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Preliminary Evaluation of Seepage Observations from the ESF South Ramp Using the Drift Seepage Abstraction Model

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ACRONYMS

ESF	Exploratory Studies Facility
SMPA	seepage model for performance assessment
TSPA	total system performance assessment
3D	three-dimensional

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1. INTRODUCTION

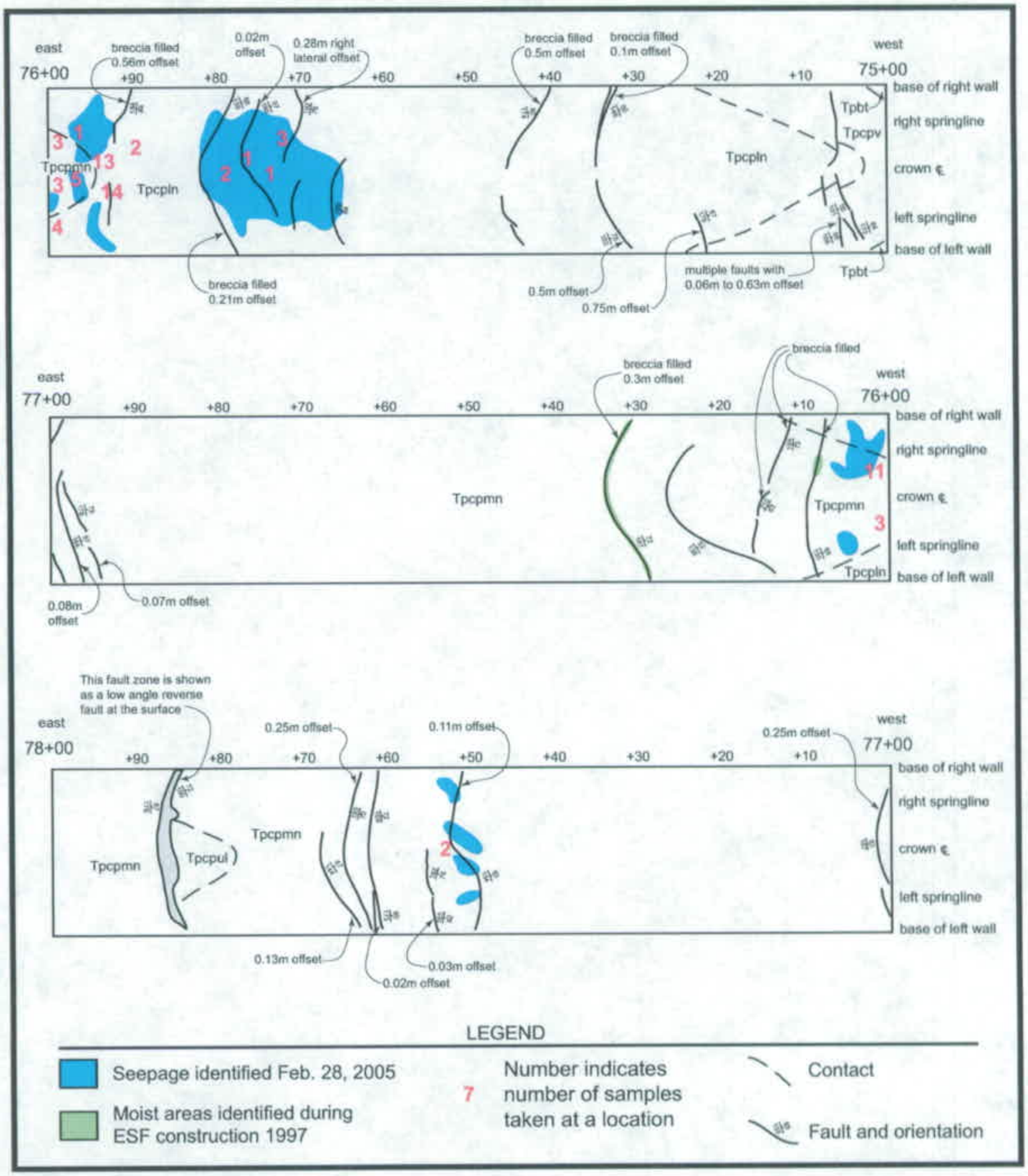
The overall purpose of this report is to address CR-5087, action 5087-001, which notes that the observation of water seeping from the crown and ribs of the ESF South Ramp is considered an "unexpected condition." The condition has been reported and documented by photographs, and water samples have been taken. Following the Corrective Action Plan, a study was conducted to evaluate and compare the observations with the conceptual and numerical models used to predict seepage into underground openings in the Tiva Canyon. CR-5087 is resolved by demonstrating that the observed seepage is consistent with model predictions, and is thus not an unexpected condition.

1.1 BACKGROUND

During the period between October 2004 and February 2005, unusually heavy precipitation—12.75 inches, which is about 3.5 times the recent nine-year average of 3.64 inches, taken over the same time period between October and February (BSC 2005 [DIRS 176148], Section 2.3)—occurred in the Yucca Mountain area. On February 28, 2005, Yucca Mountain Project personnel working in the South Ramp of the Exploratory Studies Facility (ESF) observed—in select areas—wet spots on the main drift's crown, ribs, and invert. This field observation is considered the first unambiguous evidence of seepage under ambient conditions.

As shown in Figure 1, wet areas were identified between Stations 75+62 and 75+82, Stations 75+92 and 76+07, and Stations 77+48 to 77+53. The section of the ESF South Ramp that is located in the densely welded, pervasively fractured rocks of the Tiva Canyon Tuff—i.e., where there are no intervening layers of bedded or non-welded tuffs (PTn) between the main drift and the surface—is approximately 300 m long, from Station 75+80 to the South Portal at Station 78+77.

Assuming (1) that each of the wet areas identified in Figure 1 actually resulted in drop formation and drop detachment (as opposed to film flow along the drift surface), and (2) that—for wet areas extending more than 5 m in axial direction—at least one dripping location exists for every 5 meters of continuous wet area, it can be estimated that approximately 13% of the drift section experienced seepage. Note that the actual drip area is substantially smaller than the wet area; however, given the assumptions outlined above, this does not affect the calculation of the seepage measures used in a total system performance assessment (TSPA) calculation, which are the seepage percentage and seepage fraction. Both these measures refer to seepage averaged over a reference area, which is defined as the footprint area of a 5.1-meter long drift section.



Source: BSC 2005 [DIRS 176148], Figure 1.

NOTE: Geology is taken from full periphery maps OA-46-282, -293, and –294 (DTN: GS970808314224.013 [DIRS 107497]). Normal offset is noted for most faults; however, the fault zone at 78+85 has been interpreted to be a low-angle reverse fault at the surface.

Tpcpln = Tiva Canyon Tuff lower nonlithophysal zone; Tpcpmn = Tiva Canyon Tuff middle nonlithophysal zone; Tpcpul = Tiva Canyon Tuff upper lithophysal zone

Figure 1. Full Periphery View of the ESF South Ramp from Station 75+00 to Station 78+00, Showing Seeps Identified since February 28, 2005

1.2 OBJECTIVES

The objective of this study is to examine whether the modeling approach employed to estimate seepage into waste emplacement drifts yields results that are consistent with the observed seepage in the ESF South Ramp.

It is important to realize that the modeling study reported here is *not* an attempt to predict, reproduce, or analyze the South Ramp seepage data. Such an effort would require the development of a specific model to accurately capture the hydrogeologic conditions in the South Ramp as they prevailed before and during the period of the seepage observations. Instead, the conceptual framework developed for the estimation of long-term seepage into waste emplacement drifts in the Topopah Spring unit is used with minimal adjustments to examine whether the results of the probabilistic approach employed in a TSPA calculation (which considers uncertainty and spatial variability in fracture permeability, capillary strength, and local percolation flux) would provide reasonable seepage estimates, even if applied to the conditions in the South Ramp. If so, confidence can be gained that the seepage abstraction [*Abstraction of Drift Seepage* (BSC 2004 [DIRS 169131])] captures the processes relevant for the prediction of natural seepage into large underground openings. Moreover, it can be stated that the observation of water dripping is not an "unexpected condition," but consistent with our understanding of seepage into large underground openings in the unsaturated zone of a fractured formation.

2. ANALYSES

2.1 APPROACH

The simulation and prediction approach closely follows that described in the report *Seepage Model for PA Including Drift Collapse* (BSC 2004 [DIRS 167652]):

- Develop a heterogeneous fracture-continuum model of a 5-m long section of the ESF.
- Evaluate seepage for a range of parameter values. The three seepage-relevant parameters varied are (1) reference fracture permeability, (2) van Genuchten capillary-strength parameter, and (3) average percolation flux at top model boundary.
- Develop look-up table of seepage as a function of the three seepage-relevant parameters. Note that the look-up table developed here is based on a single realization of the underlying heterogeneous fracture permeability field, whereas multiple realizations were calculated by the seepage model for performance assessment (SMPA).
- Determine probability distributions for the three seepage-relevant parameters.
- Randomly sample from the probability distributions and determine related seepage flux (either by interpolation from the seepage look-up table, or by performing Monte Carlo simulations using the process model directly).
- Determine seepage fraction (percentage of realizations with non-zero seepage).

- Compare modeling results to qualitative information from seepage observations in ESF South Ramp. Given the objectives of this study (see Section 1.2) as well as the context and limited scope of both data collection and model development, the assessment is restricted to a qualitative comparison of calculated spatial seepage frequency with the observed extent of wet areas, and an order-of-magnitude comparison between calculated seepage rates and estimates from sample collection.

Two sets of simulations are performed using iTOUGH2 V5.0 (LBNL 2002 [DIRS 160106]):

- Seepage is evaluated for many combinations of the three seepage-relevant parameters (drift-scale fracture-continuum permeability, capillary-strength parameters, and local percolation flux) to generate a seepage response surface (look-up table); see Section 2.5.

- Monte Carlo simulations are performed to estimate the likelihood of observing seepage in the South Ramp; see Section 2.6.

In both approaches, individual simulations calculate the seepage flux (defined as the flow rate into the opening divided by the footprint area of the ESF drift section) for a given parameter set. In the first approach, which can be considered an extensive sensitivity analysis, the parameter space is examined systematically within the range given in Table 1 below. A response surface can be interpolated between the discrete points evaluated by the process model, providing the seepage flux for all possible parameter combinations; it also reveals the seepage threshold. However, it does not provide information about the likelihood that seepage occurs.

In order to obtain the seepage fraction (i.e., the number of 5-m long drift sections that are likely to encounter a non-zero seepage flux), information about the probability of the three seepage-relevant parameters is required, which is used to calculate the seepage rates for the given conditions. For this validation study, a simple Monte Carlo analysis is performed with sampling distributions (see Section 2.4) that need to be different from those proposed by the seepage abstraction and used in a TSPA calculation, because the geologic and hydrologic conditions in the South Ramp are different from those in the repository horizon. Furthermore, the TSPA approach is more complex and includes multiple scenarios and seepage prediction uncertainty that are not considered in this validation study. Nevertheless, the Monte Carlo approach chosen here can be considered an alternative, reasonable attempt at estimating seepage into the ESF South Ramp.

2.2 MODEL GEOMETRY AND MESH GENERATION

A three-dimensional (3D) model for calculating seepage into the South Ramp is developed based on the SMPA (BSC 2004 [DIRS 167652]). The model domain has a length of 2.4384 m (8 ft), a width of 5.55 m (18.2 ft), and a height and 10.0 m (32.8 ft), and includes a portion of the drift of diameter 8 m. Due to symmetry, a drift section half the length of a typical waste package is modeled, and only the left-hand half of the ESF drift is represented (Figure 2). Since seepage is only expected from the upper half of the drift, the lower boundary of the model is set 0.5 m below the drift centerline.

The model domain is discretized as follows. The length along the drift axis consists of 8 grid cells of 1 foot (0.3048 m) length. The grid cells in the plane normal to the drift axis are of dimensions 0.1 m × 0.1 m. This grid resolution is identical to that of the SMPA. The grid was generated using the approach presented in *Seepage Calibration Model and Seepage Testing Data* (BSC 2004 [DIRS 171764], Appendix C), slightly modified to accommodate the larger drift size. The 3D mesh is created by (1) generating a cubic mesh of the domain with the specified discretization, (2) mapping a field of permeability modifiers onto the mesh, (3) cutting a cylindrical drift from this cubic mesh, while inserting an element representing the drift, and (4) adding extra top and bottom boundary elements.

Seepage flux will be calculated by the total amount of water entering the drift element, divided by the footprint area of the drift, i.e., half the drift diameter times the length, which amounts to an area of $(8/2) \times 2.4384 = 9.7536\ \text{m}^2$.

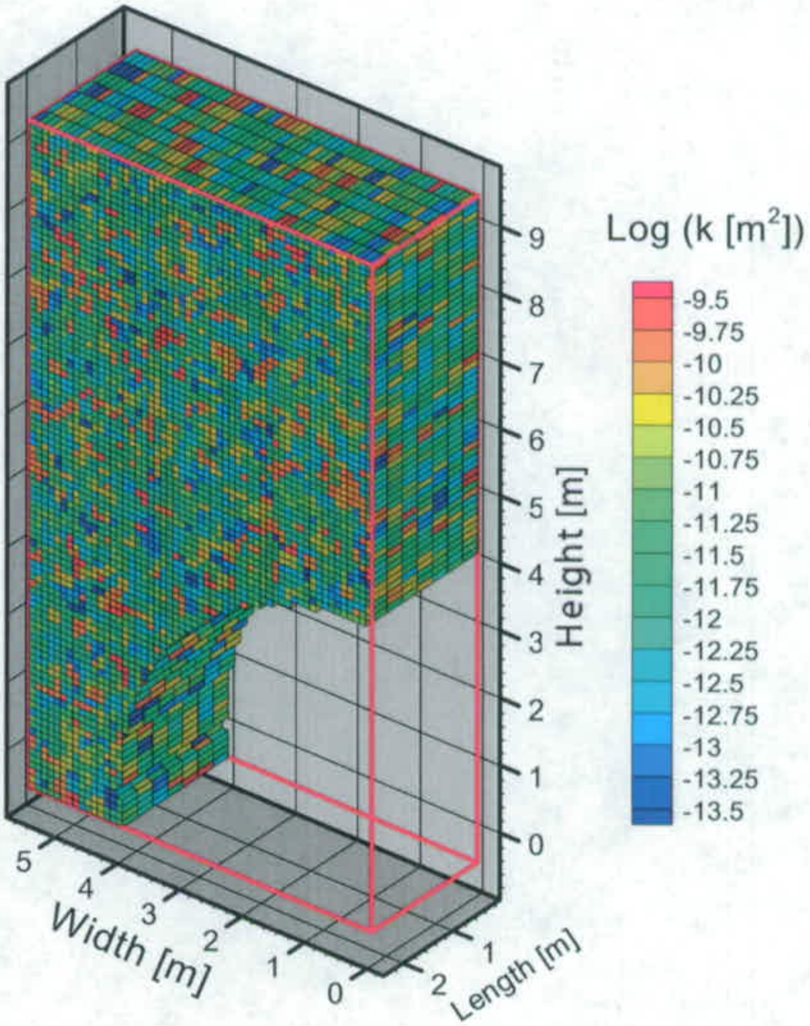


Figure 2. Model Domain and Mesh Design for South Ramp Seepage Simulation

2.3 BOUNDARY AND INITIAL CONDITIONS

The boundary conditions are similar to those used for the SMPA simulations:

- No-flow boundary conditions are specified at the left, right, front, and back sides of the model.

- A free-drainage boundary condition is applied at the bottom to prevent an unphysical capillary boundary effect.

- The elements representing the ESF are assigned a zero-capillary pressure independent of saturation, which is equivalent to assuming 100% relative humidity in the ESF. This assumption (while consistent with that in the SMPA), may not be representative of the conditions in the ESF. Including evaporation effects in the model would reduce the calculated seepage rate and seepage percentage.

- A time-dependent flux boundary condition at the top of the model needs to be specified. This flux will represent the local percolation flux 5.5 m above the crown of the ESF. In the absence of direct percolation flux measurements, the flux is usually estimated based on precipitation data, which are used to estimate net infiltration, followed by a calculation of unsaturated flow through the Tiva Canyon unit. For this validation study, no detailed infiltration and percolation calculations are performed. The following values are specified:

  - A long-term infiltration flux is specified to obtain the initial background flow field. A value of 4.2 mm/yr is applied, taken from Column a23 of the infiltration map used by the UZ flow model (BSC 2004 [DIRS 169861]) for mean present-day conditions.

  - Increased precipitation between October 2004 and February 2004 preceded the seepage observations in the South Ramp. The long-term and monthly precipitation averages are summarized in Table 1 and Figure 3. In the absence of a detailed infiltration analysis, infiltration is assumed to be on the order of 10% of precipitation.

  - The local percolation flux is inferred from the net infiltration flux, assuming that unsaturated flow in the Tiva Canyon unit is (on the scale of the length of the South Ramp) predominantly vertical. However, flow focusing effects may reduce or enhance the local percolation flux compared to the infiltration flux. Flow focusing effects are included in the specified local percolation fluxes.

  - Local percolation fluxes directly inferred from precipitation data are considered highly uncertain. The high rainfalls may lead to higher runoff, potentially reducing the ratio between infiltration and precipitation. On the other hand, evapotranspiration may be reduced compared to the annual average, leading to a higher ratio.

  - Spatial and temporal rainfall patterns affect infiltration and percolation flux distributions. Multiplication factors describing focusing and redistribution of flow are not known.

- To account for this uncertainty and flow focusing effects, and in the absence of detailed analyses of infiltration, percolation, and flow focusing, seepage is evaluated for local percolation fluxes ranging from essentially 0% to approximately 40% of the monthly precipitation flux.

Table 1. Base-Case Infiltration Fluxes

Period	Measured Precipitation Flux[a] [mm/yr]	Assumed Base-Case Infiltration Flux[b] [mm/yr]
Long-term	188.5	4.2
October	814	81.4
November	393	39.3
December	575	57.5
January	865	86.5
February	1309	130.9

[a] Green (2005).

[b] Base-case infiltration is assumed 10% of the monthly averaged precipitation; long-term infiltration is taken from the UZ flow model (BSC 2004 [DIRS 169861], Section 6.1.4).

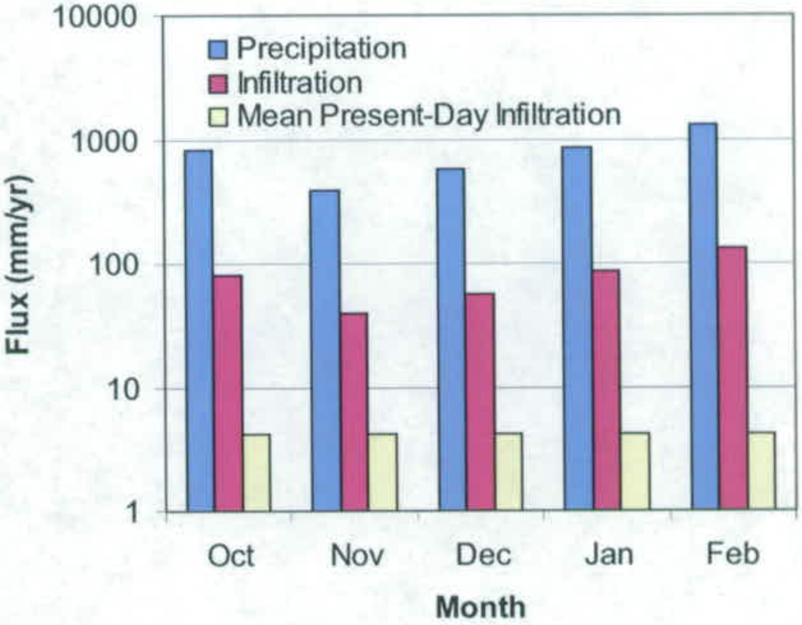


Figure 3. Total Monthly Rainfall during October 2004 to February 2005, the Conjectured Infiltration, and Surface Infiltration on Top of South Ramp for Present-Mean Infiltration Scenario

2.4 DISTRIBUTION OF SEEPAGE-RELEVANT PARAMETERS

The following three uncertain model parameters have been identified as significantly affecting seepage:

- Mean fracture-continuum permeability $\log(k_f\,[\mathrm{m}^2])$
- van Genuchten capillary-strength parameter $1/\alpha$[Pa]
- Local percolation flux q_f [mm/yr] applied at top model boundary.

Probability distributions need to be defined for these three seepage-relevant parameters to account for their respective uncertainty and spatial variability; they are summarized in Table 2 and discussed below.

The fracture permeability determines the ease with which water is diverted around the capillary barrier acting at the drift surface. The higher the permeability, the smaller the seepage rate for a given capillary strength and percolation flux. The base-case, mountain-scale log-permeability values [$\log_{10}$ m^2] of the Tiva Canyon Tuff were estimated by calibration against pneumatic pressure data to be –10.02 and –10.87, respectively (BSC 2004 [DIRS 169857], Table 6-12), which yields an approximate average of -10.5. Due to the large scale and preferential weighting of high-permeability features, this estimate is considered high and not representative of drift-scale conditions needed for seepage calculations. Air permeabilities from surface-based borehole data are significantly smaller in both the Tiva Canyon and Topopah Spring units (see Table 2). Pre-excavation, small-scale air-permeability data from the Topopah Spring unit suggest drift-scale permeabilities that are more than 1.5 orders of magnitude smaller than the mountain-scale permeabilities. However, dilation effects as a result of drift excavation may increase the pre-excavation permeabilities by 1.3 orders of magnitude for the relatively low-permeable Tptpmn unit, and 0.7 orders of magnitude for the Tptpll unit, which has a higher undisturbed permeability.

To estimate the seepage-relevant small-scale permeability of the excavation-disturbed zone around the ESF in the Tiva Canyon unit, we start with the log-permeability of -11.3, measured from surface-based boreholes. Following the analysis of permeability data from the Topopah Spring unit, we then adjust the value, reducing it by one order of magnitude to account for scale effects (see Table 2), and increasing it by 0.8 orders of magnitude to include excavation effects expected for a relatively permeable formation.

In summary, for this validation study, the mean fracture permeability is assumed to follow a log-normal distribution with a mean for $\log(k_f\,[\mathrm{m}^2])$ of -11.5 and a standard deviation of 1.0. The distribution is truncated to yield a range between -13.5 and -9.5. Note that the seepage abstraction as outlined in *Abstraction of Drift Seepage* (BSC 2004 [DIRS 169131], Section 6.6.3) uses a triangular and normal distribution to characterize, respectively, uncertainty and variability in log-permeability. The simpler approach chosen here is considered appropriate for the purpose of this validation study. Also note that this distribution represents the uncertainty and variability of the mean permeability on the drift scale (i.e., approximately the size of a 5-m long drift segment). Small-scale heterogeneity is explicitly accounted for by generating a random permeability field around this drift-scale mean, using a standard deviation of 1.0 and a correlation length of 0.3 m (see Table 4).

The van Genuchten capillary-strength parameter $1/\alpha$ characterizes the strength of the fracture network to retain the water within the formation, reducing or preventing seepage. A seepage-related capillary-strength parameter was experimentally determined through inverse modeling of seepage testing data for the Topopah Spring Welded Tuff units (Tptpll and Tptpmn). The seepage abstraction (BSC 2004 [DIRS 169131], Section 6.6.2) determined a mean value of 591 Pa and reported a range from 297 Pa to 885 Pa. As discussed in (BSC 2004 [DIRS 169131], Section 6.3.3.2), the capillary-strength parameter to be used for seepage simulations is an effective parameter, which specifically accounts for features and processes that affect seepage. Since many of these features and processes (such as surface roughness effects and film flow along the drift wall) are lumped into the effective capillary-strength parameter during model calibration, this parameter does not strongly depend on the hydrogeologic unit. It is therefore reasonable to employ a similar range for the study of seepage in the Tiva Canyon unit. A normal distribution for $1/\alpha$ was chosen, with a mean, standard deviation, and range of 591 Pa, 100 Pa, and 300 – 900 Pa, respectively. Note that the seepage abstraction (BSC 2004 [DIRS 169131], Section 6.6.2) uses a triangular and uniform distribution to characterize, respectively, uncertainty and variability of the capillary-strength parameter. The simpler approach chosen here is considered appropriate for the purpose of this validation study.

The percolation flux arriving at the drift is one of the key quantities determining seepage. Specifically, if the local percolation flux is below the seepage threshold, no seepage will occur. To account for uncertainty in precipitation, infiltration, and flow redistribution between the land surface and the South Ramp within the Tiva Canyon unit (which is less than approximately 75 m), the time-dependent precipitation fluxes as specified in Table 1 are multiplied by a normally distributed factor that has a mean of 0.1 and a standard deviation of 0.1. To avoid unreasonable local percolation fluxes during Monte Carlo sampling, the normal distribution is truncated by rejecting factors smaller than 0.01 and factors greater than 1.0. Note that this approach is different from that employed in a TSPA calculation, where the local percolation flux is taken from the multiscale thermohydrologic model and multiplied by a flow focusing factor, which is randomly sampled from a (non-Gaussian) flow focusing factor distribution.

Additional parameters affecting unsaturated flow and seepage processes are considered of less significance and are thus fixed at the values given in Table 4.

Table 2. Fracture Permeabilities from Various Sources for Selected Tiva Canyon and Topopah Spring Units and the Estimated Fracture Permeability for Seepage Simulations in the ESF South Ramp

Source	Tiva Canyon log (k [m^2])	Topopah Spring (Tptpmn) log (k [m^2])	Topopah Spring (Tptpll) log (k [m^2])
Calibrated with Pneumatic Data	−10.5[a]	−10.5[a]	−10.0[a]
Surface-Based Borehole Data	−11.3[b]	−12.2 (± 0.34)[c]	—
Small-Scale Air-Injection Test (Pre-Excavation)	***−12.3***[e]	−13.2 (± 0.85)[d]	−11.5 (± 1.12)[d]
Small-Scale Air-Injection Test (Post-Excavation)	***−11.5***[e]	−11.9 (± 0.79)[d]	−10.8 (± 1.31)[d]

[a] Based on BSC 2004 [DIRS 169857], Table 6-12; DTN: LB02091DSSCP3I.002 [DIRS 161433]

[b] BSC 2004 [DIRS 170038], Table 6-5; DTN: LB0205REVUZPRP.001 [DIRS 159525]

[c] Table 6.6-5, DTN: LB0407AMRU0120.001

[d] Table 6.6-3, DTN: LB0407AMRU0120.001

[e] Inferred from available data in the Topopah Spring unit (see discussion above).

Table 3. Seepage-Relevant Parameters

Parameter	Distribution	Mean	Standard Deviation	Lower Bound	Upper Bound
Drift-scale fracture permeability	Lognormal	−11.5	1.0	−13.5	-9.5
Capillary-strength parameter	Normal	591	100	300	900
Percolation index	Normal	0.1	0.1	0.01	1.0

Table 4. Fixed Parameters

Parameter	Value
Fracture porosity [-]	0.015[a]
Residual liquid saturation [-]	0.01[b]
Satiated saturation [-]	1.00[b]
van Genuchten parameter *m* [-]	0.633[a]
van Genuchten parameter $n = 1/(1-m)$ [-]	2.72
Geostatistical parameters for small-scale distribution of fracture permeability:	
Variogram type	Spherical[c]
Standard deviation log(*k* [m^2])	1.0[d]
Correlation length [m]	0.3[d]

[a] Source: BSC 2004 [DIRS 169857], Table 4-3; averaged from tcw12 and tcw13

[b] Assumed

[c] Source: BSC 2004 [DIRS 167652], Section 6.5.

[d] Source: BSC 2004 [DIRS 167652], Section 6.3.

2.5 SEEPAGE RESPONSE SURFACE

Predictive simulations for seepage were performed systematically for combinations of seepage-relevant parameters. The three-dimensional parameter space was subdivided into 8×8×8 equally spaced points over the parameter's respective ranges (see Table 3). For each of the 512 parameter combinations, a steady-sate simulation was performed with the long-term percolation flux of 4.2 mm/yr (see Table 1), followed by a transient simulation to capture the response of the system to the high precipitation between October 2005 and February 2005, where monthly averages (see Table 1) are multiplied by a factor between 0.01 and 1.0; the resulting local percolation flux is then applied at the top of the model. The amount of seepage into the ESF drift section is calculated, divided by the footprint of the modeled drift section, and averaged over the period of 5 months to yield the seepage flux, which is plotted in Figure 4. (Note that transient seepage fluxes are available; the results are averaged over the 5-months period to yield a result that can easily be reported. Assuming that no additional seepage will occur during the remainder of the year, the seepage rate values could be multiplied by a factor of 5/12 to yield annual averages, which are then comparable to the long-term average fluxes visualized in Figure 6-4 of BSC (2004 [DIRS 167652]).

For any given combination of seepage-relevant parameters that may be encountered along the ESF South Ramp, the look-up table visualized in Figure 4 can be used to determine whether seepage is expected to occur, and what the corresponding seepage rate is. No seepage is expected for locations with high permeability and high capillary strength. For low-permeability sections in the South Ramp, seepage into the ESF is expected even for small local percolation rates. Significant seepage is expected if capillarity is weak and the local percolation flux is high.

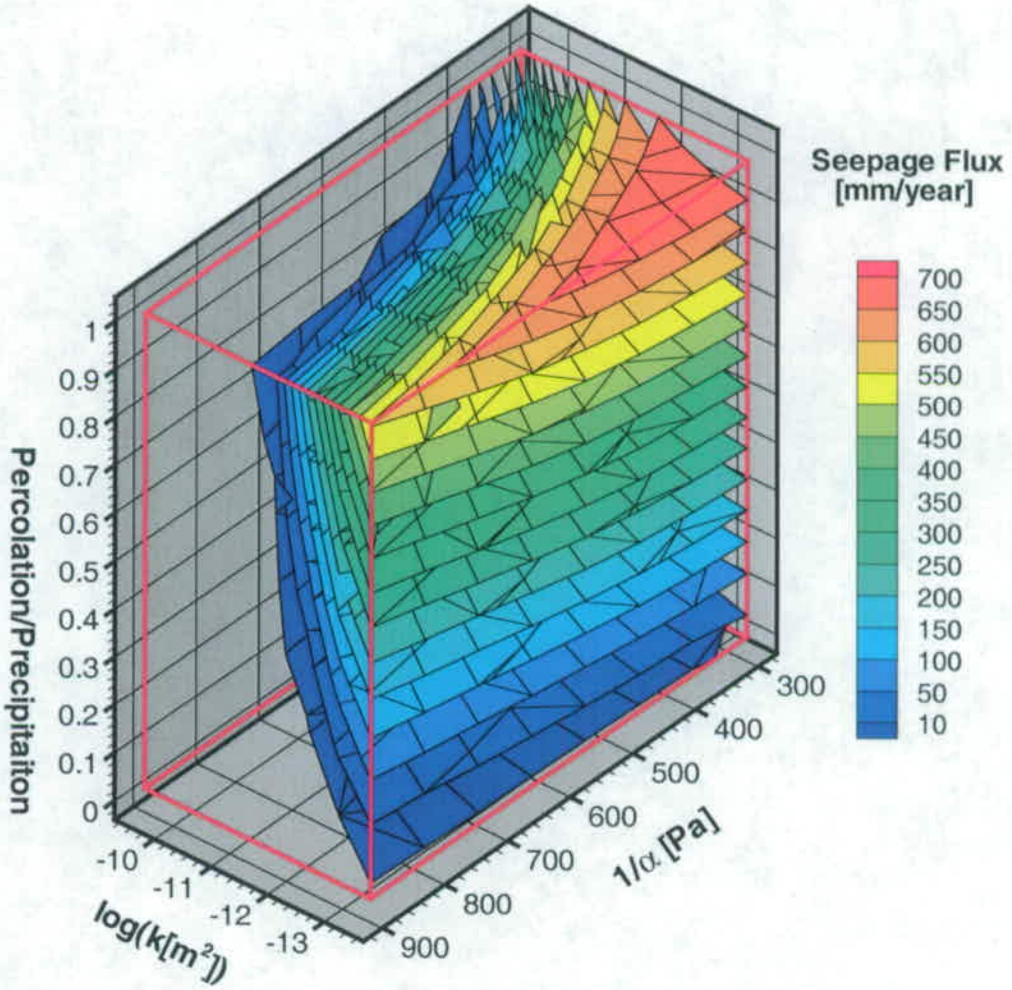


Figure 4. Calculated Average Seepage Flux into 5-m Long Section of ESF between October 2004 and February 2005 as a Function of the Three Seepage-Relevant Parameters Permeability, Capillary Strength and Local Percolation Flux (Expressed as a Fraction of Precipitation)

2.6 MONTE CARLO SIMULATIONS

As discussed in Section 2.1, Figure 4 (or the underlying look-up table) can be used in a probabilistic calculation to evaluate the seepage probability in the ESF South Ramp. In such an approach, the three seepage-relevant parameters are repeatedly sampled from their respective uncertainty and variability distributions, and the corresponding seepage flux is interpolated from the look-up table. The resulting frequency distribution of the seepage flux contains the desired information. Specifically, the fraction of realizations yielding non-zero seepage rates can be interpreted as the expected percentage of 5-m long drift sections that encounter seepage.

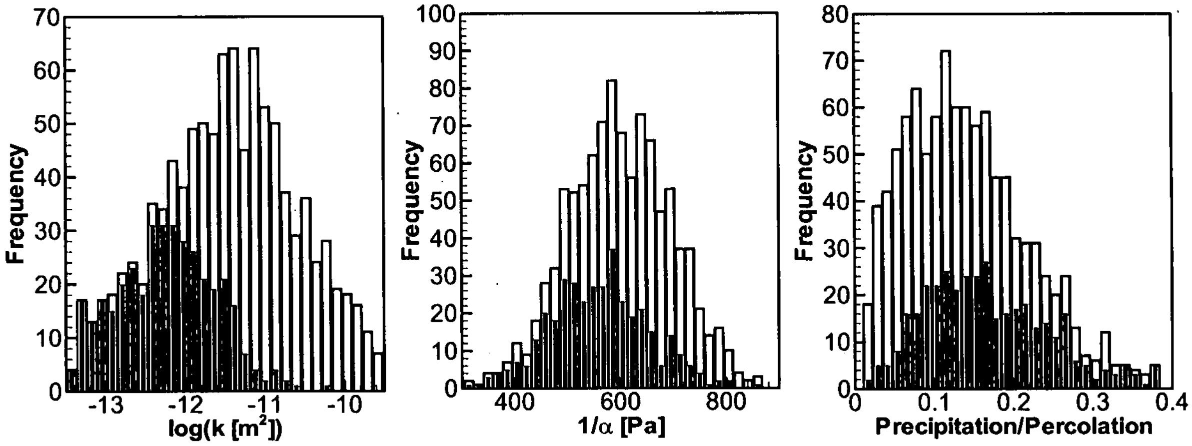
Instead of interpolating from the look-up table, we calculated the seepage flux using the seepage process model directly. Each individual simulation of unsaturated flow and seepage for a given parameter set consists of two parts. First, a steady-state simulation is performed using the long-term, present-day percolation flux. The resulting flow field is used as the initial condition for the subsequent simulation of the high-precipitation events during the period between October 2004 and February 2005, where monthly averages (see Table 1) are multiplied by a truncated, normally distributed number between 0.01 and 1.0 (with mean 0.1 and standard deviation of 0.1); the resulting local percolation flux is then applied at the top of the model.

One-thousand random, uncorrelated parameter sets were generated, approximately following the predefined probability distributions of Table 3. The histograms of the generated input parameters are shown in Figure 5, with the subset of realizations that led to seepage shown as shaded histograms. As expected, only locations with a relatively small permeability resulted in seepage. Realizations that include a relatively weak capillary-strength parameter are more likely to induce seepage. Nevertheless, seepage was predicted also for $1/\alpha$ values, if they are combined with a relatively low permeability and relatively high percolation flux. While high percolation fluxes naturally lead to seepage, in 50% of the cases seepage was induced at locations with a percolation-to-precipitation ratio of less than about 0.17.

The resulting realizations of seepage into a 5-m long drift section are shown in Figure 6. The time-dependent seepage flux reflects the changing precipitation conditions at the land surface. The relatively fast response of seepage to changes in precipitation is a result of the fact that matrix imbibition effects are ignored in the current model. Moreover, only a short distance (5.5 m) is modeled from the top of the model domain to the opening, underestimating the time needed to initiate seepage, and thus overestimating the total amount of seepage. However, given the relatively small flow distance from the ground surface to the ESF (less than 75m), as well as the absence of a dampening PTn layer, travel time of a water pulse through the Tiva Canyon unit is not expected to be very long (as evidenced by the observed onset of seepage in response to the high precipitation events), and does therefore not affect the results of this report, which is concerned with seepage fraction rather than first arrival time.

The cumulative frequency distribution of the seepage flux averaged over the 5-month simulation period is shown in Figure 7. Of the 1000 simulations, 371 (or 37.1%) yielded non-zero seepage, and 100 simulations (or 10%) yielded a 5-month average seepage flux of at least 40 mm/yr.

Within the current framework, these probabilities for seepage at a given location can also be interpreted (assuming ergodicity) as the fraction of drift sections that experiences seepage. For the 300 m long ESF South Ramp section that is not overlain by the PTn unit, these preliminary results suggest that seepage would have been observed over a total distance of approximately 110 m. This value is approximately 3 times larger than the actually observed extent of wet areas in the ESF South Ramp of approximately 40 m (see Figure 1 and related discussion). It should be realized that the prediction assumed that the ESF is not ventilated, leading to 100% relative humidity, which maximizes seepage. Many of the 371 realizations exhibit very small seepage rates, i.e., even relatively small evaporation rates would significantly reduce the number of seepage locations.



NOTE: The parameter realizations that led to seepage are shown as shaded histograms.

Figure 5. Histograms of Seepage-Relevant Input Parameters Obtained by Monte Carlo Sampling

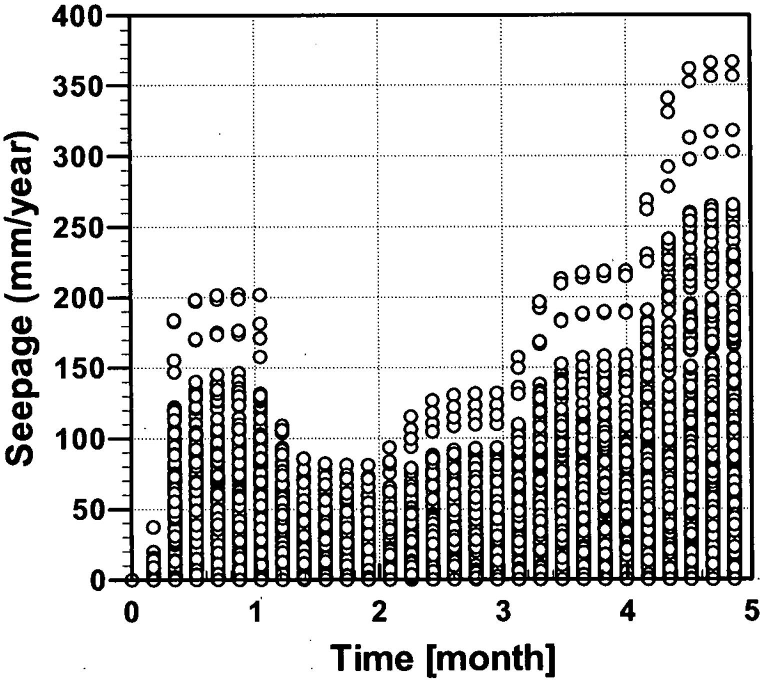
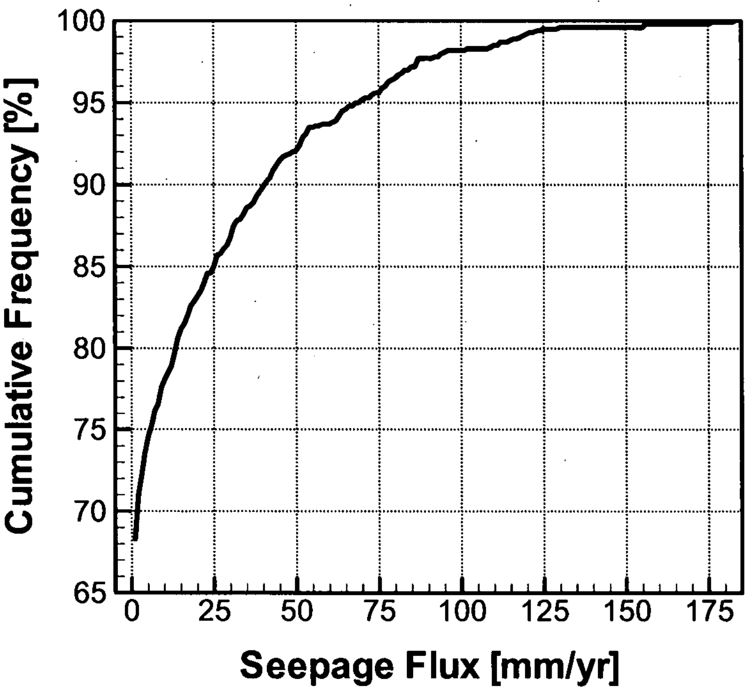


Figure 6. Seepage Flux from 1000 Transient Simulations Using Monte Carlo Sampling of Seepage-Relevant Parameters



NOTE: Approximately 63% of the Realizations did not Yield any Seepage; 68% of the Realizations Yielded a Seepage Flux of Less than 1 mm/yr; 10% of the Realizations Yielded Seepage Fluxes Greater than Approximately 40 mm/yr.

Figure 7. Cumulative Distribution Function of Seepage Flux Averaged over the Five-Month Simulation Period

3. DISCUSSION

Given the objective and limited scope of this study, the comparison of seepage fraction and seepage flux between model results and observations is performed in a qualitative manner. In particular, the comparison may be considered satisfactory if the model predicts some nonzero level of seepage flux into the drift while maintaining a seepage fraction less than one, i.e., the model should not predict seepage to occur at all locations along the section of the ESF that is not overlain by the PTn unit. The seepage simulations yielded results that are higher than but consistent with observations made in the South Ramp. Specifically, the model predicted that some but not all locations along the ESF South Ramp will encounter seepage, which is in qualitative agreement with the actual observations. About 15% of the realizations yielded a seepage flux less than 28 mm/year (corresponding to approximately 125 mL/hr), which is on the same order of magnitude as the rates measured during water sampling (BSC 2005 [DIRS 176148], Section 2.2).

Because both the observed data and the simulation results are highly uncertain and potentially biased, the following caveats must be considered when interpreting this result:

- The seepage observations are of qualitative nature. Specifically, it is not clear whether all the wet areas mapped in the ESF South Ramp (see Figure 1) actually lead to seepage as defined in *Abstraction of Drift Seepage* (BSC 2004 [DIRS 169131], Section 6.1.3). Note that the actual dripping area is likely to be substantially smaller than the wet area. The current analysis makes the assumption that at least one dripping location is present for every 5 m of wet area along the drift axis. While the presence of puddles on the invert indicates dripping, water flow along the drift surface (as described for certain locations) does not constitute seepage. On the other hand, the size of a wet spot is known to strongly depend on evaporation rates, and dripping water may have evaporated before its detection. The seepage fraction estimated from the observations is therefore highly uncertain.

- The seepage process model used as the basis for predicting seepage into the ESF South Ramp is consistent with the SMPA, including the assumption that no evaporation occurs. While this assumption is conservative and appropriate for predicting long-term seepage into waste emplacement drifts under ambient conditions, it may not represent the conditions in the ESF South Ramp. Accounting for evaporation effects would reduce the predicted seepage fraction.

- The SMPA and seepage abstraction methodology is based on the assumption that the PTn dampens episodic infiltration events to yield near-steady percolation conditions in the Topopah Spring unit. In the absence of a porous PTn layer between the land surface and the ESF South Ramp, transient effects have to be taken into account. The model described here uses time-dependent flux boundary conditions and calculates transient seepage rates. However, it does not account for storage effects in the matrix, nor for the actual thickness of the Tiva Canyon unit and its variability. While such storage effects may be minor after a time period of 5 months, they may still impact seepage results, leading to a potential overestimation of seepage by the fracture-continuum model.

- The seepage look-up table (visualized in Figure 4) and the Monte Carlo simulations are based on a single realization of the underlying small-scale permeability field. The analysis would have to be repeated for multiple realizations to obtain an estimate of the average behavior and to determine the prediction uncertainty. (Note that multiple realizations were analyzed using the SMPA.) The results from the single realization discussed here may therefore either over- or underestimate the mean seepage behavior.

- The probabilistic seepage calculation presented in Section 2.6 is strongly affected by the distributions chosen to characterize uncertainty and spatial variability of the seepage-relevant parameters. While an effort has been made to obtain reasonable distributions, the following should be noted:

  - Much less characterization data are available to describe the seepage-relevant hydrologic properties of the Tiva Canyon unit compared to those of the Topopah Spring unit, where the repository will be located. Specifically, there are no small-scale permeability data representative of the excavation-disturbed zone around the ESF, and no seepage experiments were performed in the Tiva Canyon unit to determine the seepage-specific capillary strength parameter.

- (Log)normal distributions were chosen in this study to describe the combined effect of uncertainty and spatial variability, while a combination of triangular, uniform, lognormal, and non-parametric distributions were used in the seepage abstraction (BSC 2004 [DIRS 169131], Section 6.6).

- There is currently no basis for the estimation of the infiltration flux during the high-infiltration period, and thus no basis for the deterministic component of the local percolation flux. Given the importance of the local percolation flux for seepage calculations, detailed analyses combined with process model simulations are needed to estimate infiltration rates and percolation flux.

- A TSPA calculation uses a combined deterministic-probabilistic approach to estimate the local percolation flux. Location-specific (i.e., deterministic) percolation fluxes are multiplied with a random (i.e., probabilistic) flow-focusing factor to arrive a local percolation fluxes used for seepage calculations. In this preliminary study for seepage into the ESF South Ramp, no location-specific percolation-flux estimates are available.

4. SUMMARY AND CONCLUSION

In summary, the modeling approach used to estimate long-term ambient seepage into waste emplacement drifts in the Topopah Spring unit has been minimally adapted to be able to estimate short-term, transient seepage into the ESF South Ramp located in the Tiva Canyon unit. Using probability distributions for fracture continuum permeability, capillary strength and local percolation flux that are consistent with available data and the scope of this analysis, it was estimated that seepage would occur along about 37% of the ESF South Ramp, compared with the observation that about 13% of the length of the ESF South Ramp exhibited wet spots in February 2005. Given that the simulations do not account for evaporation effects, yielding higher seepage rate estimates, these preliminary results seem to indicate that the seepage predictions made with the models and approach used in a TSPA calculation are reasonable, even when applied to a different hydrogeologic unit and different hydrologic conditions.

The preliminary results indicate that the approach for estimating seepage at the repository horizon—developed for the seepage model for performance assessment (BSC 2004 [167652]) and the seepage abstraction (BSC 2004 [169131])—gives reasonable seepage predictions even when applied to a different hydrogeologic unit and different hydrologic conditions. Therefore, the observation of seepage within the ESF South Ramp for the hydrologic conditions encountered during the winter months of 2004 and 2005 is consistent with the expectations of the Performance Assessment; it is thus not an unexpected condition.

5. REFERENCES

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