) seepage rate data, the seepage calibration model estimates seepage-related effective capillary-strength parameters specific to the test site. The seepage calibration models are developed using permeability and geometry information (including small-scale roughness for the niche tests) collected at the test sites.

K.4.1.3.2 Seepage Model for Performance Assessment

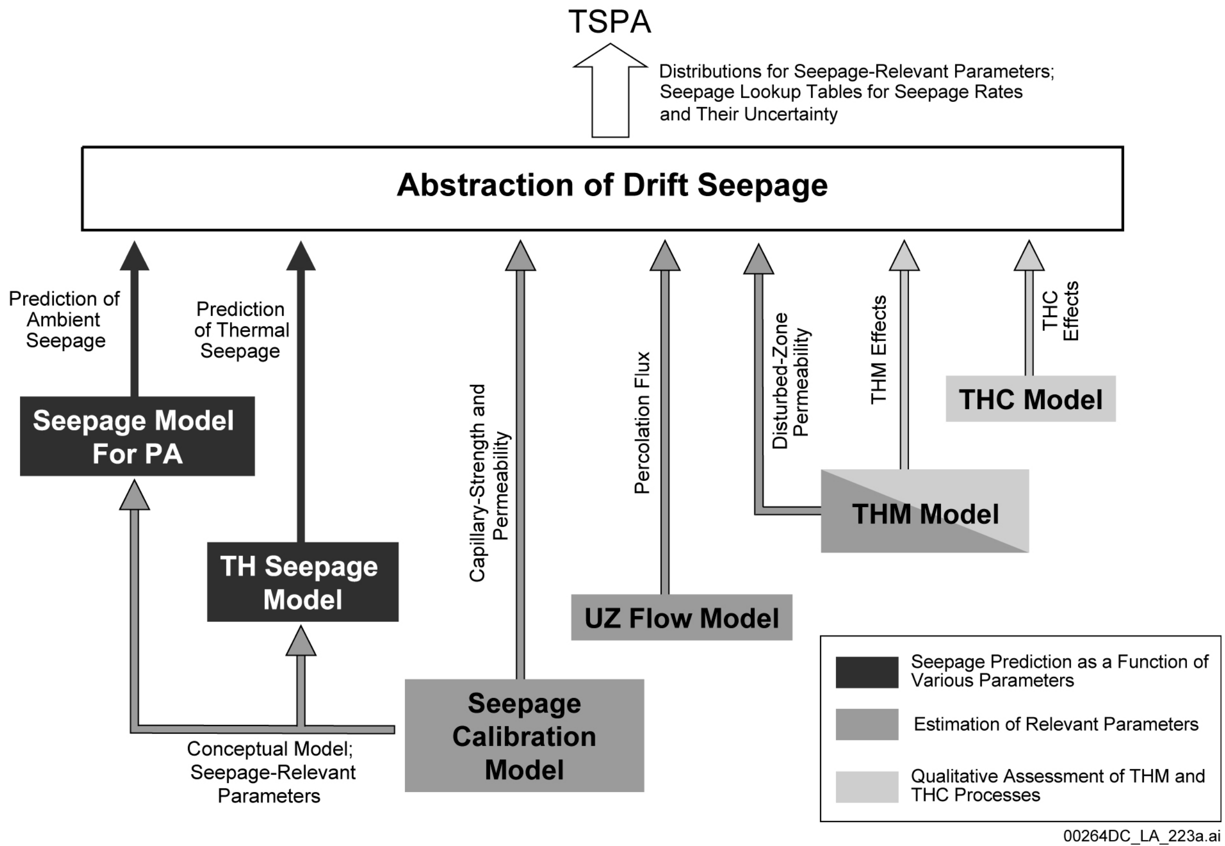
The seepage model for performance assessment adopts the conceptual framework from the seepage calibration model to conduct systematic predictions of seepage fluxes into waste emplacement drifts at Yucca Mountain under long-term ambient conditions (BSC 2004d). It utilizes a generic drift geometry representing an actual waste emplacement drift. The model output is in the form of seepage lookup tables, where seepage rates and uncertainties are given as a function of three key parameters (i.e., effective capillary-strength parameter, local permeability, and local percolation flux). Additional simulations are performed to analyze the impact of drift degradation and rockfall (BSC 2004e).

K.4.1.3.3 Thermal-Hydrologic Seepage Model

This process model predicts drift seepage during the period when water-flow processes in the drift vicinity are perturbed by heating of the rock (BSC 2003b). The transient, thermally-affected seepage rates are given relative to the long-term ambient seepage rates calculated by the seepage model for performance assessment.

In addition to the above process models, the seepage abstraction utilizes supporting information with regard to the potential impact of coupled processes on seepage-relevant parameters. The coupled thermal-hydrologic-mechanical model (BSC 2003c) and the thermal-hydrologic-chemical model (BSC 2003e) analyzed the impact of thermally induced mechanical and chemical processes, respectively, on seepage-relevant parameters.

The relationship and the information flow between the suite of primary process models important for seepage and the seepage abstraction are schematically illustrated in Figure K-6. It is important that these models are consistent in their use of water flow rates so that the seepage abstraction is based on a suite of consistent process models. This is addressed later in this section.



Source: BSC 2004e, Figure 1-1.

NOTE: THC = thermal-hydrologic-chemical; THM = thermal-hydrologic-mechanical; TH = thermal-hydrologic; PA = performance assessment.

Figure K-6. Relationship and Information Flow between Process Models and Seepage Abstraction

K.4.2 Integration between Models

The scale difference between the various models indicates that the integration among them is also scale dependent. At mountain scale, the dominant factors that determine distribution of percolation flux include the distribution of infiltration flux and properties of the hydrostratigraphic units (e.g., depth, inclination, and hydrologic properties). The three-dimensional unsaturated zone flow model accounts for these factors and provides the multiscale thermal-hydrologic model and seepage abstraction for TSPA with percolation flux distributions at different parts of the mountain. In the following sections, integrations at both mountain and drift scale are summarized.

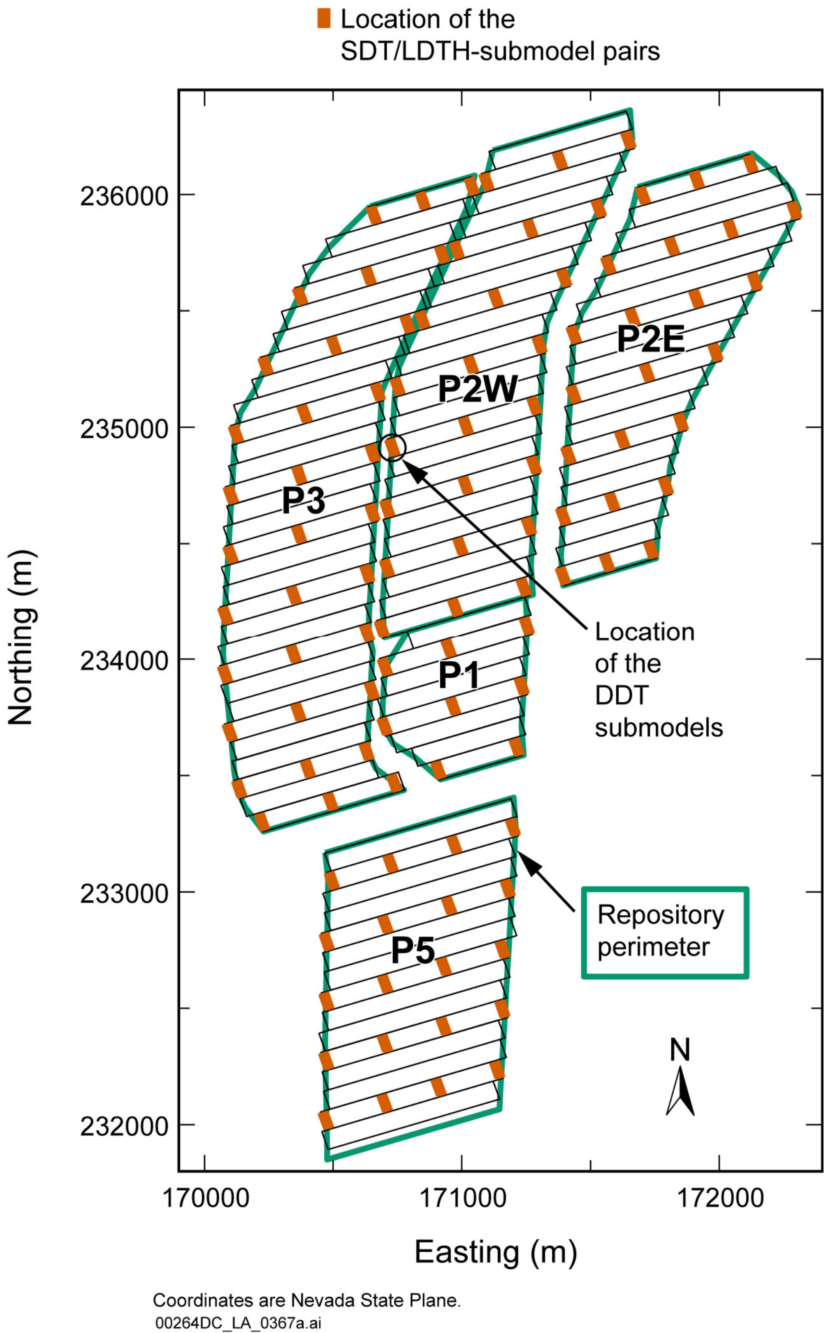
K.4.2.1 Use of the Three-Dimensional Unsaturated Zone Flow Model Results in the Multiscale Thermal-Hydrologic Model

K.4.2.1.1 Mountain-Scale Model Integration

The multiscale thermal-hydrologic model utilizes drift-scale line-average-heat-source thermal-hydrologic (LDTH) submodels (BSC 2004a, Section 6.2.7), which are distributed uniformly across the repository at 108 locations (Figure K-7). Previous (TSPA-SR) multiscale thermal-hydrologic model calculations (BSC 2001b), performed at the time this KTI agreement was reached, directly used the nine infiltration maps as the upper-boundary flux for the flow submodels. The underlying assumption in those calculations was that there is no significant lateral attenuation of infiltration in the PTn unit (or in any other unit above the repository); thus, percolation above the repository occurs strictly as one-dimensional vertical downward flow. For the TSPA multiscale thermal-hydrologic model calculations, the upper-boundary liquid-phase flux in the 108 locations of the multiscale thermal-hydrologic model (BSC 2004a, Section 6.2.7) are obtained from the distribution of percolation flux just below the base of the PTn unit calculated by the three-dimensional unsaturated zone model (BSC 2003a). Thus, the current multiscale thermal-hydrologic model accounts for the influence of lateral diversion in the PTn as represented in the three-dimensional unsaturated zone model. Further comparison of the infiltration flux used for the infiltration bins with the three-dimensional unsaturated zone flow model and the multiscale thermal-hydrologic model results is, thus, not applicable for the current calculations.

The incorporation of the nine PTn-to-TSw percolation-flux scenarios generated by the three-dimensional unsaturated zone model in the multiscale thermal-hydrologic model is carried out in three steps. First, the average percolation fluxes for each of the five repository panels (Panels 1, 2E, 2W, 3, and 5 in Figure K-7) are determined. Because Panel 1 is relatively small, Panels 1 and 2W are grouped together and treated as one contiguous repository panel. Panels 2E, 3 and 5 are treated individually. In the second step, the "raw" percolation fluxes for each of the 108 LDTH-submodel locations (shown in Figure K-7) are extracted from the three-dimensional unsaturated zone model maps. From percolation fluxes at these 108 locations, averages for the four repository panels are calculated (Panels 1 and 2W are grouped as in the first step), based on an area-weighted average of the percolation fluxes at the LDTH-submodel locations in any given panel. In the third step, the "final" percolation flux is computed using the information obtained by the first and second steps. The final percolation flux for a given LDTH-submodel location is equal to the raw percolation flux from the second step, multiplied by the ratio of the panel-average percolation flux of the first step to the panel-average percolation flux of the second step.

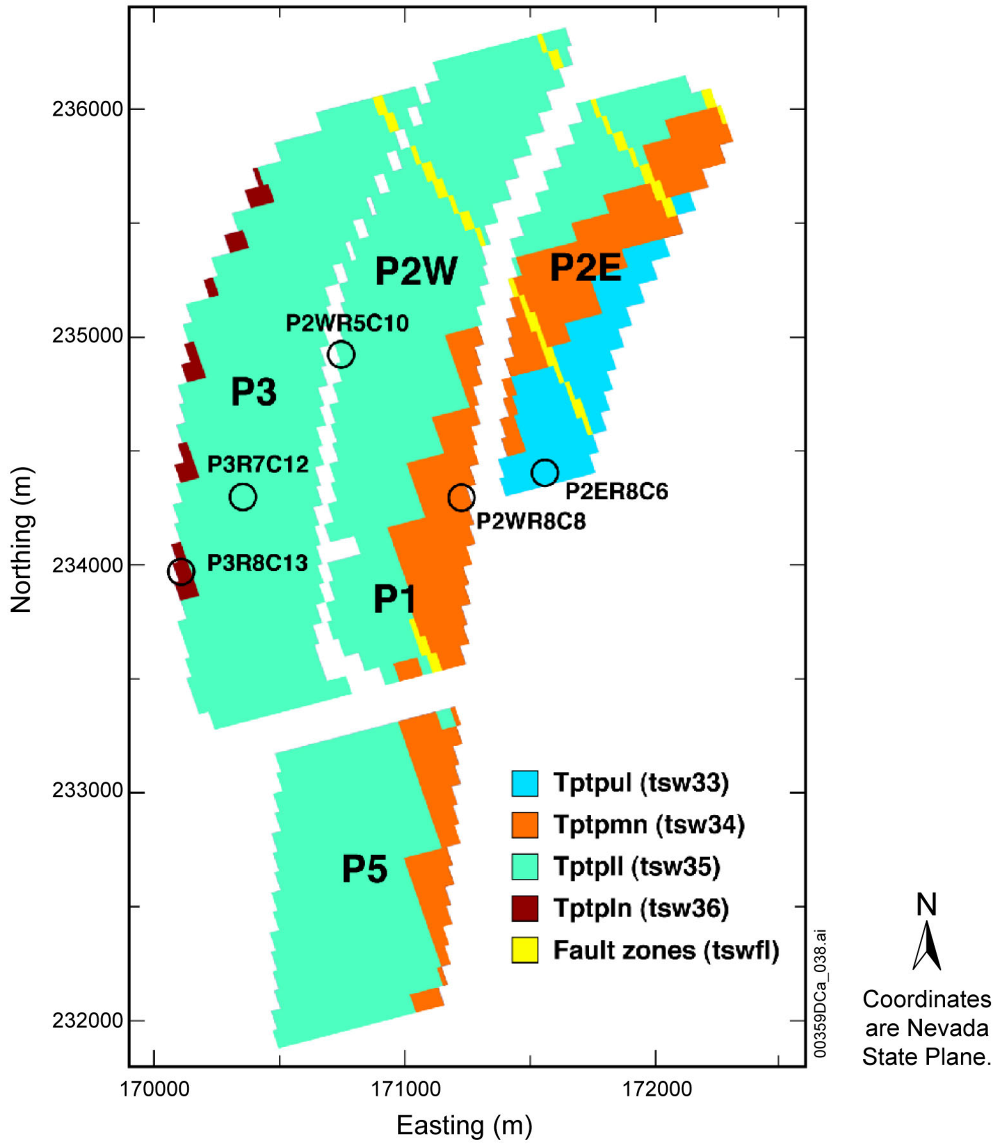
For the purpose of examining the details of thermal-hydrologic behavior in emplacement drifts, five locations were chosen that cover all four of the host-rock units (shown by circular symbols in Figure K-8). Four of these locations (P2ER8C6, P2WR8C8, P2WR5C10, and P3R8C13) are chosen because their respective values of percolation flux are relatively close to the repository-wide averages. The fifth location (P3R7C12) is chosen because it has close to the longest boiling-period duration over the entire repository area; note that this location is in a region of low percolation flux, which is a major contributing factor to its very long boiling-period duration.



Source: BSC 2004a, Figure 6.2-3.

NOTE: Orange squares show locations of the LDTH submodels.

Figure K-7. Repository Layout Used in the Multiscale Thermal-Hydrologic Model, Showing Locations of the 108 Line-Average-Heat-Source, Drift-Scale, Thermal-Hydrologic Models (LDTH) Submodels



Source: BSC 2004a, Figure 6.3-1.

NOTE: tswfl = fault zone. Also shown are the five locations selected to examine thermal-hydrologic conditions in the four primary host-rock units.

Figure K-8. Distribution of the Four Primary Host-Rock Units for Repository Layout Considered in MSTHM Calculations for the TSPA-LA Base Case

The multiscale thermal-hydrologic model is implemented in the TSPA by the selection of a representative package for each repository bin. Time-dependent thermal-hydrologic variables are abstracted from these simulations for each of the repository level bins. Abstracted outputs include:

- Waste package surface temperature and waste package surface relative humidity, drip shield temperature, and drip shield relative humidity for eight package types within discrete environments. These values are provided to drip shield, waste package, and waste form degradation models in TSPA. This information is provided as both a representative package used to describe the thermal-hydrologic response for each repository bin and as a location-specified parameter (2,874 locations in the repository footprint).

- Representative waste form temperatures, representative invert temperature, and liquid saturation in the invert for each of the five repository level bins. Waste form surface temperature will be assumed to be equal to the waste package surface temperature. These temperature and saturation values are provided to the waste form degradation and engineered barrier system transport models in TSPA.

- Representative drift wall perimeter temperature, invert relative humidity, invert evaporation rate, and liquid saturation in the invert. These values are provided to the engineered barrier system chemical environment models. The outputs are in the form of response surfaces or multidimensional tables.

- Long-term percolation flux levels above the repository at the interface between the Paintbrush Tuff nonwelded and Topopah Spring welded rock units. These values are used as inputs to the seepage response surface.

The multiscale thermal-hydrologic model receives percolation-flux maps from the three-dimensional unsaturated zone flow model at the PTn–TSw interface and applies these at the upper boundaries of the MSTHM subcomponent models, specifically the LDTH models. This is done to allow the multiscale thermal-hydrologic model to account for the thermal-hydrologic effects of the units below the ground surface (and above the TSw), while simultaneously considering the significant lateral water flow in the PTn units. Because the LDTH subcomponent models in the MSTHM are two-dimensional column models, they cannot account for the lateral flow in the PTn units any other way. The approximation invoked is that the ambient percolation flux distribution above the repository horizon is unaffected by mountain-scale, repository-heat-driven, thermal-hydrologic effects until it reaches the boiling and condensation zones surrounding the emplacement drifts. This results from the fact that sub-boiling evaporation has a negligible influence on the magnitude or direction of liquid-phase flux and that boiling does not occur in units above the TSw.

The multiscale thermal-hydrologic model differs from the three-dimensional unsaturated zone flow model in two aspects. First, the three-dimensional unsaturated zone flow model uses the property sets calibrated against lower-bound, mean, and upper-bound infiltration-flux scenarios (BSC 2004f, Section 6.2.3), while the multiscale thermal-hydrologic model uses only the property set calibrated against the mean present-day infiltration flux scenario (BSC 2003d, Section 6.3.1). Because the property sets are obtained from one-dimensional inversions performed in *Calibrated Properties Model* (BSC 2003f), adjustments for three-dimensional effects were carried out (BSC 2004e, Section 6.2.3). Second, the multiscale thermal-hydrologic model uses a modified version of the property set corresponding to the mean infiltration-flux scenario. In Section 6.6.3 of *Abstraction of Drift Seepage* (BSC 2004e), which addresses the fracture van Genuchten alpha (capillary strength parameter) and permeability distributions for the Tptpul (tsw33) and Tptpln (tsw36) units, it is noted that the Tptpul (tsw33) unit is hydrogeologically similar to the Tptpll (tsw35) unit; furthermore, it is stated that the two units with lithophysal cavities in the rock (the Tptpul and Tptpll units) should have similar hydrogeologic characteristics. The modified-mean infiltration flux property set is the same as the mean infiltration flux property set used in the three-dimensional unsaturated zone flow model (BSC 2004e) with the one modification being that the van Genuchten fracture alpha in the Tptpul (tsw33) is set to be the same (1.021×10^{-4} Pa^{-1}) as that in the Tptpll (tsw35) unit.

As is evident in the above discussions, the mountain-scale percolation flux is appropriately propagated from the three-dimensional unsaturated zone flow model to the multiscale thermal-hydrologic model.

K.4.2.1.2 Drift-Scale Model Integration

The main sources of percolation flux uncertainty in the multiscale thermal-hydrologic model are uncertainty of infiltration flux and the possibility of flow focusing within gridblocks of the three-dimensional unsaturated zone flow model. This section is concerned with the treatment of flow focusing in the multiscale thermal-hydrologic model.

The liquid-phase flux distribution applied at the upper boundary of the LDTH submodels of the multiscale thermal-hydrologic model is the percolation flux distribution at the PTn–TSw interface calculated by the three-dimensional unsaturated zone flow model (BSC 2003a, Section 6.6, Attachment III-2.1, Attachment IV). The spatial variability of percolation flux at the PTn–TSw interface does not fully capture the potential for heterogeneity between the base of the PTn sequence and the repository horizon to generate further percolation flux redistribution at the repository horizon.

Stochastic modeling analyses discussed in Volume 1 of *FY01 Supplemental Science and Performance Analyses, Volume 1: Scientific Bases and Analyses* (BSC 2001a, Section 4.3.2), using a two-dimensional, finely gridded vertical cross section of the unsaturated zone, resulted in maximum flow-focusing factors between 5 and 6. In *Drift-Scale Coupled Processes (DST and TH Seepage) Models* (BSC 2004g, Section 6.2.2.2.4), flow-focusing factors of 5 and 10 are considered in the sensitivity study to percolation flux, resulting in percolation fluxes of 30, 80, and 125 mm/yr for the present-day, monsoon, and glacial-transition climate states, respectively.

The multiscale thermal-hydrologic model assesses the impact of flow focusing as a sensitivity study of the multiscale thermal-hydrologic model calculations. This sensitivity study utilizes very high and very low percolation fluxes at four repository locations, to assess the impacts of the maximum and minimum flow-focusing values, respectively (BSC 2004a, Sections 6.3.2.1 and 6.3.2.3).

The multiscale thermal-hydrologic model uses the same value of present-day percolation flux (25 mm/yr) for the highest percolation-flux case (maximum flow focusing) at all the locations analyzed. Compared to the percolation fluxes calculated by the three-dimensional unsaturated zone flow model (see Tables K-2 and K-3), the value of 25 mm/yr represents flow focusing by a factor ranging between 3.54 and 5.59 for the different repository panels. The maximum percolation fluxes for the monsoon and glacial-transition climates are obtained by multiplying the percolation fluxes calculated by the three-dimensional unsaturated zone flow model by the respective effective flow-focusing factors. The present-day, monsoon, and glacial-transition high-percolation-flux values are similar to those used in *Drift-Scale Coupled Processes (DST and TH Seepage) Models* (BSC 2004g, Section 6.2.2.2.4) for the case with a focus factor of 5.

Table K-2. Percolation-Flux for the Lower-, Mean-, and Upper-Infiltration-Flux Cases Averaged over Five Locations in the Repository for the Mean-Infiltration-Flux Scenario

LDTH-SDT Submodel Location	Host-Rock Unit	Nevada State Coordinates		Calculated Percolation Flux for the Mean Infiltration-Flux Case (mm/yr)		
		Easting (m)	Northing (m)	Present-Day	Monsoon	Glacial Transition
P2ER8C6	Tptpul (tsw33)	171564.3	234417.3	5.41	11.70	23.03
P2WR8C8	Tptpmn (tsw34)	171240.9	234312.1	4.47	10.45	15.65
P2WR5C10	Tptpll (tsw35)	170730.3	234912.7	4.71	14.60	22.07
P3R7C12	Tptpll (tsw35)	170347.9	234277.5	0.86	3.43	6.32
P3R8C13	Tptpln (tsw36)	170080.6	233935.1	7.07	21.95	31.66

Source: Adapted from BSC 2004a, Table 6.3-7a.

Table K-3. Percolation-Flux for the Lower-, Mean-, and Upper-Infiltration-Flux Cases Averaged over Five Locations in the Repository for the Lower- and Upper-Infiltration-Flux Scenarios

LDTH-SDT Submodel Location	Percolation Flux for the Lower-Infiltration-Flux Case (mm/yr)			Calculated Percolation Flux for the Upper-Infiltration-Flux Case (mm/yr)		
	Present-Day	Monsoon	Glacial Transition	Present-Day	Monsoon	Glacial Transition
P2ER8C6	6.33×10^{-2}	3.57	1.79	7.22	14.11	34.53
P2WR8C8	2.62×10^{-3}	3.44	1.31	7.31	12.51	22.14
P2WR5C10	2.26×10^{-3}	5.58	2.02	15.22	26.12	43.60
P3R7C12	1.08×10^{-4}	0.91	0.12	6.76	12.82	24.28
P3R8C13	0.36	6.66	3.69	16.57	33.64	54.99

Source: BSC 2004a, Table 6.3-7b.

The lowest-percolation-flux case corresponds to the regions of the repository experiencing flow defocusing, because of focused flow elsewhere. To discern the influence of the local host-rock unit on thermal-hydrologic behavior the same value (0.025 mm/yr) was applied to all four analyzed locations. Considering that the minimum-percolation-flux cases are meant to correspond to regions that are shielded from significant percolation flux (regardless of the magnitude of repository-wide percolation flux) the same small value of percolation flux is used for the three climate states. This percolation-shielding effect persists during all climate states. Values of present-day percolation flux vary by a factor of 1,000 between the low- and high-percolation-flux cases.

The highest and lowest percolation fluxes (because of flow focusing) used in the sensitivity studies of the multiscale thermal-hydrologic model and the corresponding maximum effective flow-focusing factors are summarized in Table K-4.

Table K-4. Percolation-Flux for the Low, Mean, and High Percolation-Flux Cases for Four Locations in the Repository Used in the Flow-Focusing Sensitivity Analysis

LDTH-SDT Submodel Location	Percolation Flux for the Low Percolation-Flux (Defocused-Flow) Case (mm/yr)			Percolation Flux for the High Percolation-Flux (Focused-Flow) Case (mm/yr)			
	Present-Day	Monsoon	Glacial Transition	Present-Day	Monsoon[a]	Glacial Transition[a]	Effective Focus Factor[b]
P2ER8C6	0.025	0.025	0.025	25.00	54.04	106.3	4.62
P2WR8C8	0.025	0.025	0.025	25.00	58.41	87.47	5.59
P2WR5C10	0.025	0.025	0.025	25.00	77.49	117.18	5.31
P3R8C13	0.025	0.025	0.025	25.00	77.57	111.89	3.54

Source: BSC 2004a, Table 6.3-16.

NOTE: [a]The monsoon and glacial-transition percolation-flux values for the high percolation-flux case are obtained by multiplying the corresponding percolation-flux values in Table K-2 (BSC 2004a, Table 6.3-7a) by the effective focus factor for that location.

[b]The effective focus factor is obtained by dividing 25 mm/yr by the present-day percolation flux listed for the given location in Table K-2 (BSC 2004a, Table 6.3-7a).

The influence of percolation-flux uncertainty on time history of thermal-hydrologic behavior (drift-wall temperature and liquid-phase saturation, waste-package temperature and relative humidity, and invert liquid-phase saturation) at four locations (P2ER8C6, P2WR8C8, P2WR5C10, and P3R8C13) is analyzed in the report documenting the multiscale thermal-hydrologic model (BSC 2004a, Figures 6.3-21 to 6.3-24, Table 6.3-17 to 6.3-19).

Percolation-flux uncertainty is seen to have a small influence on peak drift-wall temperature and on peak waste-package temperature. Peak drift-wall temperatures only vary by 3.7% to 5.2%, and peak waste-package temperatures only vary by 2.9% to 4.3% for a 1,000-fold range of percolation flux. Compared to its influence on peak temperatures, percolation-flux uncertainty has a much stronger influence on the duration of boiling. The sensitivity of boiling-period duration to percolation-flux-uncertainty is greatest for those locations with the longest boiling-period duration, which correspond to locations farthest away from the repository edges where differences in the spatial (and temporal) extent of rock dryout (resulting from differences in percolation flux) have more time to develop. Thus, locations P2ER8C6 and P3R8C13, which are at the repository edges, have the smallest sensitivity to percolation-flux uncertainty, while location P2WR5C10, which is close to the center of the repository, has the greatest sensitivity to percolation-flux uncertainty.

Percolation-flux uncertainty has a strong influence on dryout and rewetting behavior, as shown in the drift-wall and invert liquid-phase-saturation histories. Similarly, percolation-flux uncertainty also has a strong influence on the waste-package relative-humidity histories. Because the relative humidity at the drift wall strongly depends on the liquid-phase saturation as well as on temperature at the drift wall, the variability of drift-wall relative humidity is similar to that of drift-wall liquid-phase saturation. Relative humidity on a given waste package depends on relative humidity at the adjoining drift wall. The large differences in drift-wall liquid-phase-saturation histories (between the low and high percolation-flux cases) result in large differences in waste-package relative-humidity histories between the flux cases.

K.4.2.2 Incorporation of the Three-Dimensional Unsaturated Zone Flow Model Results in the Drift Seepage Models

Incorporation of the three-dimensional unsaturated zone flow model results in the drift-scale process models that feed the seepage abstraction model is discussed below. These discussions cover the treatments of both the mountain-scale percolation flux distribution and the drift-scale flux redistributions.

The percolation fluxes simulated with the unsaturated zone flow model are mapped to the seepage calculation for TSPA through the multiscale thermal-hydrologic model grid. Spatial variability and uncertainty of percolation fluxes are represented in the seepage abstraction model by sampling from different flux distributions for alternative infiltration scenarios. Spatial heterogeneity that is below the resolution of the unsaturated zone model is accounted for by an appropriate distribution of flow-focusing factors. Flow-focusing denotes the possible concentration of downward flow in the unsaturated zone onto a particular drift segment. Multiplication of the local fluxes from the unsaturated zone flow model with the flow-focusing factors gives the local percolation flux to be used in the TSPA calculation.

K.4.2.2.1 Seepage Calibration Model

The actual percolation flux and its distribution at the liquid-release test sites are not empirically known because of the excavation dryout effects and the extremely low current percolation fluxes. Estimates of the average, steady-state percolation fluxes at the locations of the tests are taken from the three-dimensional unsaturated zone flow model (BSC 2004c, Section 6.6.2.3) and applied at the top of the corresponding drift seepage models. The seepage calibration model accounts for small-scale flow concentration by explicitly modeling small-scale heterogeneities (BSC 2004c, Section 6.6.2.1). The large-scale redistribution of infiltration and percolation fluxes is captured by the three-dimensional unsaturated zone flow model, and intermediate-scale flow concentrations are accounted for in the TSPA calculations through the use of a probabilistic flow-focusing factor. The equivalent present-day percolation fluxes used in the seepage calibration model are approximately 13.6 mm/yr for the Enhanced Characterization of the Repository Block (ECRB) Cross-Drift and Niche 5 model domains, 2.54 mm/yr for Niche 3, 2.80 mm/yr for Niche 2, and 2.02 mm/yr for Niche 4. The flow rates are applied to a single model gridblock; however, the inflow into the model is nonuniform because of the heterogeneity in the permeability field. The average background percolation flux is significantly less than the artificially released flux (BSC 2004c, Figure 18). As a result, the impact of the background percolation flux on simulated seepage rates (hence, the calibrated properties) is very limited.

K.4.2.2.2 Seepage Model for Performance Assessment

The seepage model for performance assessment is a generalized representation of the drift-seepage processes. A wide range of input parameters are used to calculate seepage, so that its results can be applicable to all locations in the repository. This process model predicts drift seepage rates for a sufficiently wide range of possible local percolation fluxes imposed at the upper model boundary. The percolation fluxes studied with the model range from 1 to 1,000 mm/yr (BSC 2003b, Section 6.6.4. For comparison, the mean fluxes at the PTn–TSw interface over the repository domain, as predicted by the three-dimensional unsaturated zone flow model, are 3.8, 11.7, and 17.9 mm/yr for the present-day, monsoon, and glacial-transition climate stages, respectively (BSC 2004e, Table 6.6-11). The corresponding maximum fluxes are 39.9, 127.9, and 192.4 mm/yr. Multiplying these maximum fluxes by the maximum flow-focusing factor (approximately 5) yields the theoretical maximum local percolation fluxes of approximately 200, 640, and 960 mm/yr for the glacial-transition climate (using the mean climate scenario). For the upper-bound scenario, the theoretical maximum flux during the glacial transition climate is more than 1,400 mm/yr, which is beyond the flux range studied with the seepage model for performance assessment. However, this theoretical maximum flux is highly unlikely, as it is caused by the very small probability that two independent events have extreme parameter values (upper-bound infiltration scenario and maximum flow focusing) at the same time. Therefore the percolation flux range of 1 to 1000 mm/yr is considered to adequately cover the possible flux variation within the unsaturated zone at Yucca Mountain during the present and future climatic scenarios.

K.4.2.2.3 Thermal-Hydrologic Seepage Model

The TSPA seepage model does not use temperature, but it monitors the boiling threshold. That is, no seepage is assumed to occur for drift wall temperatures above the boiling point of water, and no credit is taken for thermal seepage effects below the boiling point of water (i.e., ambient seepage is assumed). The thermal-hydrologic seepage model is applied to demonstrate that the evolution of thermal seepage can be characterized relative to the ambient long-term seepage rates. Thus, it is important that the percolation-flux scenarios studied with the drift-scale model cover the potential flux variability over the repository area. The thermal-hydrologic seepage model accounts for the spatial and temporal variation by using different flux boundary conditions at the top of the drift-scale model domain. Consistent with the approach used in unsaturated zone flow and transport process modeling, the thermal-hydrologic seepage model considers three long-term climate periods with constant net infiltration: the present-day climate, the monsoon climate, and the glacial-transition climate. The base-case simulation studied with the thermal-hydrologic seepage model has assigned percolation fluxes of 6, 16, and 25 mm/yr, respectively, for these three periods (BSC 2003b, Table 6.2.1.4-1). These fluxes are slightly larger than the average fluxes over the repository area for the mean climate scenario (BSC 2003b, Table 6.6-11); they are thus representative of average percolation conditions within the repository area. (The values of 6, 16, and 25 mm/yr were originally calculated as the arithmetic average over 31 repository locations in the previous multiscale thermal-hydrologic model (BSC 2004a, Section 6.3.1).)

In addition to the average case, other flux scenarios have been studied with the thermal-hydrologic seepage model to cover the expected range of percolation fluxes within the repository units. These scenarios are defined by multiplying the boundary fluxes of the base case using factors of 5, 10, 20, 40, and, in one extreme case, 100. (Smaller percolation fluxes are not studied because they are too small for seepage to occur at any time.) For the three climate periods, the resulting maximum fluxes are as high as 600, 1,600, and 2,500 mm/yr (factor 100).

Together, these cases cover the parameter distributions for percolation flux developed in the seepage abstraction model.

The percolation-flux boundary condition is applied at the top of the thermal-hydrologic seepage model domain, which represents the ground surface. The ground surface is selected as the top boundary because appropriate boundary conditions for temperature, pressure, and saturation can be easily defined. However, the definition of boundary fluxes at this location faces a conceptual difficulty for a drift-scale model, such as the thermal-hydrologic seepage model. This is because the percolation flux distribution below the PTn, which defines the thermal-hydrologic conditions in the repository units, is considerably different from the distribution of net infiltration at the ground surface, mainly a result of lateral diversion in the PTn. Since the thermal-hydrologic seepage model is essentially a vertical column model, it cannot account for lateral flow diversion in the PTn. Therefore, instead of using the net infiltration rates at the top boundary, the thermal-hydrologic seepage model uses boundary fluxes representative of the fluxes within the repository units. Thus, the flux boundary conditions at the top of the model domain are designated to represent the range of percolation fluxes below the PTn rather than the range of net infiltration at the ground surface. This approach is appropriate because the PTn fluxes are hardly affected by thermal-hydrologic processes. This is consistent with the probabilistic seepage calculation in TSPA, which uses the percolation flux distributions across the PTn-TSw boundary to provide input to the seepage lookup tables.

K.4.2.2.4 Drift-Scale Thermal-Hydrologic-Mechanical Model

The drift-scale thermal-hydrologic-mechanical model is applied to assess the magnitude and distribution of stress-induced changes in hydrologic properties and to analyze the impact of such changes on the percolation flux in the rock mass around a repository drift (BSC 2003g). The modeling framework for the thermal-hydrologic processes boundary conditions and rock properties is similar to the thermal-hydrologic seepage model, as described above. However, while the thermal-hydrologic seepage model focuses on the thermal-hydrologic conditions to evaluate seepage rates for various seepage-relevant parameter cases, the thermal-hydrologic-mechanical simulations concentrate on the heat-induced stress changes and the resulting impact on the flow field for average percolation flux conditions. Thus, the percolation fluxes applied at the top model boundary are identical to the base-case simulation studied with the thermal-hydrologic seepage model (i.e., 6, 16, and 25 mm/yr, respectively), for the three climate periods. This is a reasonable approach because the thermal-hydrologic-mechanical behavior should not be strongly affected by percolation-flux boundary conditions. A conservative abstraction approach was chosen for thermal-hydrologic-mechanical effects, neglecting the potentially beneficial effect of thermal-hydrologic-mechanical-related property changes.

K.4.2.2.5 Thermal-Hydrologic-Chemical Seepage Model

The thermal-hydrologic-chemical seepage model is a drift-scale process model for predicting the composition of gas and water that could enter waste emplacement drifts and the effects of mineral alteration on flow in rocks surrounding drifts (BSC 2003c). The latter effect can be important for seepage abstraction: mineral precipitation is predicted to form precipitation caps of calcite, silica, and other minerals above emplacement drifts, leading to changes in fracture porosity, permeability, and local percolation. The modeling framework for the thermal-hydrologic simulations (including grid design, boundary conditions, and rock properties) is similar to the thermal-hydrologic seepage model and the drift-scale thermal-hydrologic-mechanical model. The thermal-hydrologic seepage model focuses on the thermal-hydrologic conditions to evaluate seepage rates for various seepage-relevant parameter cases. The thermal-hydrologic-chemical simulations concentrate on the chemical processes and their related sensitivities, for average percolation flux conditions identical to the base-case simulation studied with the thermal-hydrologic seepage model (6, 16, and 25 mm/yr). The model includes a wide range of major and minor aqueous species and minerals. Sensitivity studies are performed to evaluate the impact of, for example, alternative geochemical systems, initial water compositions, and reaction rates. The model results indicate that a precipitation cap may form above drifts that could divert fluxes sideways and potentially reduce seepage. In a conservative abstraction approach, this thermal-hydrologic-chemical effect is neglected because of the considerable model uncertainty, part of which stems from the fact that the percolation fluxes are not varied in the study.

K.4.3 Uncertainties Regarding Evaporation Effects and Drift Degradation

GEN 1.01 (Comment 82) (Reamer 2001b) is concerned with uncertainties regarding evaporation effects and drift degradation. These issues are addressed in the current revisions of the following documents:

1. In the current revision of the seepage calibration model (BSC 2004c), uncertainties regarding evaporation effects have been directly addressed by incorporation of an isothermal vapor diffusion model, as described in the model report documentation (BSC 2004c, Section 6.6.1.3).

2. The current revision of the seepage model for performance assessment (BSC 2004d) incorporates degradation scenarios evaluated in *Drift Degradation Analysis* (BSC 2001c). Degradation scenarios considered in Revision 1 show that the impact of geometry changes on seepage is negligible for both the lithophysal and nonlithophysal units. Improved degradation analyses documented in Revision 2 of *Drift Degradation Analysis* (BSC 2004h) show that the changes in drift geometry in the nonlithophysal units are negligible. Thus, impact of degradation on seepage is also considered negligible for the nonlithophysal units. Revision 2 degradation scenarios for lithophysal units indicate that the worst-case scenario is complete collapse of drift (rubble-filled circular drift). This worst-case degradation scenario was used to perform additional seepage simulations in *Abstraction of Drift Seepage* (BSC 2004e, Section 6.4.2.4.2). Systematic seepage simulations for the collapsed drift case were conducted for the full set of parameter combinations used for the nondegraded drift simulations. The resulting seepage values are provided in a seepage lookup table for the collapsed drift scenario (DTN: LB0307SEEPDRCL.002). Moreover, to account for the uncertainties associated with the drift degradation analyses, the calculated seepage rates were increased by 20%.

K.5 REFERENCES

K.5.1 Documents Cited

Bandurraga, T.M. and Bodvarsson, G.S. 1999. "Calibrating Hydrogeologic Parameters for the 3-D Site-Scale Unsaturated Zone Model of Yucca Mountain, Nevada." *Journal of Contaminant Hydrology*, *38*, (1–3), 25–46. New York, New York: Elsevier. TIC: 244160.

Bodvarsson, G.S.; Boyle, W.; Patterson, R.; and Williams, D. 1999. "Overview of Scientific Investigations at Yucca Mountain—The Potential Repository for High-Level Nuclear Waste." *Journal of Contaminant Hydrology*, *38*, (1–3), 3–24. New York, New York: Elsevier. TIC: 244160.

BSC (Bechtel SAIC Company) 2001a. *FY 01 Supplemental Science and Performance Analyses, Volume 1: Scientific Bases and Analyses*. TDR-MGR-MD-000007 REV 00 ICN 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20010801.0404; MOL.20010712.0062; MOL.20010815.0001.

BSC 2001b. *Multiscale Thermohydrologic Model*. ANL-EBS-MD-000049 REV 00 ICN 02. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20020123.0279.

BSC 2001c. *Drift Degradation Analysis.* ANL-EBS-MD-000027 REV 01 ICN 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20011029.0311.

BSC 2002. *Thermal Conductivity of the Potential Repository Horizon Model Report*. MDL-NBS-GS-000005 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20020923.0167.

BSC 2003a. *UZ Flow Models and Submodels*. MDL-NBS-HS-000006 REV 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20030818.0002.

BSC 2003b. *Drift-Scale Coupled Processes (DST and TH Seepage) Models.* MDL-NBS-HS-000015 REV 00C. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20030910.0160.

BSC 2003c. *Drift-Scale Coupled Processes (DST and THC Seepage) Models.* MDL-NBS-HS-000001 REV 02. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20030804.0004.

BSC 2003d. *Multiscale Thermohydrologic Model.* ANL-EBS-MD-000049 REV 01G. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20031212.0037.

BSC 2003e. *Drift Scale THM Model.* MDL-NBS-HS-000017 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20030818.0003.

BSC 2003f. *Calibrated Properties Model.* MDL-NBS-HS-000003 REV 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20030219.0001.

BSC 2003g. *Repository Design, 21-PWR Waste Package Configuration.* 000-MW0-DSU0-00403-000-00A. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20030903.0007.

BSC 2004a. *Multiscale Thermohydrologic Model.* ANL-EBS-MD-000049 REV 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20040301.0004.

BSC 2004b. *UZ Flow Models and Submodels.* MDL-NBS-HS-000006 REV 01, with errata. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20030818.0002; DOC.20040211.0008.

BSC 2004c. *Seepage Calibration Model and Seepage Testing Data.* MDL-NBS-HS-000004 REV 02, with errata. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20030408.0004; DOC.20040202.0003; DOC.20040219.0003.

BSC 2004d. *Seepage Model for PA Including Drift Collapse.* MDL-NBS-HS-000002 REV 02, with errata. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20030709.0001; DOC.20040512.0002; DOC.20040615.0004.

BSC 2004e. *Abstraction of Drift Seepage.* MDL-NBS-HS-000019 REV 00 ICN 01, with errata. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20031112.0002; DOC.20040223.0001.

BSC 2004f. *UZ Flow Models and Submodels.* MDL-NBS-HS-000006 REV 01 ICN 01A. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20040126.0082.

BSC 2004g. *Drift-Scale Coupled Processes (DST and TH Seepage) Models.* MDL-NBS-HS-000015. REV 00F Redline. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20040512.0072.

BSC 2004h. *Drift Degradation Analysis.* ANL-EBS-MD-000027 REV 02, with errata. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20040325.0002; DOC.20030709.0003.

Nitao, J.J. 1998. *Reference Manual for the NUFT Flow and Transport Code, Version 2.0.* UCRL-MA-130651. Livermore, California: Lawrence Livermore National Laboratory. TIC: 238072. ACC: MOL.19980810.0391.

NRC (U.S. Nuclear Regulatory Commission) 2002. *Integrated Issue Resolution Status Report.* NUREG-1762. Washington, D.C.: U.S. Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguards. TIC: 253064.

Reamer, C.W. 2001a. U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Total System Performance Assessment and Integration (August 6 through 10, 2001). Letter from C.W. Reamer (NRC) to S. Brocoum (DOE/YMSCO), August 23, 2001, with enclosure. ACC: MOL.20011029.0281.

Reamer, C.W. 2001b. U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Range of Operating Temperatures (September 18–19, 2001). Letter from C.W. Reamer (NRC) to S. Brocoum (DOE), October 2, 2001, 1018010176, with enclosures. ACC: MOL.20020102.0138.

USGS (U.S. Geological Survey) 2001a. *Future Climate Analysis.* ANL-NBS-GS-000008 REV 00 ICN 01. Denver, Colorado: U.S. Geological Survey. ACC: MOL.20011107.0004.

USGS 2001b. *Simulation of Net Infiltration for Modern and Potential Future Climates.* ANL-NBS-HS-000032 REV 00 ICN 02. Denver, Colorado: U.S. Geological Survey. ACC: MOL.20011119.0334.

Wu, Y.S.; Haukwa, C.; and Bodvarsson, G.S. 1999. "A Site-Scale Model for Fluid and Heat Flow in the Unsaturated Zone of Yucca Mountain, Nevada." *Journal of Contaminant Hydrology*, *38*, (1–3), 185–215. New York, New York: Elsevier. TIC: 244160.

Wu, Y.-S.; Pan, L.; Zhang, W.; and Bodvarsson, G.S. 2002. "Characterization of Flow and Transport Processes within the Unsaturated Zone of Yucca Mountain, Nevada, Under Current and Future Climates." *Journal of Contaminant Hydrology*, *54*, (3–4), 215-247. New York, New York: Elsevier. TIC: 253316.

K.5.2 Data, Listed by Data Tracking Number

GS000308311221.005. Net Infiltration Modeling Results for 3 Climate Scenarios for FY99. Submittal date: 03/01/2000.

LB0307SEEPDRCL.002. Seepage Into Collapsed Drift: Data Summary. Submittal date: 07/21/2003.

INTENTIONALLY LEFT BLANK