APPENDIX I

REPRESENTING VARIABILITY AND UNCERTAINTY IN THERMAL EFFECTS ON FLOW SIMULATIONS (RESPONSE TO TEF 2.10 AIN-1)

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 I

REPRESENTING VARIABILITY AND UNCERTAINTY IN THERMAL EFFECTS ON FLOW SIMULATIONS (RESPONSE TO TEF 2.10 AIN-1)

This appendix provides a response for Key Technical Issue (KTI) agreement Thermal Effects on Flow (TEF) 2.10 additional information need (AIN)-1. This agreement relates to the propagation of variability and uncertainty in TEF simulations (in general) and in the multiscale thermal-hydrologic model simulations (in particular), which support the total system performance assessment for the license application (TSPA-LA). The NRC concern is that the full range of model and parameter uncertainty be incorporated in the TSPA-LA.

I.1 KEY TECHNICAL ISSUE AGREEMENT

I.1.1 TEF 2.10

Agreement TEF 2.10 was reached during the NRC/U. S. Department of Energy (DOE) Technical Exchange and Management Meeting on Thermal Effects on Flow held January 8 and 9, 2001, in Pleasanton, California (Reamer and Williams 2001). This meeting was convened to discuss two TEF subissues: (1) features, events, and processes related to thermal effects on flow and (2) thermal-hydrologic modeling for the current repository design. During the course of this meeting, TEF 2.10 was reached under Subissue 2.

The wording of the agreement is as follows:

TEF 2.10

> Represent the full variability/uncertainty in the results of the TEF simulations in the abstraction of thermodynamic variables to other models, or provide technical basis that a reduced representation is appropriate (considering risk significance).

The NRC staff clarified its concern regarding the representation of the full range of model and parameter uncertainty in the results of the TEF simulations and informed DOE of additional information needs (Reamer 2002).

Reamer (2002) states:

> The NRC concern is that the full range of model and parameter uncertainty be incorporated in the TSPA. The multiscale thermohydrologic model (MSTH) is an ensemble of process models linked by abstractions. The MSTH is also linked directly or indirectly to other process models. For example, the NRC is concerned that variability/uncertainty in calibrated properties is treated by using high and low infiltration boundary conditions in addition to the mean in the least-squares inversion to obtain calibrated properties. The NRC believes this accounts for variability/uncertainty only in the infiltration boundary condition. As discussed in TEF IRSR, Rev 03, there are other sources of variability/uncertainty that are not accounted for in this methodology. These include: model uncertainty

> as seen in results from various alternative conceptual models and data uncertainty in (i) measurement error, bias, and scale-dependence in the saturation, water potential, and pneumatic pressure data used for model parameter calibration, (ii) heterogeneity and spatial variability in thermohydrologic properties, and (iii) variability in model results using the various property sets found to be valid for thermohydrologic modeling and model uncertainty as seen in results from various alternative conceptual models.
>
> The NRC has reviewed the other TEF agreements and believe that the supporting material for satisfying this issue is covered by TEF Agreements 2.08, 2.11, and 2.12. TEF Agreement 2.08 states that DOE will "provide…results of the outlined items on page 20 of the OI 7 presentation," TEF 2.11 states that DOE will "incorporate uncertainty from all significant sources" in the calibrated properties and TEF 2.12 states that DOE will "provide…resolution of issues on page 5 of the OI 8 presentation" on representation of model uncertainty. The NRC staff believes that TEF Agreements 2.08, 2.11, and 2.12 form the basis for determining the full range of possible state variables (temperature, pressure, relative humidity, liquid and vapor flux, etc.). TEF Agreement 2.10 would be satisfied if: (i) the full range of state variables are abstracted for use in TSPA, or (ii) a basis is provided for a reduced representation of model and parameter uncertainty in the TSPA. Documentation of either option should be presented in future AMRs completed prior to license application.

The wording of the AIN is as follows:

TEF 2.10 AIN 1

> DOE should inform the NRC staff how it plans to address this issue and where it will be documented.

I.1.2 Related Key Technical Issue Agreements

Agreements TEF 2.08, 2.11, and 2.12 are related to TEF 2.10. TEF 2.11 states that DOE will incorporate uncertainty from all significant sources in the calibrated properties, and TEF 2.12 states that DOE will address model uncertainty.

I.2 RELEVANCE TO REPOSITORY PERFORMANCE

The primary TEF model that is affected by TEF 2.10 is the multiscale thermal-hydrologic model. The multiscale thermal-hydrologic model (BSC 2004a) calculates the following thermal-hydrologic (state) variables: temperature, relative humidity, liquid-phase saturation, evaporation rate, air mass fraction, gas-phase pressure, capillary pressure, and liquid- and gas-phase fluxes. These variables are determined throughout the repository area and for each of the waste package types, including waste packages containing commercial spent nuclear fuel and waste packages containing DOE high-level radioactive waste. These thermal-hydrologic variables are used by various process models and abstractions in TSPA that address the following:

- General corrosion of the waste package
- Localized corrosion of the waste package
- Waste-form degradation
- Radionuclide solubility
- In-drift seepage chemistry evolution and thermal seepage
- Dust-leachate evolution
- Radionuclide transport in the engineered barrier system.

TSPA utilizes (abstracts) the full range of thermal-hydrologic (state) variables calculated by the multiscale thermal-hydrologic model for each of the emplacement drifts across the repository area.

I.3 RESPONSE

The TSPA uses an approach that fully addresses the range of thermal-hydrologic (state) variables across the repository arising as a result of all significant factors, parameters, and conditions contributing to that variability and uncertainty. The TSPA accomplishes this by utilizing the range of thermal-hydrologic (state) variables calculated by the *Multiscale Thermohydrologic Model* (BSC 2004b). The propagation of parametric variability and uncertainty in the multiscale thermal-hydrologic model addresses the key natural system parameters: host-rock thermal conductivity and percolation flux (BSC 2004b, Section 8.2). A sensitivity study of the influence of hydrologic-property uncertainty (BSC 2004a, Section 6.3.2.4) supports the conclusion (BSC 2004a, Section 8.2) that hydrologic-property uncertainty does not need to be propagated in the multiscale thermal-hydrologic model calculations of in-drift temperature and relative humidity. The propagation of percolation-flux variability/uncertainty and host-rock thermal conductivity variability/uncertainty on repository-wide multiscale thermal-hydrologic model output is captured with five infiltration-flux/host-rock-thermal-conductivity cases:

1. Lower-bound infiltration flux case with low (mean minus one standard deviation) host-rock thermal conductivity

2. Lower-bound infiltration flux case with mean host-rock thermal conductivity

3. Mean infiltration flux case with mean host-rock thermal conductivity

4. Upper-bound infiltration flux case with mean host-rock thermal conductivity

5. Upper-bound infiltration flux case with high (mean plus one standard deviation) host-rock thermal conductivity.

These five cases, together with their associated probabilities (see Table I-1 in Section I.4.1), bound the range of parametric variability/uncertainty of the key natural system parameters that are responsible for variability in the thermal-hydrologic (state) variables across the repository: host-rock thermal conductivity and percolation flux (BSC 2004b, Table 6.3-35). The multiscale thermal-hydrologic model also addresses the influence of the other key factors resulting in the variability in thermal-hydrologic (state) variables across the repository, notably: (1) waste-package-to-waste-package variability in heat output and (2) the repository footprint shape, which influences the evolution of the edge-cooling effect that increases with proximity to the repository edges.

Conceptual-model uncertainty has also been addressed for the primary TEF models that support TSPA. As discussed in *Abstraction of Drift Seepage* (BSC 2003a, Section 6.4.3.2), conceptual-model uncertainty related to the thermal-hydrologic seepage model has been addressed in *Drift-Scale Coupled Processes (DST and TH Seepage) Models* (BSC 2003b, Sections 7 and 8.2) by careful validation of the coupled thermal-hydrologic processes in comparison with in situ heater tests. *Multiscale Thermohydrologic Model* (BSC 2004a, Section 7.3) validates the multiscale thermal-hydrologic model against an alternative conceptual model, showing that the small differences in predicted thermal-hydrologic conditions (between the multiscale thermal-hydrologic model and the alternative conceptual model) in the repository are much smaller than the range of predicted thermal-hydrologic conditions arising from parameter uncertainty of host-rock thermal conductivity and percolation flux above the repository. The differences between the multiscale thermal-hydrologic model and the alternative conceptual model are much smaller than the differences in predicted thermal-hydrologic conditions that arise as a result of proximity to the repository edges (i.e., the edge-cooling effect) and as a result of waste package–to–waste package variability in heat output. Therefore, *Multiscale Thermohydrologic Model* (BSC 2004b, Section 8.2) concludes that it is unnecessary to propagate conceptual-model uncertainty in the results of the multiscale thermal-hydrologic model.

The information in this report is responsive to AIN request TEF 2.10 AIN-1. This report contains the information that DOE considers necessary for NRC review for closure of this agreement.

I.4 BASIS FOR THE RESPONSE

I.4.1 Propagating Parameter Variability and Uncertainty in Thermal Effects on Flow Simulations

The multiscale thermal-hydrologic model is the primary TEF model that provides TSPA the range of thermal-hydrologic (state) variables across the repository. The multiscale thermal-hydrologic model calculates the following thermal-hydrologic (state) variables: temperature, relative humidity, liquid-phase saturation, evaporation rate, air-mass fraction, gas-phase pressure, capillary pressure, and liquid- and gas-phase fluxes (BSC 2004a, Section 1). The thermal-hydrologic variables are determined as a function of position along each of the emplacement drifts in the repository and as a function of waste package type. These variables are determined at various representative locations within the emplacement drifts, including the waste package and drip shield surfaces and in the invert; they are also determined at various generic locations in the adjoining host rock. These variables are determined every 20 m for each emplacement drift in the repository. Each emplacement drift is represented with its precise coordinate location, as well as each of the emplacement panels in the repository area. The multiscale thermal-hydrologic model also accounts for the manner in which the emplacement drifts are to be ventilated during the preclosure period, including how heat-removal efficiency from drift ventilation varies as a function of time and distance along each of the emplacement drifts. The multiscale thermal-hydrologic model accounts for three-dimensional drift-scale and mountain-scale heat flow. The multiscale thermal-hydrologic model captures the influence of the key engineering-design variables and natural system factors affecting thermal-hydrologic conditions in the emplacement drifts and adjoining host rock, including the following:

- Repository-scale variability of percolation flux above the repository
- Temporal variability of percolation flux (as influenced by climate change)
- Uncertainty in percolation flux (as addressed by the low-, mean-, and high-percolation flux cases)
- Repository-scale variability of thermal conductivity (notably in host rock)
- Uncertainty in host-rock thermal conductivity (notably in the host rock)
- Repository-scale variability of bulk-rock density and specific heat
- Repository-scale variability of hydrologic properties of the rock matrix
- Repository-scale variability of hydrologic properties of fractures
- Repository-scale variability in overburden thickness
- Overall areal heat-generation density of the waste inventory, which is quantified by the areal mass loading (expressed in metric tons of uranium per acre)
- Line-averaged thermal load along emplacement drifts, which is quantified by the lineal power density (expressed in kilowatts per meter)
- Distance between emplacement drifts (also called drift spacing)
- Age of spent nuclear fuel at time of emplacement
- Location of the repository with respect to the stratigraphy
- Repository footprint shape, which influences the evolution of the edge-cooling effect that increases with proximity to the repository edges

- Dimensions of the in-drift design (waste packages, drip shield, and invert)
- Properties of the in-drift engineered barrier system components
- Waste-package-to-waste-package variability in heat output
- Time- and distance-dependent heat-removal efficiency of preclosure drift ventilation
- Duration and heat-removal efficiency of drift ventilation.

Although the multiscale thermal-hydrologic model addresses all of these factors that give rise to variability in the thermal-hydrologic (state) variables across the repository, a relatively small number of parameters and factors are responsible for the vast majority of variability in thermal-hydrologic conditions in the repository. In order of importance, these are:

1. Edge-cooling effect, which increases with proximity to the edges of the repository
2. Variability and uncertainty in host-rock thermal conductivity
3. Variability and uncertainty in percolation flux above the repository
4. Waste-package-to-waste-package variability in heat output.

Multiscale Thermohydrologic Model (BSC 2004b, Section 6.3) discusses this ranking in an evaluation of the primary contributors to thermal-hydrologic variability across the repository. The multiscale thermal-hydrologic model simulations supporting TSPA address the influence of these four items by incorporating five infiltration-flux/host-rock-thermal-conductivity cases and their associated probabilities (Table I-1). The rationale for these five selected cases and their associated probabilities is given in *Multiscale Thermohydrologic Model* (BSC 2004b, Section 6.3.4). A sensitivity study of the influence of hydrologic-property uncertainty (BSC 2004a, Section 6.3.2.4) supports the conclusion (BSC 2004a, Section 8.2) that hydrologic-property uncertainty does not need to be propagated in the multiscale thermal-hydrologic model calculations of in-drift temperature and relative humidity.

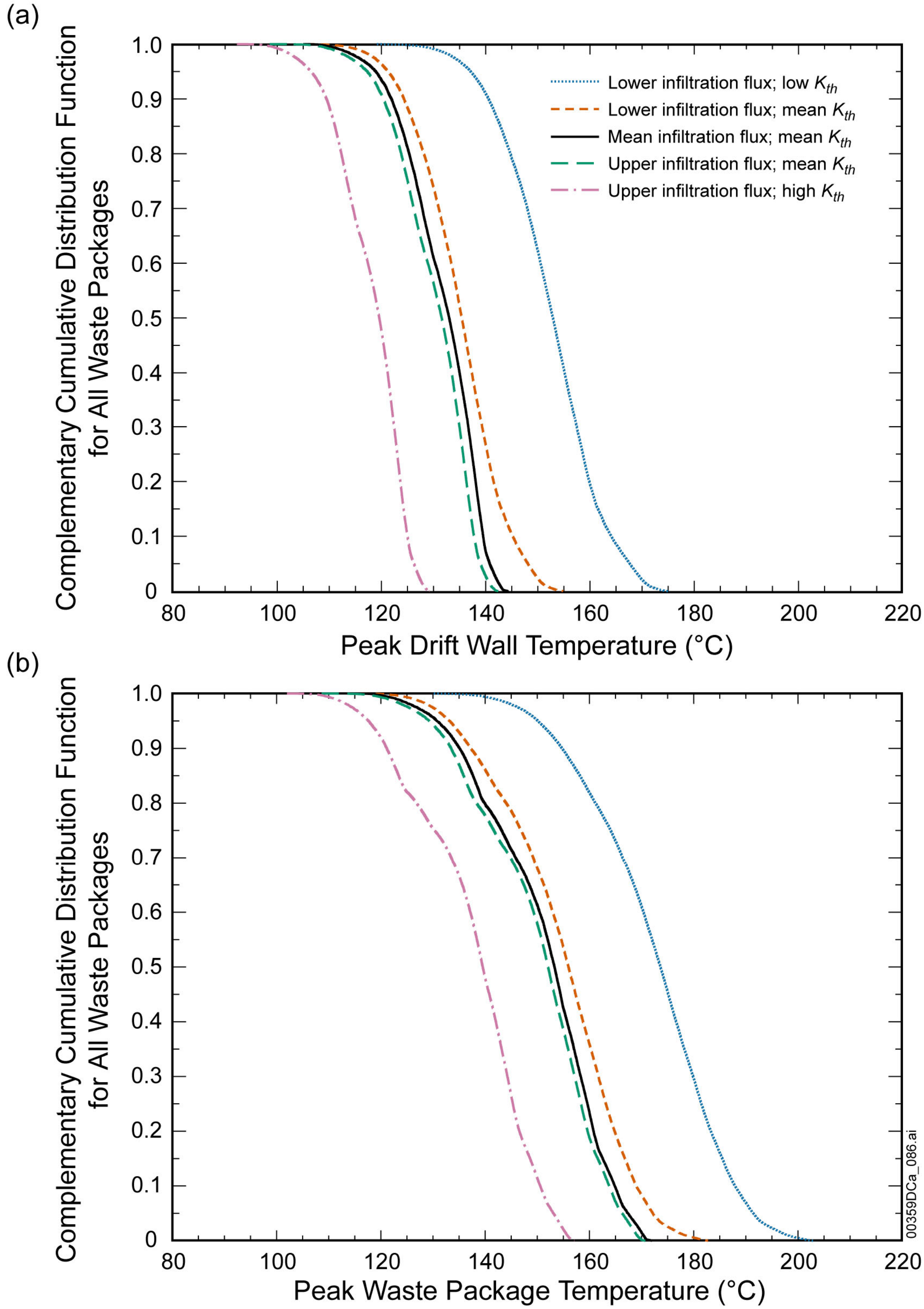
Table I-1. Probabilities of the Combinations of the Three Infiltration Flux Cases and the Three Host-Rock Thermal Conductivity Cases

	Probability			
	Host-Rock Thermal-Conductivity Case			
Flux Case	**All**	**Low (Mean −1 SD)**	**Infiltration Mean**	**High (Mean +1 SD)**
All	1.0000	0.33333	0.33333	0.33333
Lower	0.2400	0.08000	0.21667	
Mean	0.4100		0.33333	
Upper	0.3500		0.25334	0.11666

Source: BSC 2004b, Table 6.3-35.

NOTE: SD = standard deviation. As discussed in *Multiscale Thermohydrologic Model* (BSC 2004b, Section 6.3.4), the four cases without listed probabilities are addressed by grouping them into equivalent cases. Thus, the mean-infiltration flux low-thermal-conductivity case is grouped into the lower-infiltration flux mean-thermal-conductivity case, while the mean-infiltration-flux high-thermal-conductivity case is grouped into the upper-infiltration-flux mean-thermal-conductivity case. Both the lower-infiltration-flux high-thermal-conductivity case and the upper-infiltration-flux low-thermal-conductivity case are grouped into the mean-infiltration flux mean-thermal-conductivity case.

These five cases result in a wide range of simulated thermal-hydrologic conditions across the repository area. Figure I-1 gives the complementary cumulative distribution function for the peak temperature on the drift wall and on waste packages for the five infiltration-flux/host-rock-thermal-conductivity cases. These complementary cumulative distribution functions are for all waste packages over the entire repository area. Table I-2 gives the coolest, median, and hottest peak drift wall and waste package temperatures for these five cases. Because there are 2,874 locations in the multiscale thermal-hydrologic model (BSC 2004a, Table 6.2-1) and eight different waste packages that are represented at each location, there are a total of 22,992 waste package histories provided in each of the five cases for which repository-wide multiscale thermal-hydrologic model calculations were conducted.



Source: BSC 2004b, Figure 6.3-50.

NOTE: The five cases cover the range of percolation-flux and host-rock thermal-conductivity uncertainty addressed in Table I-1.

Figure I-1. The Complementary Cumulative Distribution Function for Peak Temperature on the (a) Drift Wall and (b) Waste Packages for Five Infiltration Flux Cases

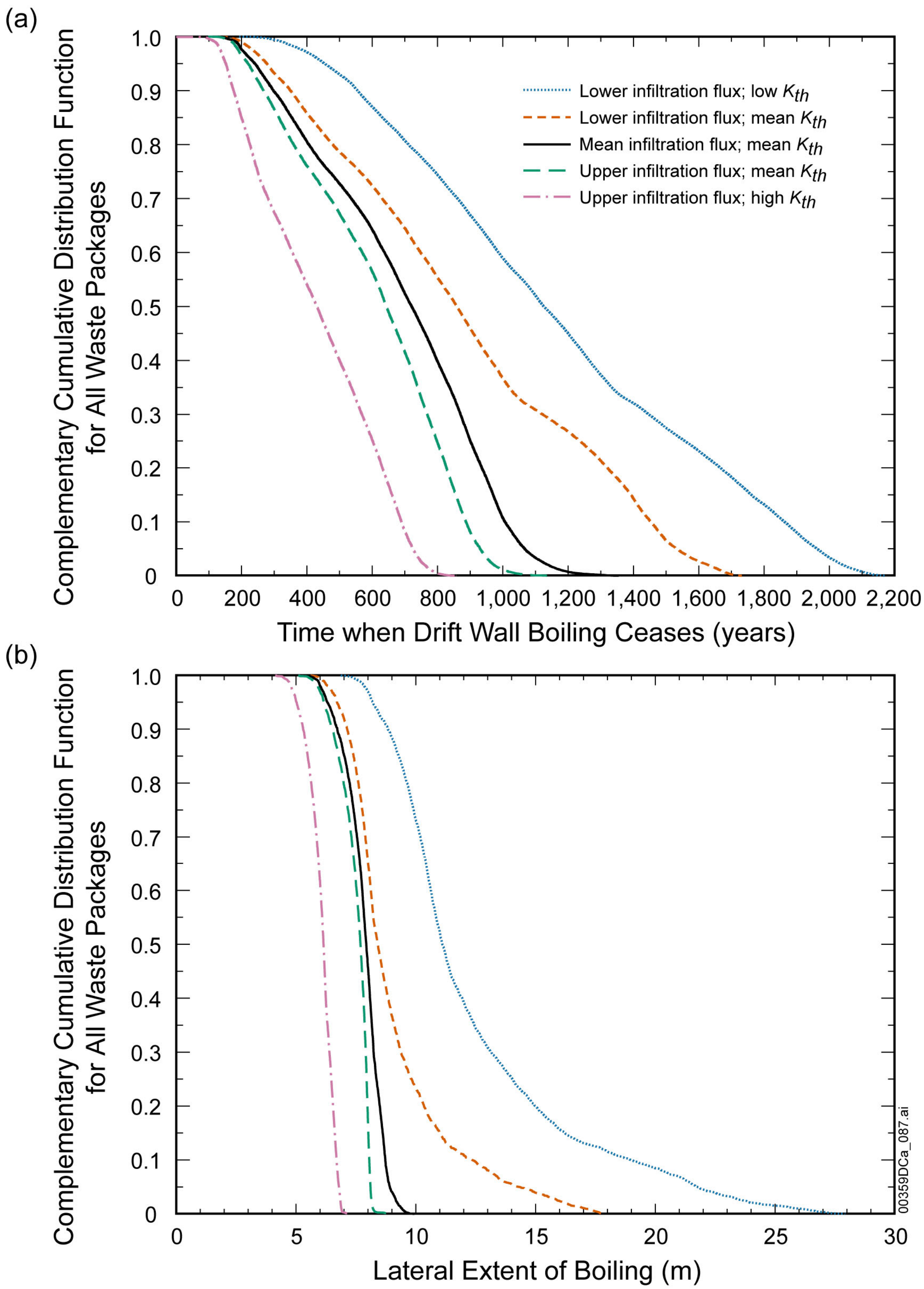
Table I-2. Peak Drift-Wall and Waste Package Temperatures for Five Cases Covering the Range of Percolation-Flux and Host-Rock Thermal-Conductivity Uncertainty

Case	Peak Drift Wall Temperature (°C)			Peak Waste Package Temperature (°C)		
	Coolest	Median	Hottest	Coolest	Median	Hottest
Lower-bound infiltration flux, low-thermal-conductivity	119.1	152.9	175.2	130.1	173.6	203.1
Lower-bound infiltration flux, mean-thermal-conductivity	105.7	135.4	154.8	116.3	156.0	182.9
Mean infiltration flux, mean thermal-conductivity	105.0	133.0	144.2	115.6	153.3	172.0
Upper-bound infiltration flux, mean thermal-conductivity	98.6	131.6	142.5	108.6	152.1	170.8
Upper-bound infiltration flux, high thermal-conductivity	92.3	119.6	129.3	102.0	139.5	157.2

Source: BSC 2004b, Table 6.3-36.

NOTE: This table is based on Figure I-1.

Figure I-2a plots the complementary cumulative distribution function for the time when boiling at the drift wall ceases for each of the five infiltration-flux–host-rock-thermal-conductivity cases. These complementary cumulative distribution functions are for all waste package locations in the repository. Table I-3 lists the coolest, median, and hottest waste-package locations for each of these five cases. As was the case for peak temperatures, the boiling-period duration increases with decreasing percolation flux and with decreasing host-rock thermal conductivity. Figure I-2b and Table I-4 give the complementary cumulative distribution function for the maximum lateral extent of the boiling-point isotherm for the five cases. As was the case for the peak temperatures and boiling-period duration, the maximum lateral extent of boiling increases with decreasing percolation flux and with decreasing host-rock thermal conductivity. Figure I-3 gives the temperature and relative humidity histories for all waste packages in the repository. The plots in Figure I-3, sometimes referred to as horsetail plots, also break down the ranges in temperature and relative humidity histories into two groupings: (1) commercial spent nuclear fuel and (2) defense high-level radioactive waste.



Source: BSC 2004b, Figure 6.3-51.

NOTE: The five cases cover the range of percolation-flux and host-rock thermal-conductivity uncertainty addressed in Table I-1.

Figure I-2. Complementary Cumulative Distribution Functions for (a) Time when Boiling at the Drift Wall Ceases and (b) Maximum Lateral Extent of the Boiling-Point Isotherm (96°C) from the Drift Centerline for Five Infiltration Flux Cases

Table I-3. Time When Boiling Ceases at the Drift Wall for Five Cases Covering the Range of Percolation-Flux and Host-Rock Thermal-Conductivity Uncertainty

Infiltration-Flux, Host-Rock Thermal-Conductivity Case	Time When Boiling at the Drift Wall Ceases (years)						
	Shortest	10th Percentile	30th Percentile	Median	70th Percentile	90th Percentile	Longest
Lower-bound infiltration flux, low thermal-conductivity	192.6	555.3	861.6	1125.4	1447.4	1862.7	2176.5
Lower-bound infiltration flux, mean thermal-conductivity	130.2	349.9	630.9	859.6	1122.5	1453.3	1734.6
Mean infiltration-flux, mean thermal-conductivity	127.2	297.5	535.8	721.0	870.6	1006.5	1356.0
Upper-bound infiltration flux, mean thermal-conductivity	97.7	267.7	471.6	643.7	768.6	887.2	1162.9
Upper-bound infiltration flux, high-thermal-conductivity	NA*	175.7	281.6	430.4	568.9	689.5	859.5

Source: BSC 2004b, Table 6.3-37 and Figure 6.3-51a.

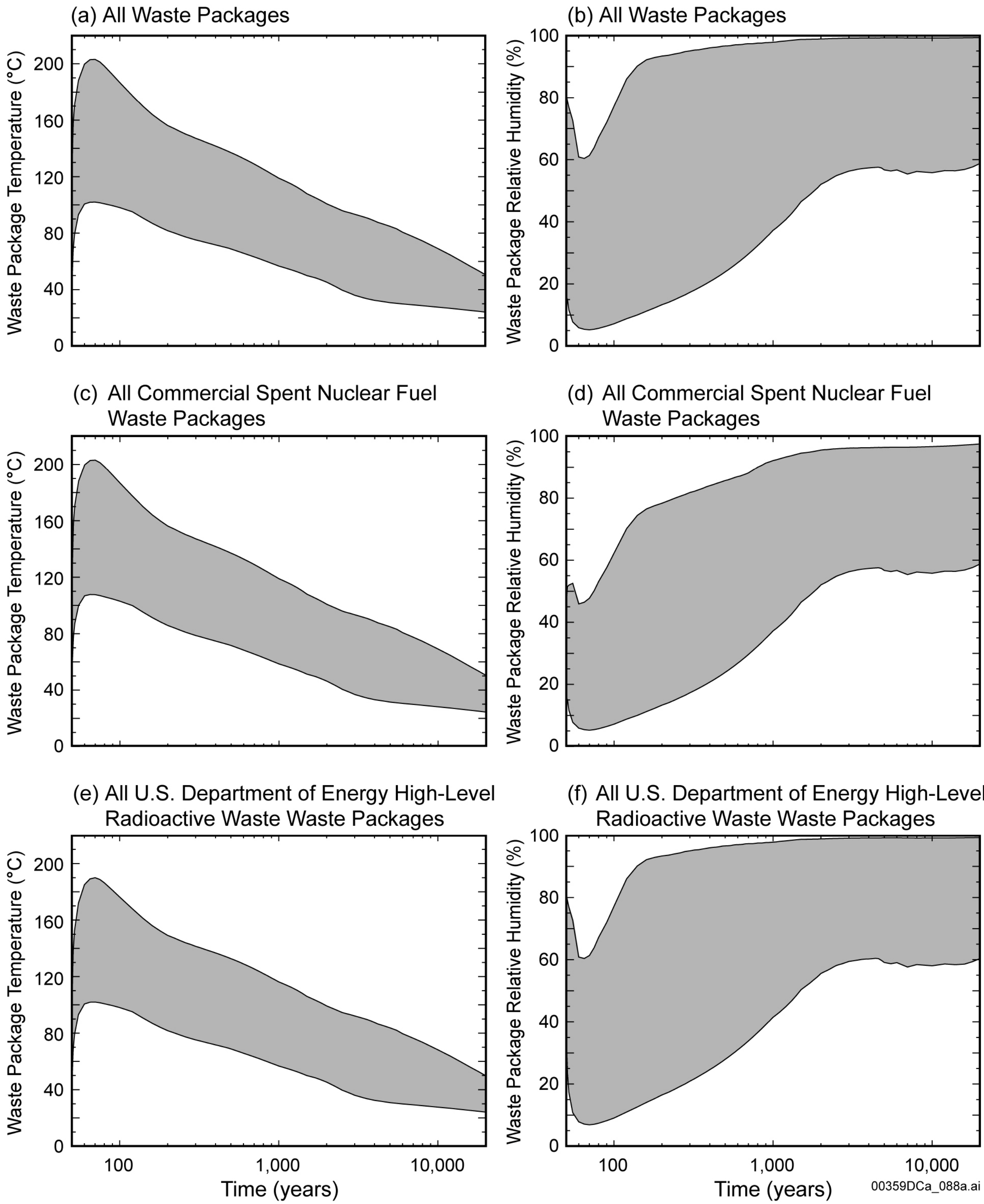
NOTE: *22 out of 22,992 waste package/location combinations (or 0.1% of the total) never experience boiling at the drift wall.
This table is based on Figure I-2a.

Table I-4. Maximum Lateral Extent of the Boiling-Point Isotherm (96°C), Measured from Drift Centerline, for Five Cases Covering the Range of Percolation-Flux and Host-Rock Thermal-Conductivity Uncertainty

Infiltration-Flux, Host-Rock Thermal-Conductivity Case	Maximum Lateral Extent of Boiling (Temperature > 96°C) (m)						
	Least	10th Percentile	30th Percentile	Median	70th Percentile	90th Percentile	Greatest
Lower-bound infiltration flux, low-thermal-conductivity	6.9	8.8	10.2	11.1	13.2	19.0	27.9
Lower-bound infiltration flux, mean thermal-conductivity	5.6	7.1	7.9	8.4	9.4	12.3	17.8
Mean infiltration flux, mean thermal-conductivity	5.3	6.7	7.5	7.9	8.2	8.7	9.9
Upper-bound infiltration flux, mean thermal-conductivity	5.1	6.5	7.3	7.7	7.9	8.1	9.0
Upper-bound infiltration flux, high-thermal-conductivity	4.1*	5.3	5.9	6.1	6.4	6.7	7.2

Source: BSC 2004b, Table 6.3-38 and Figure 6.3-51b.

NOTE: *22 out of 22,992 waste package/location combinations (or 0.1% of the total) never experience boiling at the drift wall; therefore, for those locations, the lateral extent of boiling is inside the emplacement drift.
This table is based on Figure I-2b.



Source: BSC 2004b, Figure 6.3-52.

NOTE: The ranges include the five cases listed in Table I-1.

Figure I-3. Range of Waste Package Temperature and Relative Humidity Histories for all Waste Packages (a, b), for Commercial Spent Nuclear Fuel Waste Packages (c, d), and for Defense High-Level Radioactive Waste Packages (e, f)

As discussed above, the multiscale thermal-hydrologic model simulations supporting the TSPA address a wide range in percolation flux above the repository, which is the percolation flux at the base of the PTn unit (DTN: LB0302PTNTSW9I.001). Table I-5 lists the repository-wide-averaged percolation flux for the lower-bound, mean, and upper-bound infiltration flux cases. Table I-6 lists the range of percolation fluxes for the present-day climate across the repository area for each of these cases. As is apparent, the multiscale thermal-hydrologic model addresses a very wide range in percolation flux above the repository.

Table I-5. Repository-Wide-Averaged Percolation Flux for Lower-Bound, Mean, and Upper-Bound Infiltration Flux Cases

Infiltration Flux Case	Repository-Wide Averaged Percolation Flux (mm/yr)		
	Present-Day (0 years < *t* < 600 years)	Monsoonal (600 years < *t* < 2,000 years)	Glacial-Transition (2,000 years < *t*)
Lower	0.41	4.23	1.95
Mean	3.77	11.15	17.29
Upper	10.84	19.48	34.35

Source: BSC 2004a, Table 6.3-3.

NOTE: These averages are based on averaging the percolation data from DTN: LB0302PTNTSW9I.001 over the heated repository footprint represented in the SMT submodel (BSC 2004a, Attachment I).

Table I-6. Range of Percolation Fluxes for the Multiscale Thermal-Hydrologic Model for the Lower-Bound, Mean, and Upper-Bound Infiltration Flux Cases for the Present-Day Climate

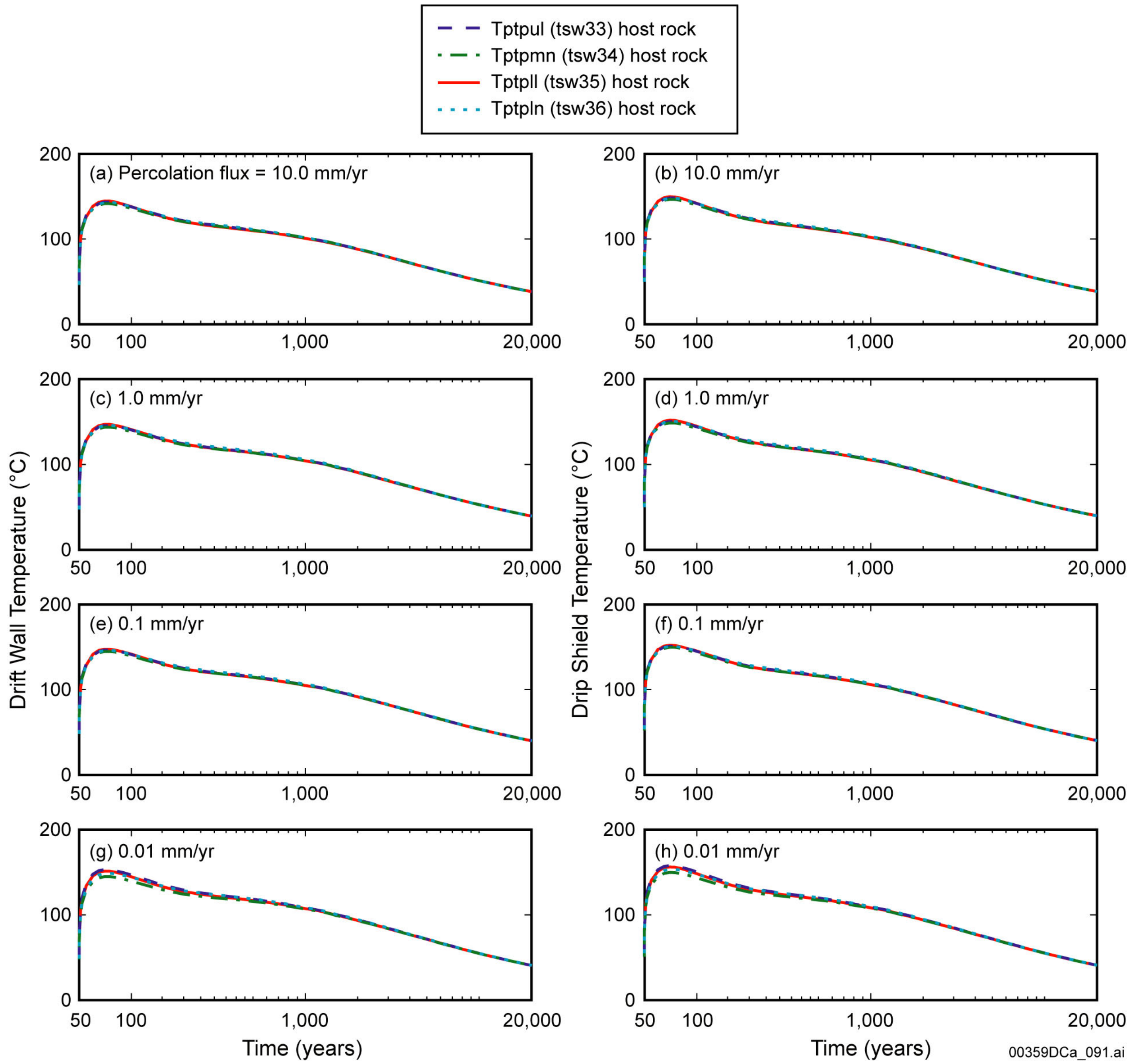
	Percolation flux (mm/yr)		
	Lower infiltration flux case	Mean infiltration flux case	Upper infiltration flux case
Lowest value	2.8×10^{-5}	0.24	1.12
Mean value	0.41	3.77	10.84
Highest value	3.47	13.74	36.18

Source: DTN: LL030808623122.036.

While the multiscale thermal-hydrologic model simulations that support TSPA address repository-scale variability in percolation flux above the repository, the question arises about whether it is necessary to address heterogeneity at a finer (meter) scale in these simulations. This question is addressed in a previous version of *Multiscale Thermohydrologic Model* (BSC 2001, Section 6.14), which discusses a sensitivity study of the influence of fine-scale (meter-scale) heterogeneity in fracture permeability and in the percolation-flux distribution above the repository on multiscale thermal-hydrologic model simulations. This study concluded that the thermal-hydrologic conditions simulated by the multiscale thermal-hydrologic model would not be changed during the boiling period by virtue of adding the influence of fine-scale heterogeneity of fracture permeability and percolation flux above the repository (BSC 2001, Section 7.2). It was also concluded that temperatures calculated by the multiscale thermal-hydrologic model would not be significantly changed during either the boiling or postboiling period by virtue of adding the influence of fine-scale heterogeneity of fracture permeability and percolation flux above the repository (BSC 2001, Section 7.2).

The multiscale thermal-hydrologic model addresses repository-scale variability of hydrologic properties. A sensitivity study of hydrologic-property variability, described below, for the four host-rock types (Tptpul, Tptpmn, Tptpll, and Tptpln) demonstrates that multiscale thermal-hydrologic model-simulated in-drift and near-field thermal-hydrologic conditions are insensitive to differences in the hydrologic property values for these respective host-rock units. The reason for this lack of sensitivity is provided in the discussion that follows the description of the hydrologic-property sensitivity analysis.

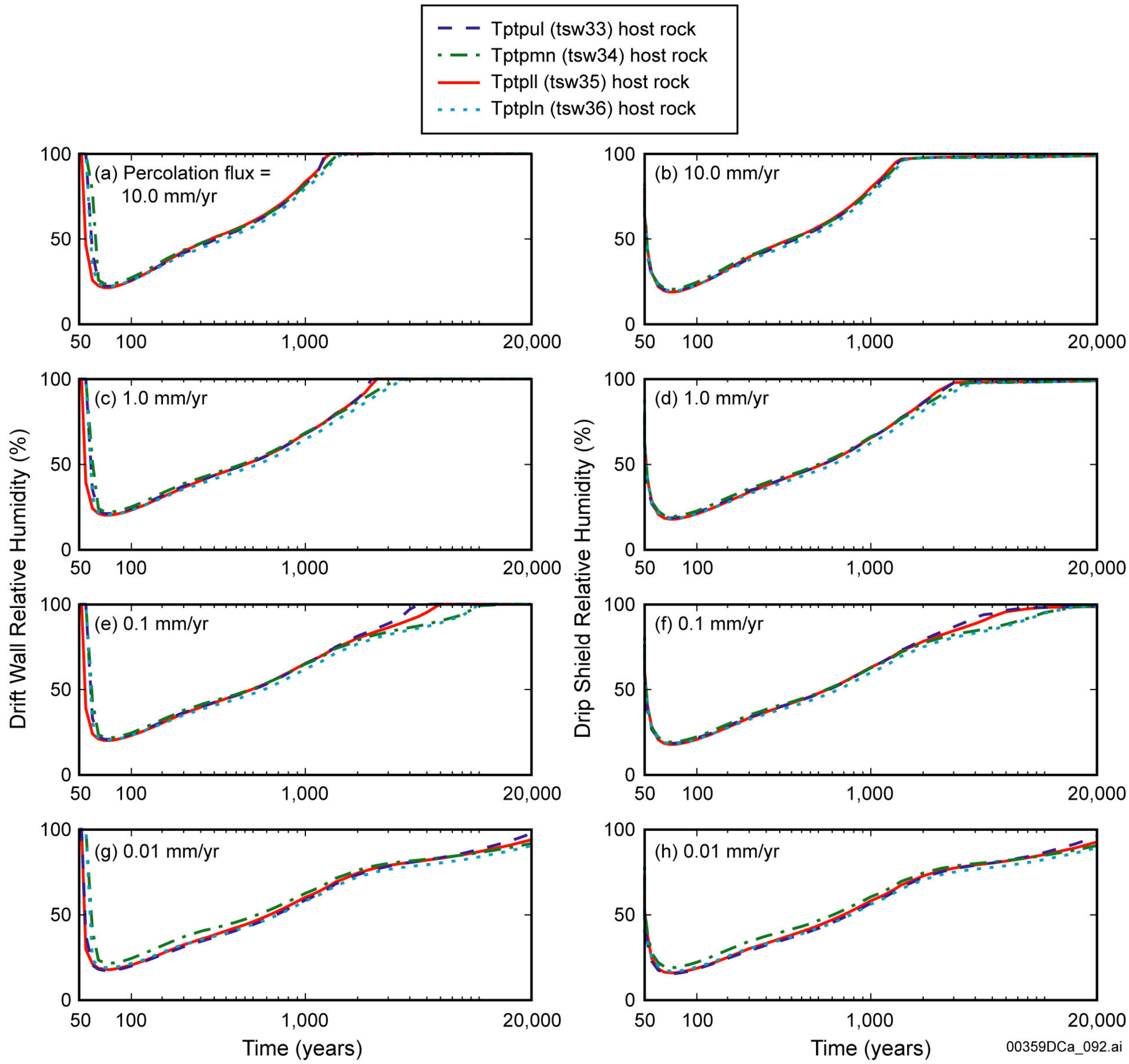
Figure I-4 gives the drift-wall and drip-shield temperature histories at a representative location at the center of the repository for percolation flux values ranging from 0.1 to 10 mm/yr. Figure I-5 gives the corresponding drift-wall and drip-shield relative humidity histories for this location. This location (the P2WR5C10 location shown in *Multiscale Thermohydrologic Model* (BSC 2004a, Figure 6.3-1)) happens to be in the Tptpll host-rock unit, which is the predominant host-rock type in the repository (BSC 2004a, Table 6.3-2). For the purpose of showing the influence of hydrologic-property variability, model calculations were made using the line-averaged-heat-source drift-scale thermal-hydrologic (LDTH) submodel (BSC 2004a, Section 6.2.6) applying the hydrologic property values for each of the host-rock types (Tptpul, Tptpmn, Tptpll, and Tptpln), respectively. For a percolation flux of 0.1 mm/yr or greater, temperature is insensitive to hydrologic properties (Figures I-4a to I-4f). For a percolation flux of 0.01 mm/yr, hydrologic properties exert a minor influence on temperature (Figures I-4g and I-4h). For a percolation flux of 1 mm/yr or greater, relative humidity is insensitive to hydrologic properties (Figures I-5a to I-5d). For a percolation flux of 0.1 mm/yr or less, hydrologic properties exert a minor influence on relative humidity (Figures I-5e to I-5h).



Source: DTN: LL040501323122.046.

NOTE: The drift-wall temperature is obtained by volume averaging the temperatures for the host rock gridblocks surrounding the perimeter of the drift, extracted from the output (.ext) files for the respective cases. The drip-shield temperature is obtained by volume averaging the temperatures for the drip shield gridblocks at the perimeter of the drip shield extracted from the output (.ext) files for the respective cases. The temperature histories are calculated by the LDTH submodel of the multiscale thermal-hydrologic model (BSC 2004a, Section 6.2.6). These temperature histories are calculated for a location close to the center of the repository (the P2WR5C10 location shown in *Multiscale Thermohydrologic Model* (BSC 2004a, Figure 6.3-1). All cases use the thermal properties, including the mean thermal conductivity, of the Tptpll host-rock unit (see *Multiscale Thermohydrologic Model* (BSC 2004a, Table 6.3-20) for thermal conductivity).

Figure I-4. Drift-Wall and Drip-Shield Temperature History at the Repository Center for Four Values of Percolation Flux and for the Hydrologic Properties of Each of the Host-Rock Types

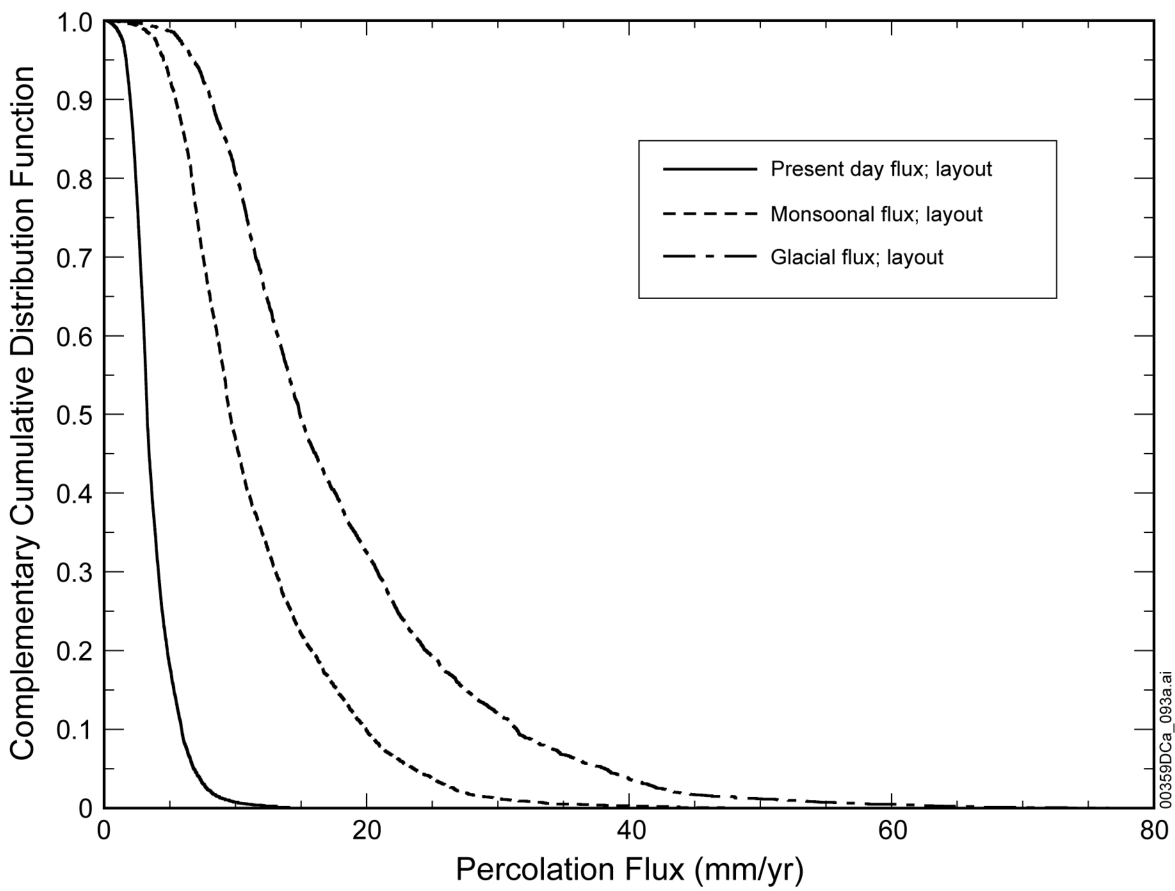


Source: DTN: LL040501323122.046.

NOTE: The relative-humidity histories are calculated by the LDTH submodel of the multiscale thermal-hydrologic model (BSC 2004a, Section 6.2.6). These relative-humidity histories are calculated for a location close to the center of the repository (the P2WR5C10 location shown in *Multiscale Thermohydrologic Model* (BSC 2004a, Figure 6.3-1). All cases use the thermal properties, including the mean thermal conductivity, of the Tptpll host-rock unit (see *Multiscale Thermohydrologic Model* (BSC 2004a, Table 6.3-20) for thermal conductivity).

Figure I-5. Drift-Wall and Drip-Shield Relative-Humidity History at the Repository Center for Four Values of Percolation Flux and for the Hydrologic Properties of Each of the Host-Rock Types

The small influence that hydrologic properties exert on temperature and relative humidity is insignificant for two reasons. First, it is insignificant compared to the influence of host-rock thermal conductivity and percolation flux, as evident in Figures I-1 and I-2. Second, the percolation flux range for which hydrologic properties exert a small influence (equal to or less than 0.1 mm/yr) constitutes a small portion of the repository for the three (present-day, monsoonal, and glacial) climate states, as is evident in Figure I-6.



Source: BSC 2004b, Figure 5.8-2.

NOTE: The distributions are given for the repository layout (BSC 2004b, Section 5.8).

Figure I-6. Complementary Cumulative Distribution Function for the Percolation Flux Distribution above the Repository for the Present-Day, Monsoonal, and Glacial Climate States

The lack of sensitivity of in-drift and near-field temperature and relative humidity to hydrologic properties can be understood by considering the key processes and factors governing thermal-hydrologic behavior in and around emplacement drifts. Thermal-hydrologic behavior in and around emplacement drifts consists of three fundamental processes:

1. **Heat Flow**–Occurs in emplacement drifts, primarily by thermal radiation, and in the adjoining host rock, primarily by thermal conduction. Consequently, host-rock thermal conductivity is the key natural-system parameter determining the magnitude of temperature buildup in the host rock.

2. **Host-Rock Dryout**–Occurs as a result of evaporation (boiling), which lowers the liquid-phase saturation in the host rock, thereby lowering the relative humidity in the host rock and in the emplacement drifts. Dryout is influenced by permeability in the fractures and in the matrix and by fracture spacing.

3. **Host-Rock Rewetting**–Primarily occurs as a result of gravity-driven percolation in fractures, with capillary-driven imbibition into the adjoining matrix. The rate of rewetting is controlled by the local percolation flux except in regions of very low percolation flux (less than approximately 0.1 mm/yr), where it is controlled by capillary-driven imbibition in the matrix. The approximate percolation-flux threshold of 0.1 mm/yr is obtained by observing the sensitivity of temperature (Figure I-4) and relative humidity (Figure I-5) to percolation flux, which is discussed above.

The processes of dryout and rewetting are opposing. Dryout is driven by temperature buildup, while rewetting is primarily driven by the local percolation flux, except in regions of very low percolation flux (0.1 mm/yr or less), where it is controlled by capillary-driven imbibition. Net host-rock dryout, which is the balance between dryout and rewetting, is greatest in regions with a combination of low host-rock thermal conductivity (which facilitates greater temperature buildup) and low local percolation flux (which facilitates slower rewetting).

Net host-rock dryout is least in regions with a combination of high host-rock thermal conductivity (which facilitates smaller temperature buildup) and high local percolation flux (which facilitates faster rewetting).

Hydrologic properties influence the following processes:

- Gas-phase flow, affecting
  - Vapor flow from the evaporation (boiling) zone to the condensation zone
  - The magnitude of buoyant gas-phase convection.

- Liquid-phase flow, affecting
  - Gravity- and capillary-driven flow in fractures
  - Capillary-driven imbibition in the matrix.

For the range of host-rock hydrologic properties of the four host-rock units, vapor flow from the boiling to the condensation zone essentially occurs in an unthrottled (i.e., unrestricted) fashion. Permeability in the fractures and matrix and fracture spacing are always sufficiently large to result in a (negligibly) small gas-phase pressure buildup with respect to boiling. Consequently, the gas-phase pressure buildup is small enough to not throttle (i.e., restrict) the rate at which boiling occurs and the resulting vapor flux from the boiling zone to the condensation zone. Thus, the range in hydrologic properties for the host rock does not result in differences in the rate at which boiling occurs in the host rock.

For the range of host-rock hydrologic properties of the four host-rock units, the contribution of buoyant gas-phase convection to overall heat flow is small compared to that of thermal convection. Thus, the range in host-rock thermal-hydrologic properties of the four host-rock types does not result in differences in the temperature buildup in the host rock, as is evident in Figure I-4.

For the range of hydrologic properties of the four host-rock units, fracture permeability is sufficiently large and fractures are sufficiently well connected to allow gravity-driven drainage of percolation to occur in an unrestricted fashion. Thus, percolation flux, not fracture permeability, is the rate-limiting quantity governing the magnitude of gravity-driven liquid-phase flow to the boiling–dryout zone. One important caveat to this generalization relates to flow focusing, which arises due to heterogeneity in fracture permeability. The influence of flow focusing is approximated by including areal variability of percolation flux, which results in a very broad range of percolation flux over the repository footprint (Table I-6), and by including uncertainty, as is addressed in the lower, mean, and upper infiltration flux cases (Table I-5). Thus, the manner in which hydrologic properties primarily affect rewetting (and, thus, net dryout) behavior is related to the manner in which those properties affect capillary-driven flow, which primarily occurs as imbibition in the matrix.

For the range of host-rock hydrologic properties of the four host-rock units, capillary-driven imbibition always results in a rewetting magnitude that is effectively less than approximately 0.1 mm/yr. Accordingly, only in regions with very low percolation flux (less than 0.1 mm/yr) do the hydrologic properties exert a small but insignificant influence on dryout and rewetting behavior in the host rock, as is evident in Figure I-5. For areas of the repository with a local percolation flux greater than 0.1 mm/yr (which is the vast majority of the repository area for all three climate states, as shown in Figure I-6), differences in host-rock hydrologic properties exert a negligible influence on dryout and rewetting behavior. Even in areas with low percolation flux, the influence of hydrologic properties on dryout and rewetting behavior is small compared to that of host-rock thermal conductivity and percolation flux, as is evident in Figures I-1 and I-2.

I.4.2 Propagating Conceptual-Model Uncertainty in Simulations of Thermal Effects on Flow

Conceptual-model uncertainty has also been addressed for the primary models of thermal effects on flow supporting TSPA. As discussed in *Abstraction of Drift Seepage* (BSC 2003a, Section 6.4.3.2), conceptual model uncertainty related to the thermal-hydrologic seepage model has been addressed in *Drift-Scale Coupled Processes (DST and TH Seepage) Models* (BSC 2003b, Sections 7 and 8.2) by careful validation of the coupled thermal-hydrologic processes in comparison with in situ heater tests. *Multiscale Thermohydrologic Model* (BSC 2004a, Section 7.3) validates the multiscale thermal-hydrologic model against an alternative conceptual model, showing that the small differences in predicted thermal-hydrologic conditions in the repository are much smaller than the range of predicted thermal-hydrologic conditions arising from parameter uncertainty of host-rock thermal conductivity and percolation flux above the repository. Therefore, it is unnecessary to propagate conceptual-model uncertainty in the results of the multiscale thermal-hydrologic model (BSC 2004b, Section 8.2).

I.4.3 Summary

The primary TEF model that is affected by TEF 2.10 is the multiscale thermal-hydrologic model. The multiscale thermal-hydrologic model (BSC 2004a) calculates the thermal-hydrologic (state) variables required by TSPA: temperature, relative humidity, liquid-phase saturation, evaporation rate, air mass fraction, gas-phase pressure, capillary pressure, and liquid- and gas-phase fluxes. These variables are determined throughout the repository area and for each of the waste package types, including waste packages containing commercial spent nuclear fuel and waste packages containing DOE high-level radioactive waste. TSPA utilizes (abstracts) the full range of thermal-hydrologic (state) variables calculated by the multiscale thermal-hydrologic model for each of the emplacement drifts across the repository area. The propagation of parametric variability and uncertainty in the multiscale thermal-hydrologic model addresses the key natural system parameters: host-rock thermal conductivity and percolation flux (BSC 2004b, Section 8.2). The multiscale thermal-hydrologic model also addresses the influence of the other key factors resulting in the variability in thermal-hydrologic (state) variables across the repository, notably: (1) waste package–to–waste package variability in heat output and (2) the repository footprint shape, which influences the evolution of the edge-cooling effect that increases with proximity to the repository edges. Analyses of the influence of hydrologic properties on in-drift and near-field thermal-hydrologic conditions justify the conclusion that hydrologic-property uncertainty does not need to be propagated through the multiscale thermal-hydrologic model. Conceptual-model uncertainty has also been addressed for the primary TEF models supporting TSPA through various model validation studies. As a result of those studies, it is found to be unnecessary to propagate conceptual-model uncertainty in the results of the TEF models supporting TSPA.

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I.5.2 Data, Listed by Data Tracking Number

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LL030808623122.036. Input and Output Files for NUFT MSTHM Sub-Models Supporting LA Multi-Scale Analyses. Submittal date: 09/11/03.

LL040501323122.046. Input and Output Files for the Sensitivity Studies for (1) Host-Rock Hydrologic Properties, (2) Invert Intragranular Hydrologic Properties, and (3) Rubble Heat Capacity for the Low-Probability-Seismic, Collapsed-Drift Cases. Submittal date: 05/19/04.

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