APPENDIX J

REPRESENTATION OF, OR THE NEGLECT OF, DRIPPING FROM ROCK BOLTS IN THE ENHANCED CHARACTERIZATION OF THE REPOSITORY BLOCK CROSS-DRIFT (RESPONSE TO TSPAI 3.07 AND GEN 1.01 (COMMENTS 13 AND 95))

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 J

REPRESENTATION OF, OR THE NEGLECT OF, DRIPPING FROM ROCK BOLTS IN THE ENHANCED CHARACTERIZATION OF THE REPOSITORY BLOCK CROSS-DRIFT (RESPONSE TO TSPAI 3.07 AND GEN 1.01 (COMMENTS 13 AND 95))

This appendix provides responses for Key Technical Issue agreement Total System Performance Assessment and Integration (TSPAI) 3.07 and General Agreement (GEN) 1.01 (Comments 13 and 95). This KTI agreement relates to the U.S. Department of Energy (DOE) representation of, or neglect of, dripping from rock bolts in the Enhanced Characterization of the Repository Block (ECRB) Cross-Drift in performance assessments.

J.1 KEY TECHNICAL ISSUE AGREEMENTS

J.1.1 TSPAI 3.07 and GEN 1.01 (Comments 13 and 95)

TSPAI 3.07 was reached during the U.S. Nuclear Regulatory Commission (NRC)/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 3.07 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 13), which pertains to water dripping from rock bolts, and GEN 1.01 (Comment 95), which is concerned with observed seepage enhancement in the Exploratory Studies Facility (ESF). The specific page number referral cited below as part of GEN 1.01 (Comment 15) is from *FY 01 Supplemental Science and Performance Analyses, Volume 1: Scientific Bases and Analyses* (BSC 2001a).

The wording of the agreements is as follows.

TSPAI 3.07[1]

> Provide technical basis for representation of or the neglect of dripping from rock bolts in the ECRB in performance assessment, including the impacts on hydrology, chemistry, and other impacted models. Appropriate consideration will be given to the uncertainties in the source of the moisture, and how those uncertainties impact other models (ENG3.1.1). DOE will provide technical basis for determination of future sources of water in the ECRB, will evaluate the

[1]ENG3.1.1 in this agreement refers to item 3.1 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 dripping observed in the sealed portion of the ECRB Cross-Drift.

possibility of preferential dripping from engineered materials, and will give appropriate consideration to the uncertainties of the water sources, as well as their potential impact on other models. The work done to date as well as the additional work will be documented in the AMR on In-Situ Field Testing Processes (ANL-NBS-HS-000005) or other documents. This AMR will be available to NRC in FY 2003. DOE will evaluate the role of condensation as a source of water and any impacts of this on hydrologic and chemical conditions in the drift, and DOE will document this work. The effects of condensation will be included in TSPA if found to be potentially important to performance.

GEN 1.01 (Comment 13)

The SSPA argues that rock bolts will not enhance seepage, contrary to the Seepage Model for PA including Drift Collapse AMR, which indicates increased seepage due to rock bolts.

Basis: Puddles of water were observed directly under rock bolts in Alcove 5. An explanation provided by DOE for this observation was that water was used for drilling these rock bolts in place. Dripping has been observed from rock bolts in the sealed ECRB. The explanation provided by DOE (so far) for this observation is that this is condensation.

GEN 1.01 (Comment 95)

Page 4-31: The explanation of the observed seepage enhancement in the ESF and associated tunnels appears to be speculation that is not supported by any concrete evidence.

J.1.2 Related Key Technical Issue Agreements

GEN 1.01 (Comment 16) covers material related to agreement TSPAI 3.07 in that it is also concerned with pathways for water to enter a drift. This agreement will be addressed in a separate response.

J.2 RELEVANCE TO REPOSITORY PERFORMANCE

This KTI agreement relates to uncertainties in the drift seepage process model and drift seepage abstraction. Observations in the passive seepage test in the east–west ECRB Cross-Drift indicated that condensation might occur at the location of rock bolts, where puddles of water were seen (NRC 2002).

At the August 2001 technical exchange on TSPAI, NRC and DOE discussed the observations of moisture dripping from rock bolts with regard to NRC comments about the quantity and chemistry of water contacting waste packages and waste forms model abstraction. KTI agreement TSPAI 3.07 was developed to assess the impact of this moisture on hydrology, chemistry, and other applicable models (Cornell 2001). Specifically, the intent was to evaluate the source of this moisture in the ECRB Cross-Drift and to provide technical bases for the representation or neglect of condensate in seepage models and the multiscale thermal-hydrologic model for license application.

The agreement is relevant to repository performance because several models used in performance assessment (i.e., drip seepage models and the multiscale thermal-hydrologic model) could be affected by conclusions reached with regard to the source of moisture originating at rock bolt locations.

J.3 RESPONSE

This agreement deals with four main issues: (1) impact of rock bolts on hydrology, chemistry, and other applicable models (Section J.3.1); (2) seepage enhancement due to rock bolts (Section J.3.2); (3) uncertainties regarding the source of the moisture in the sealed portion of the ECRB Cross-Drift, which indicate the dripping may result from seepage or condensation (Section J.3.3); and (4) future sources of water in the ECRB Cross-Drift, related uncertainties, and potential impact on models (Section J.3.4).

J.3.1 Impact of Rock Bolts on Hydrology, Chemistry, and Other Applicable Models

This appendix provides a technical basis for the representation of dripping from rock bolts and its impact on hydrology, chemistry, and other applicable models.

To evaluate the impact of rock bolts on hydrology, a refined seepage model including rock bolts was developed (BSC 2003a). See Section J.4.1 for details regarding processes that affect seepage.

The chemical effect of rock bolts and their corrosion products entering the drift is documented (BSC 2004a). The current design for rock bolts calls for using Stainless Steel Type 316L (BSC 2003b, Note 6) in the drift ground-support system. Details are discussed in Section J.4.1.2.

Results from hydrologic and chemical models indicate that the impact of rock bolts on seepage and chemistry are negligible. Due to the negligible impact of rock bolts, this factor has not been propagated to downstream models and subsystems (e.g., in-drift chemical environment, waste package and drip shield corrosion, engineered barrier system transport, unsaturated zone transport). However, it is discussed in Section J.4.1.3 and documented in *Abstraction of Drift Seepage* (BSC 2003c).

J.3.2 Seepage Enhancement Due to Rock Bolts

GEN 1.01 (Comment 13) mentions inconsistency between *FY 01 Supplemental Science and Performance Analyses, Volume 1: Scientific Bases and Analyses* (BSC 2001a) and *Seepage Model for PA Including Drift Collapse* (CRWMS M&O 2000). However, in *FY 01 Supplemental Science and Performance Analyses, Volume 1: Scientific Bases and Analyses* (BSC 2001a), this initial inconsistency has been resolved. The early version of *Seepage Model for PA Including Drift Collapse* (CRWMS M&O 2000) used a simple conceptual model, in which rock bolts are represented as needles and the rock matrix is not accounted for. This simple model was incomplete, and so a revised and more realistic model was developed. In this revised model, fractures and the matrix are represented by very fine gridding, and a wider range of parameter values for hydrologic properties is included. Even with these improvements to the model, no enhancement to seepage results from rock bolts. The model is discussed in Section J.4.1.

GEN 1.01 (Comment 95) states that the explanation of the observed enhancement in the ESF and associated tunnels appears to be speculation that is not supported by any concrete evidence.

Although puddles of water have been observed in the ESF and ECRB Cross-Drift, documentation is lacking that describes puddling or seepage enhancement caused by rock bolts in the ESF. As discussed in Section J.4.1, the model results (that apply to the ESF and ECRB Cross-Drift) indicate no seepage enhancement resulting from rock bolts. A full discussion on dripping in the ECRB Cross-Drift is presented in Section J.4.2. Although lithologies in the ESF and ECRB Cross-Drift are different, rock bolts would be expected to have similar influence.

J.3.3 Uncertainties Regarding the Source of the Moisture in the Sealed Portion of the Enhanced Characterization of the Repository Block Cross-Drift

NRC indicated that the dripping observed in the ECRB Cross-Drift may result from vapor-phase mobilization of water and condensation on surfaces of rock bolts, ventilation ducts, and utility conduits under small thermal gradients. In an unventilated near-field environment, where waste-canister heat causes spatial temperature variability, this process could result in significant dripping. Condensate could react with metal at elevated but below-boiling temperatures. Dripping in the ECRB Cross-Drift may also have resulted from seepage into the drift. Data are not sufficient to conclusively determine whether water observed in the ECRB Cross-Drift was condensate or seepage. However, two factors suggest that condensate contributed to the observed water in the ECRB Cross-Drift rather than seepage: (1) visual observations of droplets on impermeable engineered materials, such as a vent tube, a conveyor belt, and overhead cables (Section J.4.2.1); and (2) chemical analysis of water (Section J.4.2.2). These factors are documented in *In-Situ Field Testing of Processes* (BSC 2003d). Although seepage may also occur in the sealed drift, the available data do not conclusively identify the source of water as being seepage.

J.3.4 Future Sources of Water in the Enhanced Characterization of the Repository Block Cross-Drift, Related Uncertainties, and Potential Impact on Models

This appendix provides the technical bases to address future sources of water in the ECRB Cross-Drift (Section J.4.3). Seepage is predicted by the seepage model for performance assessment (BSC 2003a) for ambient conditions and by the thermal-hydrologic seepage model (BSC 2003e) for elevated temperature conditions. The model and uncertainties of ambient and thermal seepage are addressed in Sections J.4.3.1 and J.4.3.2, respectively.

Condensation is likely to occur as a result of small temperature gradients and natural convection processes as observed in the ECRB Cross-Drift and described in Section J.4.2. While the role of condensation as a source of water in the ECRB Cross-Drift has not been modeled, *In-Drift Natural Convection and Condensation* (BSC 2003f) predicts condensation in the emplacement drift. Although the in-drift condensation model is not directly applicable for the ECRB Cross-Drift, the observation of condensate formation in the ECRB Cross-Drift is not inconsistent with the results from the in-drift condensation model, as discussed in Section J.4.3.3. Considerations regarding the future source of water in the models are discussed in Section J.4.3.4.

The role of condensation as a source of water in the drift is being evaluated. Temperature is expected to vary considerably in different parts of the repository, resulting in vapor dispersion, evaporation, and condensation effects. *In-Drift Natural Convection and Condensation* (BSC 2003f) provides documentation of the in-drift convection and condensation models.

The information in this report is responsive to agreements TSPAI 3.07 and GEN 1.01 (Comments 13 and 95) made between the DOE and NRC. The report contains the information that DOE considers necessary for NRC review for closure of these agreements.

J.4 BASIS FOR THE RESPONSE

J.4.1 Processes Affecting Seepage

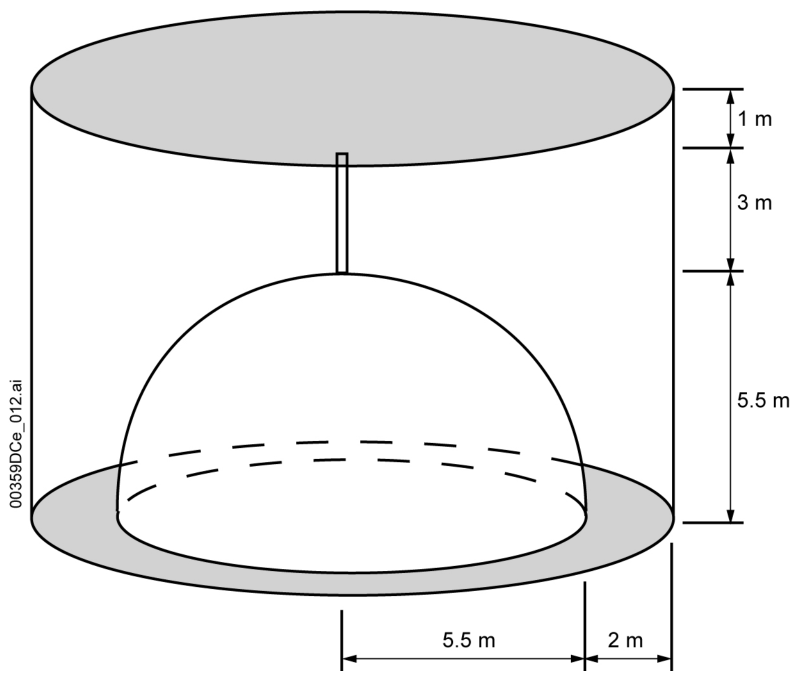
Many factors influence the amount of water that may seep into emplacement drifts. Beyond the primary factors (e.g., the average incident percolation flux, the hydrologic characteristics of the rock, the extent of in-drift ventilation, and the size and general shape of the drifts), the presence of rock bolts may also affect the amount of seepage. This section describes potential seepage enhancement due to rock bolts (Section J.4.1.1), chemical reaction of water with material rock bolts (Section J.4.1.2), and evaluation of rock bolts in the seepage abstraction (Section J.4.1.3).

J.4.1.1 Effect of Rock Bolts on Seepage

Rock bolts, which are an element of the ground support for the emplacement drifts at Yucca Mountain (BSC 2001b), are stainless steel rods inserted into a borehole normal to the drift wall used to anchor potentially lose rock in place. Typically, they are 3 m long (BSC 2001b, Section 6.5.1.2.2) with a diameter of 1 in. (0.0254 m) and are either held in place by friction or in conjunction with grout. Rock bolts used within the emplacement drifts are friction bolts and do not use grout (BSC 2004b, Section 6.8.2). Rock bolts pose a potential concern with respect to seepage because they provide a direct flow conduit to the drift wall and may increase the likelihood of seepage into drifts (BSC 2003a).

A model has been developed for evaluating the effect of rock bolts on seepage. The model includes both grout and no-grout cases. Because the current design excludes the use of grout in emplacement drifts (BSC 2004b), only the no-grout case was evaluated. Using the model, a range of properties for the formation, including the no-grout case for a mechanically anchored bolt and a range of percolation rates, was investigated. Figure J-1 shows a schematic of the model. The model uses a two-dimensional, radially symmetric grid with a vertical symmetry axis generated using the software TOUGH2 V1.4 (LBNL 2000). The grid size is 10 cm, with finer discretization (down to 0.1 mm) at the interface between the rock bolt and the surrounding rock. Because this is a radially symmetric grid, the drift opening is spherical instead of cylindrical. Knight et al. (1989, p. 37) find that seepage exclusion from a cylindrical cavity is similar to that of a spherical cavity of twice the radius. This is explained by relating the seepage exclusion potential of an opening to the total curvature of the boundary of the opening. For a cylindrical cavity, the radius of curvature is infinite along the axis of the cylinder and finite perpendicular to the axis. For a spherical cavity, the radius of curvature is finite and equal in any direction. As a result, the equivalent radius of the spherical drift in the model is twice that of the design drift radius. This relationship is used in the calculation of seepage enhancement due to the presence of rock bolts (BSC 2003a).

As a base case, seepage into the opening without rock bolts was modeled. Since this was treated as a sensitivity study, the low and high percolation rates of 5 and 500 mm/yr were applied uniformly to the upper model boundary. A constant capillary pressure equal to 0 is specified at the drift wall boundary, a gravity-drainage condition at the lower boundary, and a no-flow condition on the lateral boundary. The fracture continuum permeability used in the calculation is the mean of data for the Topopah Spring Tuff middle nonlithophysal unit (Tptpmn) (i.e., log k_{FC} equal to –11.86). The van Genuchten capillary-strength ($1/\alpha$) values of 200 and 400 Pa were used for the rock. An additional calculation with a $1/\alpha$ value of 589 Pa (a number between the calibrated values for the Tptpmn and the Topopah Spring crystal-poor lower lithophysal unit (Tptpll) (BSC 2003g, Table 16)) was also performed as part of the sensitivity analysis.



Source: BSC 2003a, Figure 6-2.

NOTE: The radius of the spherical drift is taken to be 5.5 m, making its curvature equivalent to that of a cylindrical drift with a radius of 2.75 m. The rock bolt hole is at the crown of the drift with length of 3 m.

Figure J-1. Model to Evaluate Effect of Rock Bolt

To investigate the effect of a rock bolt on seepage, only the case of a rock bolt borehole extending vertically upward from the crown of the drift was modeled. Rock bolts at different angles will not have a larger effect on seepage than rock bolts at vertical angles. If there is negligible effect on the model, this case is sufficient to resolve the question of the effect on seepage caused by rock bolts, because the presence of the rock bolt borehole will not significantly change the calculated seepage values. Three grids are prepared to explore diversion capacity away from the rock bolt borehole. Case 1 allows flow between the rock bolt borehole and the surrounding rock along the entire length of the borehole. Case 2 prevents flow between the rock bolt borehole and the surrounding rock for 10 cm above the drift crown. Case 3 restricts flow between the rock bolt borehole and the surrounding rock for 50 cm above the drift crown. That is, Cases 2 and 3 represent scenarios in which the first geologic feature capable of carrying flow away from the rock bolt borehole is found 10 or 50 cm, respectively, into the borehole. A 1-in. (0.0254 m) radius rock bolt borehole with a 0.5-in. (0.0127 m) radius rock bolt was modeled. This configuration resulted in a conservative model because the modeled bolt hole has less potential as a capillary barrier to exclude water inflow but a larger surface area to intercept flow, thus providing a greater opportunity to conduct flow to the drift wall.

Results for the Effect of Rock Bolts–Modeling results for seepage enhancement caused by the presence of a vertical rock bolt are shown in Table J-1. Here, a seepage enhancement factor is defined as:

$$\text{Enhancement Factor } = 1 - \frac{SeepageWithTheRockbolts}{SeepageWithoutTheRockbolts} \quad \text{(Eq. J-1)}$$

Table J-1. Results on Seepage Enhancement Factor Due to a Rock Bolt in Drift Ceiling

Rock 1/α (Pa)	Seepage Percentage (without Rock Bolt)	Seepage Enhancement Factor (with Rock Bolt)	
		Mesh Design Case	No Grout Condition
200	100	C1 C2 C3	0 0 0
400	53	C1 C2 C3	0 0 0
589	0.034	C1 C2 C3	–0.0034 –0.0113 –0.0156

Source: DTN: LB0304SMDCREV2.001; BSC 2003a, Table 6-4.

Thus, the enhancement factor is negative if the seepage increases because of the presence of a rock bolt and is positive if it decreases. Table J-1 shows results only for a percolation flux (Q_p) of 500 mm/yr because, with a percolation flux of 5 mm/yr, seepage rates in all cases are 0, and enhancements are also found to be 0. In Table J-1, cases C1, C2, and C3 represent three variations in mesh design for representing connections between rock bolt boreholes and the rock. As shown in Table J-1, seepage enhancement is negligible. This result is understandable, considering that the cross-sectional area of the rock bolt borehole, which may be intersected by flow, is small and that the borehole can exchange moisture with the rock along its length. For a vertical rock bolt, if only the horizontal surface is considered, the area is about 0.002 m^2. For a nonvertical rock bolt, because the area of rock bolt projected onto a horizontal plane is larger, the potential for flow from the rock bolt borehole to the rock matrix around it is also increased.

The results are not sensitive to the alternative mesh design cases C1, C2, and C3. Furthermore, since the changes are very small, the presence of five or six rock bolts do not change seepage significantly.

J.4.1.2 Effects of Rock Bolts on Chemistry

This section examines the effect of water that may drip from a rock bolt. The principal ground support in the emplacement drifts is expected to be Stainless Steel Type 316L rock bolts and steel sheets (BSC 2003b, p. 1). Predominant Stainless Steel Type 316L oxidation products include iron(III) and chromium(III). The effects of steel ground support on aqueous chemistry are documented in *Engineered Barrier System: Physical and Chemical Environment Model* (BSC 2004a, Section 6.8) (see also the response to ENFE 2.14).

Seepage water composition is abstracted from the thermal-hydrologic-chemical model. An abstraction method is used to generate lookup tables for possible in-drift water compositions, incorporating the effects of seepage water evaporation and deliquescence of salt minerals (in dust on the drip shield and waste package) as a function of environmental conditions. This is accomplished by sorting seepage water and dust leachate compositions into bins. Each bin contains a group of seepage water or dust leachate compositions that yield chemically similar solutions when they are concentrated by evaporation. Then, a median water composition in each bin is identified that serves to approximate all of the water compositions in the group. As a result, 11 bins that yield chemically similar solution composition were defined. Bin 11 contains the largest number of waters, and this is the most likely median water. Details about the abstraction and binning method are documented in *Engineered Barrier System: Physical and Chemical Environment Model* (BSC 2004a, Section 6.6).

The model considered the interaction of Bin 11 water with Stainless Steel Type 316L ground support materials. Interaction with the abstracted Bin 11 seepage water was chosen because it occurs in almost 40% of the abstracted periods (BSC 2004a, Table 6.6-4), and thus is the most likely water to be present. In addition, in the model, Bin 11 water occurs during the relevant period for the corrosion of Stainless Steel Type 316L, which is in the range of about 500 to 5,000 years for four of the five seepage water compositions (BSC 2004a, Tables 6.6-8 to 6.6-12).

Iron(III) and chromium(III) have been selected as the corrosion end products influencing the seepage water chemistry. Selection of iron(III) as opposed to iron(II), is justified, given the relatively oxidizing conditions (i.e., atmospheric O_2 concentrations leading to significant dissolved oxygen content) and the mild pH ranges of the seepage waters.

Selection of chromium(III) over that of the more soluble chromium(VI) species is based on the experimental observation of corrosion products and the kinetics and conditions required to obtain the fully oxidized chromium(VI) state (Smith and Purdy 1995), even though this is contrary to the prediction of equilibrium thermodynamics under oxidizing conditions. Smith and Purdy's examination of the actual chromium speciation as a result of corrosion of Stainless Steel Type 316 demonstrated a predominance of the less soluble chromium(III) species, except under the conditions of hot, concentrated nitric acid (111°C and greater than 7 molar HNO_3) (Smith and Purdy 1995, Figure 6).

Results of Chemical Analysis and Uncertainties–The effect of dissolving the abstracted Stainless Steel Type 316L species into Bin 11 water is found to be negligible. The Bin 11 water with and without the 5.52×10^{-5} moles of Stainless Steel Type 316L added is found to have only two differences in the water chemistries at the sixth significant figure for ionic strength and carbon total molality (BSC 2004a, Section 6.8.4.3).

Use of Bin 7 seepage water was selected as an uncertainty case (BSC 2004a, Section 6.12.4.1). There is effectively no change in the aqueous water chemistry caused by abstracted stainless steel corrosion and corrosion product formation in this case, as with the base-case Bin 11 seepage water (BSC 2004a, Section 6.12.4.1.3).

J.4.1.3 Effect of Rock Bolts in Other Models

Because of the negligible effect of rock bolts on hydrologic and chemical models, rock bolts have not been considered in the downstream models and subsystems.

The repository design uses rock bolts without grout (BSC 2003c, Section 6.3.1). Results of the simulations with explicit consideration of rock bolts (BSC 2003a, Section 6.6.4) are summarized in Section J.4.1.1. The simulated rock bolt cases indicated that there is essentially no seepage enhancement for nongrouted boreholes. Therefore, the effect of rock bolts is neglected in the seepage abstraction (BSC 2003c, Section 6.5.1.6).

J.4.1.4 Summary

Hydrologic and chemical studies conducted at the drift scale indicate that dripping from rock bolts as seepage is negligible. Abstraction models suggest no seepage enhancement for nongrouted boreholes housing rock bolts. Therefore, rock bolts have been excluded from TSPA models.

J.4.2 Uncertainties Regarding the Source of Observed Water in the Sealed Portion of the Enhanced Characterization of the Repository Block Cross-Drift

To address NRC's concern regarding uncertainties in the source of dripping from impermeable engineered materials as the result of seepage or condensation, three factors suggesting condensation in the ECRB Cross-Drift are provided (Sections J.4.2.1, J.4.2.2, and J.4.2.3). Section J.4.2.1 also addresses the NRC concern regarding the possibility of preferential dripping from engineered materials.

J.4.2.1 Visual Observations of Dripping from Engineered Materials

In ventilated drift sections, no continuous dripping was observed in either the ESF loop or in the ECRB Cross-Drift. This lack of seepage may be explained by the capillary barrier mechanism, with capillary forces holding water within the rock mass. The other explanation is related to ventilation. Ventilation can remove large amounts of moisture, dry the rock behind the drift walls, and suppress seepage.

To determine if seepage returns when ventilation effects are stopped, the last one-third of the ECRB Cross-Drift was sealed with multiple bulkheads, and the moisture conditions were monitored to evaluate the presence of dripping or seepage. The bulkheads are located at Stations 17+63, 25+03, and 25+99. The last bulkhead was installed to isolate the influence of the tunnel boring machine, which acted as a heat source on tunnel conditions (BSC 2003d, Section 6.10).

Visual and photographic observations on October 1, 2001, in the bulkhead at Station 17+63 indicated dry stalactites on the vent tube just inside of the first bulkhead (Figure J-2). The deposits were probably from redistribution of vent tube materials from dissolutions associated with early condensations, driven by temperature variations near the bulkhead. The lights in the same area have precipitate on them but were dry during the observation. The drift was dry from the first bulkhead to about Station 18+00.

The drift was wet from Station 18+00 to about Station 19+00. The first sign of moisture was observed on the left rib at Station 17+90, with drips on utility conduits. The dripped water on the utility conduits appeared slightly rusty. Vent lines and walls were uniformly covered with liquid, and there were puddles on the belt. There was a large puddle on the conveyer belt at Station 18+25 (Figure J-3).

The wet sections of the conveyer belt had water droplets approximately evenly spaced on the rubber surfaces (i.e., top, bottom, and in-between belts). The droplets sometimes ran together if there was a depression in the belt, creating puddles.

Dampness was prevalent on the shotcrete after the Station 25+03 bulkhead (Figure J-4) and behind the Station 25+99 bulkhead. The drift was dry again from Station 19+00 to about Station 21+50. The walls began to dry out towards the tunnel boring machine.

From observations on October 2, 2001, after the bulkhead doors were left open overnight, most of the water droplets from the previous day had evaporated, with some of the rock remaining damp. A patch of paint on the rock surface was observed to have beads of water on its surface, with no similar beads observed on the surrounding rock surfaces (Figure J-5). Since the paint is impermeable, the observed beads were likely the results of condensation, not of seepage through the rocks below the painted patch. This observation supports the hypothesis that the observed water originated from condensation as the result of local temperature variations.

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Source: BSC 2003d, Figure 6.10.2-10.

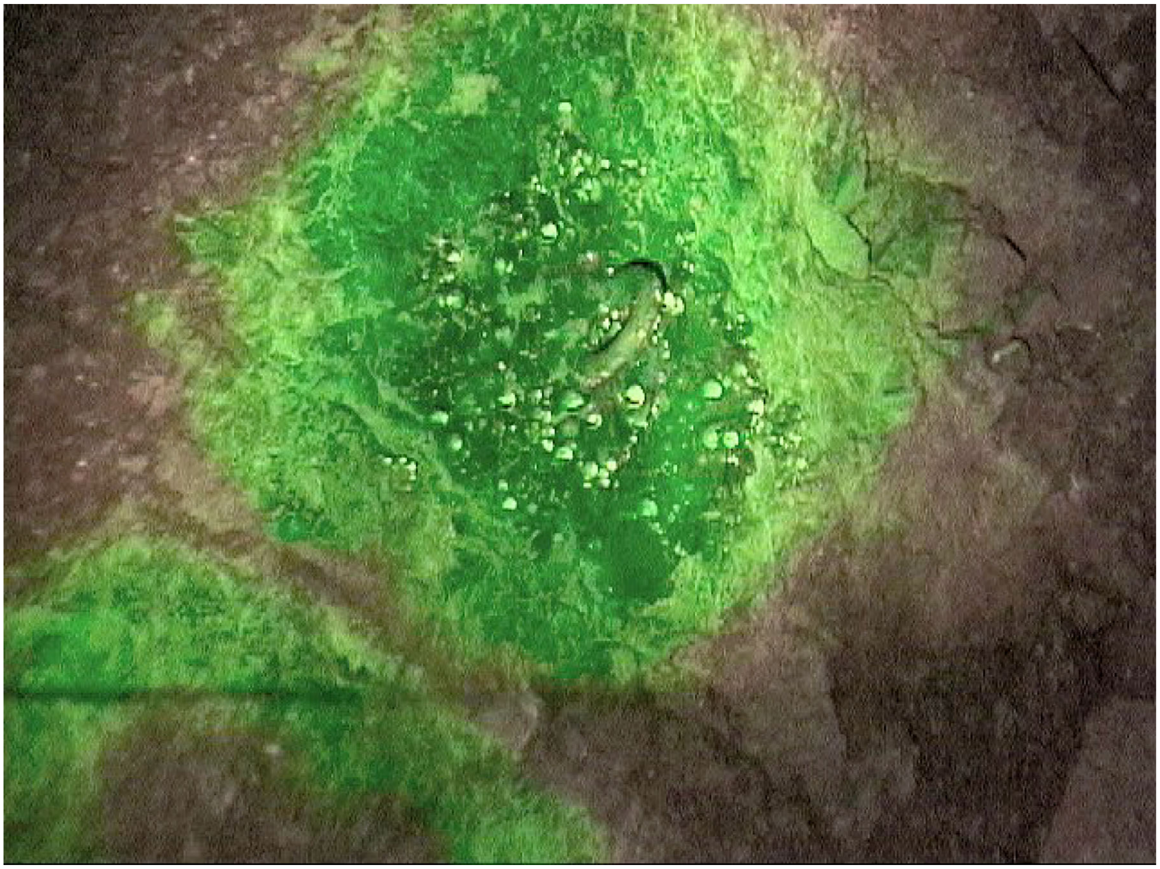
Figure J-2. Stalactites Near First Bulkhead at Station 17+63

Source: BSC 2003d, Figure 6.10.2-11.

Figure J-3. Water Puddle and Condensate on Conveyer at Station 18+25

Source: BSC 2003d, Figure 6.10.2-13.

Figure J-4. Condensate on Shotcrete after Second Bulkhead



Source: BSC 2003d, Figure 6.10.2-9.

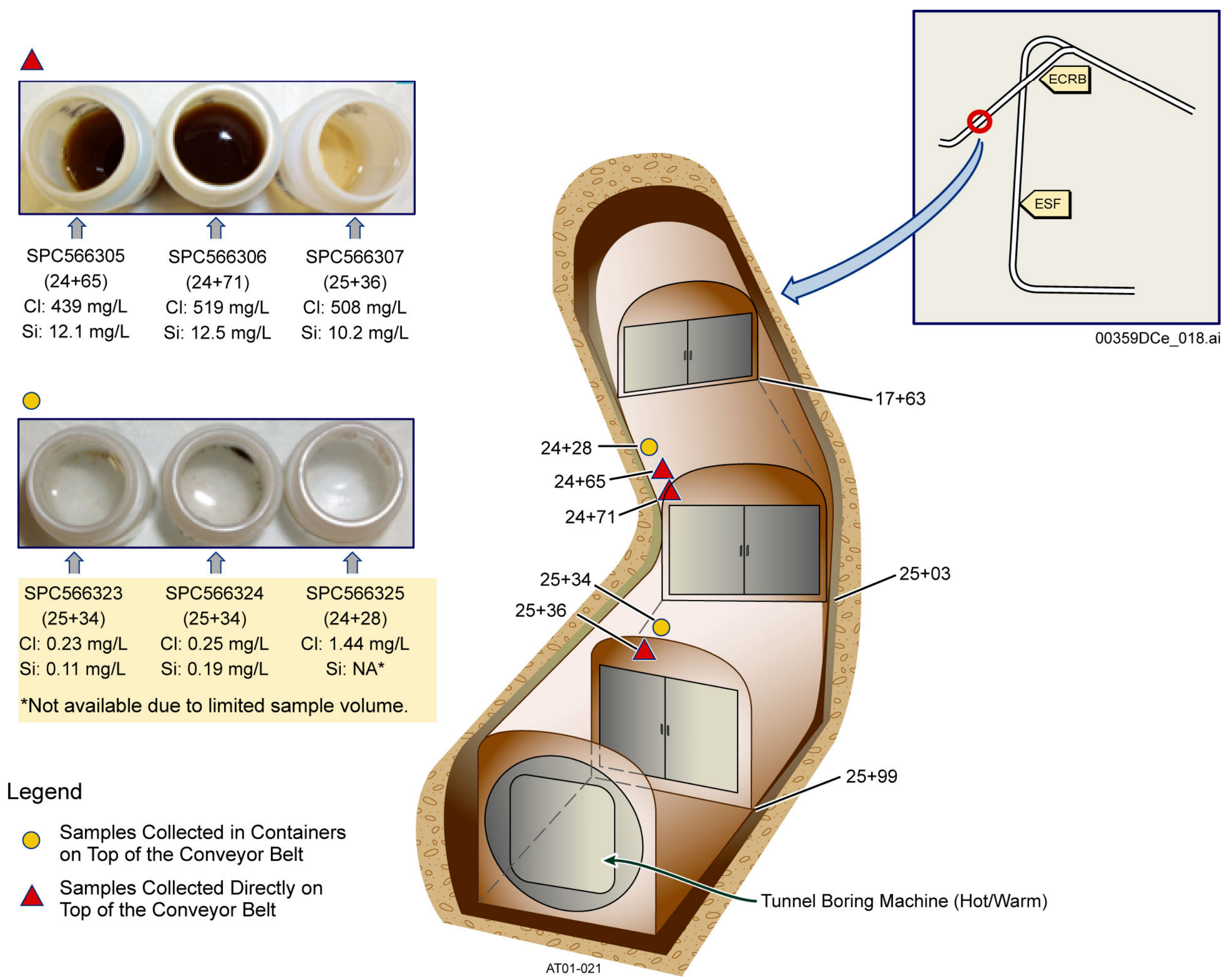
Figure J-5. Condensate Hanging from the Green Paint on the Crown of the Enhanced Characterization of the Repository Block Cross-Drift (but Not on Surrounding Rock Surface) at Station 24+70

J.4.2.2 Chemical Analysis of Water Samples Collected during Bulkhead Entries

The nonventilated sections of the ECRB Cross-Drift were opened four times from January 2000 to January 2001, and water samples were collected. The chemical analyses were on major anionic and cationic constituents, including bromide, chloride, and lithium, in the liquid samples (BSC 2003d).

Most of the initial samples were collected directly from pools that had formed on the conveyor belt, and these samples were of brownish to dark brown color; some examples are shown in Figure J-6. Their chemical compositions show high and variable concentrations of many constituents (BSC 2003d, Table 6.10.3-1). These samples are likely contaminated from the conveyor belt, resulting from the belt operation before ECRB Cross-Drift closure, with the degree of contamination unknown and unable to be quantified. Contamination of the conveyor belt may include salt accumulated from water evaporation following transportation of the tuff debris, as well as other miscellaneous contamination. Consequently, these samples do not yield useful information about the origin of the water (i.e., condensate or seepage) observed in the

ECRB Cross-Drift behind bulkheads; however, chemical analyses of other samples indicate condensation.

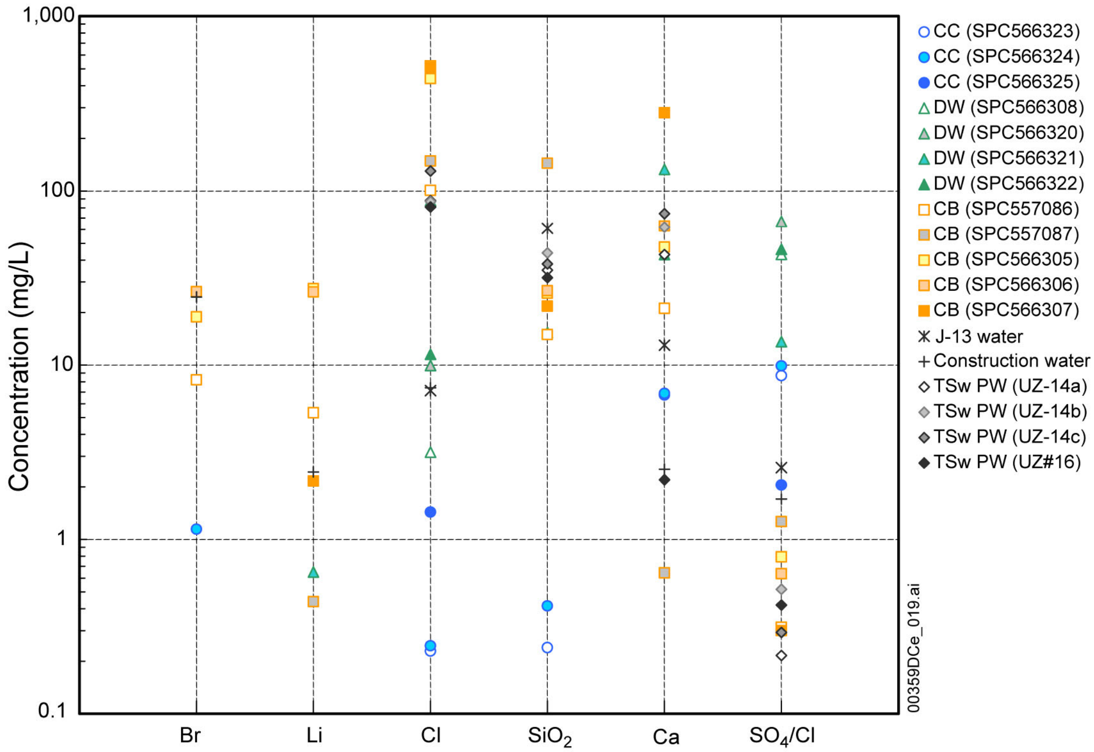


Source: BSC 2003d, Figure 6.10.3-1.

Figure J-6. Chemical Analyses of Liquid Samples Collected during Bulkhead Entries

Three other samples were collected from uncovered collection containers placed on the top of the conveyor belt. These samples are clear (Figure J-6), and their chemistry (Figure J-7) shows particularly low chloride and silica content. These clear samples also show a relatively high amount of calcium and a high sulfate–chloride ratio, indicating some minor contamination from either rock grout or rock dust (Figure J-7). Samples collected on the drift wall show an even higher concentration of calcium and a larger sulfate–chloride ratio, resulting from the direct contact of the sample with the rock. Some grout or dust present along the drift crown above the sampling containers and drift wall may have dissolved in the condensate prior to collection. The water does not have the chemical signature of construction water, which contains about 20 mg/L of lithium bromide added to J-13 well water. The results of chemical analysis suggest that the water in these samples is condensate.

Dripping could occur as a result of condensation associated with local temperature variations in a humid environment. The moisture conditions measured by humidity and temperature probes support the presence of drift moisture variations.



Source: BSC 2003d, Figure 6.10.3-2.

NOTE: Unit of the y-axis is in mg/L, except for the ratio of sulfate to chloride (dimensionless). ECRB Cross-Drift samples are grouped as follows: CC in collection container, DW on drift wall, and CB on conveyor belt. TSw PW is pore water in Topopah Spring welded tuff unit. Construction water data presented here are an average value from seven samples.

Figure J-7. Comparison of Chemical Signatures

J.4.2.3 Results from the Chemical Water Analysis of Preferential Dripping from Engineered Material

Visual observations and results from chemical analysis of water collected in the ECRB Cross-Drift indicate that the water originated from condensation. Although seepage may also occur in the sealed drift, its presence in the samples cannot be identified from the water's chemical signature.

J.4.3 Future Sources of Water in the Enhanced Characterization of the Repository Block Cross-Drift: Uncertainties and Potential Impact in Other Models

Dripping in the ECRB Cross-Drift may have resulted from seepage or condensation into the drift. Because of the negligible effect of rock bolts on seepage in the hydrologic and chemical models, rock bolts have not been considered as a water pathway into the drift or a factor in determining in-drift chemistry. This section evaluates the potential of future source of water from seepage and condensation. Numerical modeling was performed to predict seepage under ambient condition (BSC 2003a) and thermal conditions (BSC 2004c) and to address the related uncertainties in the model (Sections J.4.3.1 and J.4.3.2). The role of condensation in the emplacement drift is addressed in *In-Drift Natural Convection and Condensation* (BSC 2003f), Section J.4.3.3. The impact of seepage on other models is summarized in Section J.4.3.4.

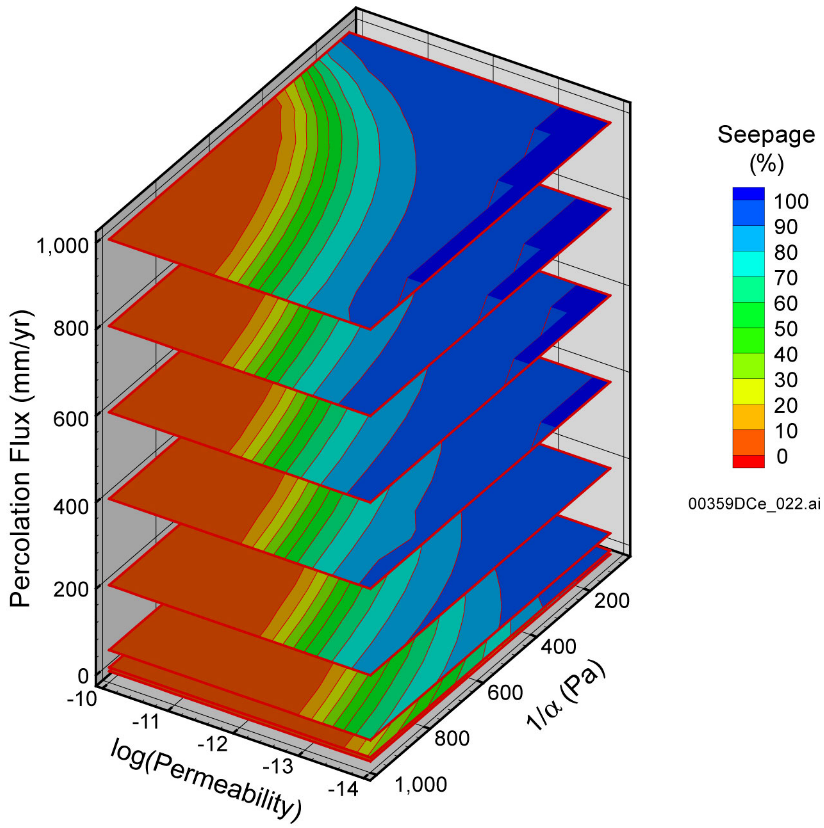
J.4.3.1 Prediction of Ambient Seepage and Uncertainties

While the seepage calibration model simulates liquid-release tests and seepage into niches and the ECRB Cross-Drift for calibration and validation purposes, the seepage model for performance assessment predicts average seepage into a section of a waste emplacement drift under ambient percolation conditions (BSC 2003a). Isothermal flow simulations are performed for selected key parameters that vary over wide ranges. Consistent with the seepage calibration model, the predictive seepage model for performance assessment is a three-dimensional drift-scale model that employs a stochastic continuum representation for the small-scale heterogeneity of fractured rock in the drift vicinity. The seepage percentage (i.e., the ratio between the seepage and percolation fluxes) directly indicates the flow diversion capabilities in the vicinity of the drift opening. The simulated total seepage rate into a drift of 5.5-m diameter and 5.1-m length (length of a waste canister) is performed for selected key parameters. The calculation is repeated for different parameter combinations and different realizations of the underlying stochastic permeability field. Results are provided in the form of a lookup table, giving seepage rates and related seepage estimation uncertainty as a function of these key parameters. During a probabilistic TSPA calculation, values of input parameters are sampled from their respective probability distributions, and the corresponding seepage rate is extracted from the lookup table.

The key parameters affecting ambient seepage are the effective capillary-strength parameter, the reference permeability, and the local percolation flux imposed at the upper model boundary. Sensitivity analyses are performed to examine the impact of the stochastic parameters (standard deviation and correlation) describing the small-scale heterogeneity of the permeability field.

The systematic simulations performed by the seepage model for performance assessment cover a wide range of capillary-strength values $1/\alpha$ (from 100 to 1,000 Pa), mean permeability values ($\log(k)$ from -14 to -10), and local percolation flux (from 1 to 1,000 mm/yr). For each parameter combination, 20 realizations of the heterogeneous permeability fields were simulated. The range of results from the 20 realizations provides information about the estimation uncertainty in the predicted seepage rates due to uncertainty in the stochastic small-scale heterogeneity.

Example results from the seepage model for performance assessment are illustrated in Figure J-8. The figure gives contours of the simulated seepage percentage as a function of the capillary-strength parameter $1/\alpha$ and the mean fracture permeability for selected percolation fluxes between 1 and 1,000 mm/yr. As expected, the seepage percentage is large for small capillary strength, small permeability, and large percolation flux. In these cases, seepage may be as high as 100%; that is, there is no flow diversion at the drift wall, and the entire fraction of the percolation flux seeps into the drift. In contrast, the seepage percentage is small for those cases with strong capillarity, large permeability, and small percolation flux. In many of these cases, there is no seepage; that is, the entire percolation flux is diverted around the drift by capillary forces because the percolation flux is below the seepage threshold for the given parameters.



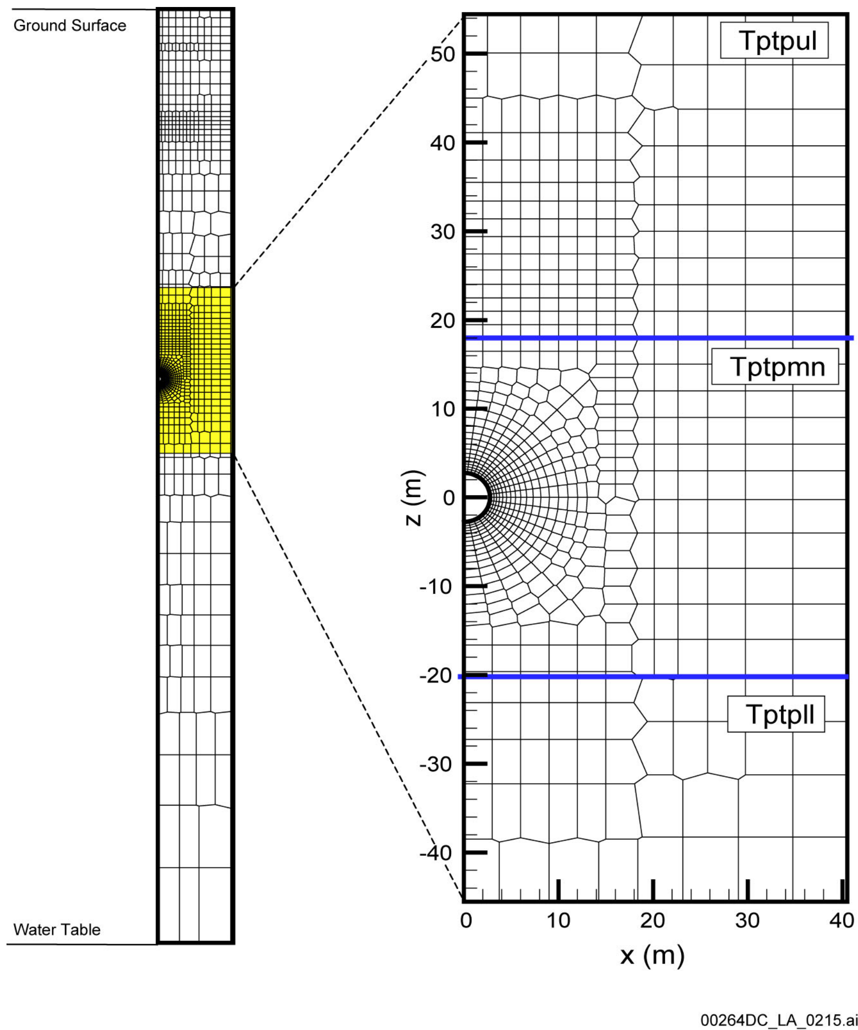
Source: BSC 2003a, Figure 6-8.

Figure J-8. Mean Seepage Percentage as a Function of Capillary-Strength Parameter and Mean Permeability for a Percolation Flux of 1,10, 50, 200, 400, 600, 800, and 1,000 mm/yr

J.4.3.2 Predictions of Thermal Seepage and Uncertainties

A thermal-hydrologic seepage model (BSC 2004c) has been developed to evaluate the coupled thermal-hydrologic processes in the vicinity of waste emplacement drifts during the heating phase of the repository. This drift-scale process model is designed to analyze the combined effect of the two features or processes that limit seepage into drifts at elevated temperatures: (1) capillary barrier, which is independent of the thermal conditions, and (2) dryout zone, which is in effect while temperature is elevated above the boiling point. The thermal-hydrologic seepage model accounts for the important flow and energy-transport processes in response to the elevated thermal conditions, including the movement of both gaseous and liquid phases, transport of latent and sensible heat, the phase transition between liquid and vapor, and the lowering of the vapor pressure.

Transient simulations in a two-dimensional cross section extending from the ground surface to the water table (Figure J-9) are performed to explicitly calculate percolation to the drift during the heating phase of the repository and to directly calculate transient seepage rates into the drift under elevated temperature conditions. Relevant parameters that vary in the evaluation of thermal seepage are the thermal operating mode, the local percolation flux, and selected rock properties. Results of this model are used in the seepage abstraction to develop an appropriate methodology for performance assessment to account for thermally perturbed conditions.



Source: BSC 2004c, Figure 6.2.1.2-1.

NOTE: In this example, the emplacement drift is located in the Tptpmn unit (Tptpmn submodel).

Figure J-9. Example of Numerical Grid for the Thermal-Hydrologic Seepage Model

The thermal-hydrologic seepage model is validated by comparison with three in situ heater tests conducted at Yucca Mountain (BSC 2004c, Section 7), with particular focus on the Drift Scale Test. The model validation included quantitative evaluation of measured temperature data, including all analysis of subtle temperature signals indicative of thermal-hydrologic coupling, as well as qualitative evaluation of periodic measurements that monitored moisture redistribution processes using geophysical methods, air-injection data, and withdrawal of liquid water in packed-off boreholes. The consistency between the data and the model show that the uncertainty of predicted temperature, saturation, and water flux data is within acceptable ranges (BSC 2004c, Table 6.2.1.3-1), thus validating the model.

In general, thermal seepage is possible only when (1) water arrives at the drift wall (depending on the vaporization impact), and (2) the saturation at the drift wall exceeds a given threshold value, defined by the capillary barrier effect at the rock–drift interface. The modeling results consistently demonstrate that the thermal perturbation of the flow field, which causes increased downward flux from the condensation zone toward the drifts, is strongest during the first few hundred years after closure, corresponding to the time period when rock temperature is highest and vaporization is most effective. Even for high percolation fluxes into the model domain and strong flow channeling as a result of fracture heterogeneity, water cannot penetrate far into the heated rock during the time that the rock temperature is above boiling. Thus, the potential for seepage is small. The majority of the vaporized (and subsequently condensed) matrix water is diverted around the dryout zone and drains away from the drift.

J.4.3.3 Evaporation/Condensation Model and Uncertainties

In-Drift Natural Convection and Condensation (BSC 2003f) predicts local evaporation/condensation rates as well as the axial transport of heat and vapor down the entire length of a waste emplacement drift. It utilizes heat and mass surface transfer correlations to model the transfer between solid surfaces and the gas. The model evaluates the process of evaporation and condensation in the repository emplacement drift, which is driven by temperature difference. The outer periphery of the repository will be cooler than the center because of the three-dimensional nature of the conductive cooling. This produces a temperature gradient in the drift that evaporates water near the center of the repository and deposits it near the cooler end of the tunnels.

The in-drift convection and condensation model consists of the following:

- A three-dimensional computational fluid dynamics (CFD) in-drift convection model (with associated two-dimensional studies) using FLUENT that represents convective mixing in a unit-cell drift-segment and develops a dispersion coefficient parameter for use in the one-dimensional axial dispersion model.

- A steady-state network condensation model that incorporates axial dispersion of water vapor in an emplacement drift and represents the waste packages, drip shields, invert, and drift wall as nodes.

The network condensation model represents every waste package in a specific emplacement drift and also represents the unheated exhaust standoff and access turnout sections located at the ends of the drift. These features are represented as nodes in a network, so the reported temperatures are lumped local averages. Line-source thermal conduction solutions are used to approximate the drift wall temperature variation for each emplacement drift, using the drift locations in the repository layout, and representing the contribution of every drift to mountain-scale heat transport. Heat transfer between the nodes (waste package to drip shield, drip shield to drift wall, etc.) is based on literature correlations for natural convection heat and mass transfer for the particular geometry. Thermal radiation is calculated based on surface-to-surface radiation and the appropriate view factors. Only heat transfer in the radial direction is considered; the effect of axial heat transfer in the drip shield and waste packages is assumed to be small because (1) heat conduction along the drip shield is insignificant due to its small cross-sectional area, and (2) heat transfer between waste packages is limited to radiation across the gap between individual packages. Neglecting axial heat transfer along the drip shields and waste packages increases spatial temperature gradients and may, thus, slightly increase evaporation and condensation.

Temperatures for the surfaces of the waste package, drip shield, invert, and drift wall are estimated for each waste package location in the drift using the specific waste package heat output. Local evaporation and condensation rates are computed using heat/mass transfer correlations based on temperatures and vapor mass fractions. The vapor fraction of the gas is calculated as a function of axial position (BSC 2003f).

The axial dispersion coefficient is determined from three-dimensional FLUENT CFD natural convection calculations for a unit cell in the emplacement drift that contains a repeated pattern of hot and cold waste packages. The model grid represents a 71-m-long segment of drift containing 14 waste packages. Individual waste packages are modeled, including the drip shield, invert, and the 5 m of rock surrounding the drift. Individual waste package heat output functions are used for different waste package types. Natural convection and thermal radiation are calculated based on the Navier-Stokes equations, including turbulence. The resulting natural convection flow pattern shows that local convection cells develop around adjacent hot and cold waste packages, and larger convection cells form within the 71-m drift segment. The flow patterns are a strong function of the temperature gradient in the rock surrounding the drift.

Once these natural convection cells are calculated by FLUENT, the dispersion coefficient needed by the condensation model is evaluated. The concentration difference of a neutrally buoyant trace gas is applied at the axial ends of the unit cell and the trace gas mass flux is calculated by FLUENT. A reasonable lower bound for the dispersion coefficient (low dispersion) is calculated, which does not include the effect of the axial temperature gradient on the flow in the unit cell. A reasonable upper bound value for the dispersion coefficient (high dispersion) is calculated by applying an axial temperature gradient to the unit cell. These two values bound the uncertainty of the axial dispersion coefficient (BSC 2003f).

In the condensation model, the evaporation rates from the drift wall and invert surfaces are limited by the rate at which water is supplied from the rock. At each waste package location, the possible sources of water are at the drift wall and the top of the invert. Where evaporation occurs, the local partial pressure of water vapor is the saturation vapor pressure at the calculated temperature. The rate of evaporation is based on the local vapor pressure difference among the evaporating surface, the local partial pressure, and the corresponding mass transfer correlation.

The result of the condensation model indicates that, progressing from the drift center, the gas vapor pressure reaches a point where it is slightly higher than the equilibrium vapor pressure at the drift wall. A portion of the axially transported water vapor condenses on the drift wall on both sides. The rate of condensation on the drift wall in these regions is determined by the vapor mass fraction difference between the gas and the wall and the thickness of the gas boundary layer.

In the regions between the two condensation zones and the nonemplacement portions of the drift (the access turnout and the exhaust standoff), the vapor mass fraction in the gas again dips below the equilibrium mass fraction at the wall. As in the center of the drift, water evaporates from the drift wall in the two regions. This evaporated water combines with the axially transported water vapor that made it through the condensation zones and condenses in the nonemplacement region of the drift.

The results of the condensation model and the observation in the ECRB Cross-Drift are not inconsistent. The observation that the liquid water behind the ECRB Cross-Drift bulkhead is the result of condensation is consistent with a conceptual representation that liquid water can (1) be evaporated from warmer areas of the drift, (2) be transported along the drift through natural convection processes (due to barometric pumping or heterogeneous gas pressures and permeabilities) or small thermal gradients along the drift, and (3) condense in cooler areas of the drift or on other cooler materials in the drift (such as the conveyor belt) (BSC 2003d). A similar process is expected to take place within the repository emplacement drifts. Water from the rock will evaporate from the drift walls at warmer locations and condense on colder surfaces. Those surfaces are likely to include the drift walls at cooler locations and may also include cooler waste packages and drip shields. The rates of evaporation and condensation, and the rate of water vapor transport in the drift, will determine the humidity in the drift, the extent of condensation, and may affect the liquid saturation of the invert. As a result, this process, although excluded from the TSPA for the Site Recommendation, is being screened in for the purposes of the License Application.

J.4.3.4 Effect of Future Source of Water on Other Models

This section discusses the effect of future sources of water (i.e., seepage and condensation) on the models.

The amount of seepage water entering the drift has a direct impact on corrosion of engineered barriers, dissolution, and release and transport of radionuclides. The parameters related to flow have been used to predict seepage, as discussed in Section J.4.3. Seepage model results provide the basis for the seepage abstraction and are propagated through the TSPA model.

Section J.4.2 describes the evidence of dripping in the ECRB Cross-Drift that indicates condensation as an additional source of water. In a sealed drift with boiling temperature, evaporation of liquid promotes an increase in the moisture content and, therefore, condensation and dripping under the drift shield. In the case of water dripping on the drip shield or waste canister, it may promote corrosion. Chemical analysis of water from condensation in the ECRB Cross-Drift (Section J.4.2.2) indicates no major change in chemistry, indicating the condensate does not have a significant effect on corrosion. Furthermore, uncertainties of condensate accumulation and dripping in waste emplacement drifts have been evaluated (BSC 2003f). Uncertainties in the axial dispersion coefficient and the vapor pressure at the invert surface are the two major contributors to uncertainties. Each one is modeled using the respective low and high bounding values producing four calculations, and the resulting cases are given equal weight in the TSPA-LA. Use of this bound provides clear insight into the relative importance of the underlying phenomena to the safety case. The calculations are repeated for lower-bound, mean, and upper-bound infiltration rates.

J.4.3.5 Summary

The seepage rate is a function of fracture medium permeability, the van Genuchten parameter (1/α), percolation flux, and drift temperature. The seepage is found to be larger for smaller fracture continuum permeability, smaller van Genuchten parameter, and larger percolation flux values.

Simulations indicate that, under elevated temperature conditions, seepage is not likely to penetrate through the heated rock during the first several hundred years of heating when the rock temperature is high, and boiling conditions exist in a sufficiently large dryout zone above the drifts. Later, when the dryout zone is small and the impact of vaporization is limited, seepage reoccur at the drift.

Seepage is accounted for in the TSPA calculations. The amount of dripping from rock bolts and other engineered materials, and the related impact on hydrologic and chemical conditions of the waste canister, are excluded from the performance assessment calculations because the quantities and effects are inconsequential.

The in-drift convection of moisture, the resultant distribution (in both space and time), and the amount of condensation are evaluated using analyses derived from a model, which describes these processes. *In-Drift Natural Convection and Condensation* (BSC 2003f) provides the TSPA model with both the probability of condensation in the waste emplacement drift and, when the probability is not zero, the magnitude of condensation correlated with percolation rate. When condensation occurs, the TSPA model treats it in the same manner as seepage (i.e., as a source of liquid water flow into the drift having the same chemistry as crown seepage).

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J.5.2 Data, Listed by Data Tracking Number

LB0304SMDCREV2.001. Seepage Modeling for Performance Assessment, Including Drift Collapse: Input/Output Files. Submittal date: 04/11/2003.

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