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Effect of heterogeneity in fracture permeability on the potential for liquid seepage into a heated emplacement drift of the potential repository

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Abstract

A numerical model was used to investigate the effect of spatial variability in fracture permeability on liquid seepage and moisture distribution in the vicinity of a waste emplacement drift in the unsaturated zone (UZ) of Yucca Mountain. The model is based on a two-dimensional, crosssectional, dual-permeability model of the unsaturated zone at Yucca Mountain and uses a stochastic approach to investigate the effect of small-scale heterogeneous features. The studies were conducted using one uniform fracture permeability case, three realizations of stochastically generated fracture permeability, one discrete permeability feature case, and one increased ambient liquid flux case. In all cases, the models predict that completely dry drift conditions will develop above and below the drift in 10-100 years and remain dry for 1000-2000 years. During this period, the models predict no seepage into drifts, although liquid flux above the drifts and within the drift pillars may increase by up to two orders of magnitude above ambient flux. This is because the heat released by the emplaced waste is sufficient to vaporize liquid flux of one to two orders of magnitude higher than present-day ambient flux for over 1000 years. The results also show that unsaturated zone thermalhydrological (TH) models with uniform layer permeability can adequately predict the evolution of seepage and moisture distribution in the rock mass surrounding the repository drifts. The models further show that although variability in fracture permeability may focus and enhance liquid flow in regions of enhanced liquid saturation (due to condensation above the drifts), vaporization and vapor diffusion can maintain a dry environment within the drifts for thousands of years. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Thermal hydrological response; Liquid seepage; Fracture flow; Stochastic fracture permeability

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1. Introduction

Yucca Mountain is being investigated as a potential site for a high-level nuclear waste repository. The host rocks of the potential repository lie within the unsaturated zone (UZ) and consist of variably welded and altered fractured volcanic tuffs. Emplacement of heat-generating high-level nuclear waste in such a system will create complex, multiphase fluid flow and heat transfer processes. The physical mechanisms include conductive and convective heat transfer, phase change phenomena (boiling and condensation), flow of liquid and gas phases under variably saturated conditions, diffusion and dispersion of vapor and gas, vapor sorption, and vapor pressure lowering effects.

These thermal-hydrological (TH) processes will significantly redistribute the in situ moisture and will alter the ambient flux above and below the repository over hundreds or thousands of years. In particular, they will affect the water flow or seepage into and around the waste emplacement drifts. Wet emplacement drifts, i.e. those subjected to significant seepage, could promote the corrosion of the waste emplacement canisters and increase the potential for the transport of radionuclides away from the drifts by the liquid phase to the water table. In the characterization of a potential repository, it is therefore important to predict how long drifts are expected to remain dry and how much liquid can potentially flow into and around the emplacement drifts when they are wet, and the conditions that will promote or limit seepage into the drifts.

For a given repository design, the potential for liquid seepage into drifts depends significantly on the flow and transport properties of the UZ within the model domain and the spatial distribution and temporal evolution of these properties. The spatial distribution of these flow properties can be obtained from field and model calibration studies. For example, measurements of fracture permeability at 1-m intervals within the drifts show large spatial variability in properties, even within the same hydrogeological unit. This variation arises primarily from two sources: (1) heterogeneity and (2) scale effects (mapping of data from core and drift-scale measurements to drift-scale and mountain-scale models). For example, in the current UZ models, the data is based on in situ and core measurement from eight boreholes. This data is assumed to be applicable to the mountain-scale model in a domain that exceeds 40 km². On a drift scale, a single set of flow properties means that in situ measurements on a few small holes, spaced 1/3 m to a few meters apart, are applied to all potential drifts in the UZ model domain.

The variation in UZ properties can result from large-scale fractures and faults that cross many geological units. Variations also result from small-scale fractures and varying degrees of welding and mineral alteration in the volcanic tuffs. Thermal perturbation within such a system may be affected by preferential flow of fluids (focused liquid flux) along high-permeability features and ponding above impermeable features that may result in perched water bodies. Small-scale heterogeneity within hydrogeologic units can promote liquid fingering and fast flow that will impact the fluid flow and moisture movement around and into the emplacement drift. In the UZ, the effects of heat on flow will be dominant within the TSw, where the drifts are to be located. The impact of thermal load on mountain-scale TH processes is discussed in a companion paper (Haukwa et al., 2003). For small-scale models such as the drift-scale model considered here, these variations suggest that a single set of parameters may not sufficiently describe expected flow and transport processes even within

a hydrogeological unit. These variations in flow properties can be incorporated in such models using geostatistical approaches, if a geostatistical variation of the properties can be developed.

The ability of numerical models to predict UZ flow depends on the validity of the numerical and conceptual models of the coupled fluid and heat flow processes. The continued effort to characterize the UZ at Yucca Mountain as a potential repository for high-level nuclear waste has generated extensive research in numerical and conceptual approaches for modeling flow and transport in unsaturated fractured rocks (Bodyarsson and Tsang, 1999; Robinson et al., 1996; Pruess et al., 1999; Liu et al., 1998; Ho, 1997). To reliably assess the performance of a potential repository, we need to predict the impact of heat on flow and transport processes within the UZ over thousands of years. Complex physical mechanisms control flow and transport processes in heated, unsaturated fractured rocks. These complex flow mechanisms include fracture-matrix interaction processes resulting from large contrasts in the hydraulic properties between fractures and the matrix; hysteresis effects on thermally enhanced unsaturated flow; and vaporization, condensation, and vapor diffusion processes. The effect of heat on liquid seepage near the drifts necessitates an examination of the numerical approaches for modeling fracture-matrix flow and the contribution of conductive, convective, and diffusive flow, particularly under dripping (fingering) flow and (alternatively) when fractures are completely dry.

2. Previous work

Numerical models of nonisothermal fluid and heat transport processes can be used to analyze the performance of a potential repository over any desired period of time and over any desired spatial scale. Such models have been used to predict thermal-hydrologic conditions associated with heat-releasing nuclear waste buried in geological repositories since the early 1980s. Although the models have used different assumptions about the influence of global and local hydrological properties, they were generally based on the continuum or the discrete-fracture-network approach. Excellent reviews on these approaches (which have been developed and used in different fields, including oil reservoir engineering, groundwater hydrology, geothermal reservoir engineering, and soil physics) can be found in Bear et al. (1993) and National Research Council (1996). The continuum approach is preferred for most applications that are encountered in practice (National Research Council, 1996). This approach has been used for ambient and TH modeling of flow and transport within the UZ at Yucca Mountain (Tsang and Pruess, 1987; Pruess et al., 1990, Buscheck et al., 1991, 1994; Buscheck and Nitao, 1993a,b,c; Pruess and Tsang, 1994; Haukwa et al., 1999; Tsang and Birkholzer, 1999; Wu et al., 1999).

The mountain-scale TH modeling studies of Yucca Mountain have been conducted in two and three dimensions using both the effective continuum method (ECM) (Wu et al., 1995; Francis et al., 1996) and dual-permeability (dual-k) (Haukwa et al., 1996, 1999, 2003) conceptualizations. The latter conceptual model treats the fractures and matrix as two distinct and interacting continua. Repository performance predictions based on the dual-kmodels indicate that waste emplacement drifts will remain dry for 1000–2000 years even with increased ambient liquid flux resulting from a monsoon climate (Haukwa et al., 2003). These continuum numerical models incorporate large-scale heterogeneities that are most important for global flow such as faults and hydrogeological units, in which uniform properties are assigned to each "layer". However, a "layered model" representation of Yucca Mountain may not give reliable predictions of the liquid seepage when heterogeneity exists within the hydrogeological units. For example, spatial heterogeneity in permeability within the layers may produce preferential flow paths that may influence the repository performance—by promoting seepage in some drifts while keeping others dry.

3. Objectives

The main objective of this study is to quantify the effects of thermal load on seepage at the drift scale and to evaluate conditions and processes that will promote or limit liquid seepage. In particular, the model evaluates the effect of spatial variability in fracture permeability, the main conduit for seepage, on the TH processes near the drifts in the UZ at Yucca Mountain and the corresponding effects on liquid saturation and seepage. Conditions that are likely to promote seepage (like the presence of large-scale fractures and development of perched water conditions) are also investigated. A secondary objective of this work is to evaluate conceptual numerical approaches that impact the predicted liquid seepage and adopt numerical approaches that allow for a more realistic representation of the observed fluid flow. The model therefore incorporates the effect of liquid fingering flow within fractures, as well as fracture–fracture vapor diffusion.

4. Approach

In this study, we use the continuum approach to model the nonisothermal fluid and heat flow processes within the UZ. Simulations of TH response were conducted using TOUGH2 (Pruess, 1991; Wu et al., 1996), a general-purpose simulator for multidimensional, coupled fluid and heat flow of multiphase, multicomponent fluid mixtures in porous and fractured media. We ignore vapor lowering and enhanced vapor diffusion effects.

4.1. Numerical grid

A locally refined integral finite difference dual-permeability 2D numerical grid is used to model the detailed response of the unsaturated zone near an emplacement drift. The numerical grid is based on a simplified representation of the UZ model at the center of the potential waste repository, in which 5-m drifts are effectively spaced 83 m apart due to the design orientation of the drift relative to that of the UZ TH north–south cross-section. The model domain is 41.5 m wide (half the drift spacing) and vertically extends from an elevation of 1420 masl (the average top elevation in the mountain-scale UZ model) to the water table (730 masl). A uniform grid spacing of 1.0 m is used laterally. A 5.0-m drift is located at 1070 masl, the mean elevation of emplacement drifts at the center of the potential repository. A vertical grid spacing of 1.0 m is used up to 10 m above and below

the drift. Then, a grid spacing of 5 m is used for the next 100 m, followed by a 10-m grid to the top elevation and to the water table (Fig. 1). A grid spacing of 100 m is used in the conduction-only section extending below the water table. The resulting numerical grid has a total of 9723 elements and 23,944 connections in dual-permeability formulation.

4.2. Fracture-matrix interaction

4.2.1. Fracture-matrix liquid flow

The fracture-matrix interaction processes have a large influence on the movement of the thermally mobilized liquid. In this study, the active fracture model concept (Liu et al., 1998) is used to model the fracture-matrix liquid flow resulting from fingering flow in unsaturated fractures (Glass et al., 1996; Pruess, 1999; Pruess et al., 1999) under the thermally induced drying and condensation processes. In this model, liquid flow occurs only within the active (liquid-occupied) fracture continuum. For this active fracture model, the ratio of the interface area contributing to the flow between fractures and the matrix to the total interface area is called the fracture-matrix interface area reduction factor. For flow from fractures to the matrix, this factor, R, is given by Liu et al. (1998) as:

$$R = S_{\rm e}^{1+\gamma} \tag{1}$$

where S_e is the effective fracture saturation and $\gamma < 1$ is a positive factor describing "activity" of the unsaturated connected fractures. For flow from matrix to fracture, R=1.



Numerical Grid for TH Simulations

Fig. 1. Numerical grid for UZ TH studies.

A detailed derivation of these constitutive relations for the active fracture model is found in Liu et al. (1998).

4.2.2. Fracture-matrix heat conduction

The amount of heat transferred from the matrix to the liquid in the fractures depends on the extent to which liquid covers the fracture-matrix surface. Under fingering flow, the liquid covers only a small area of the fracture-matrix surface. Using the grid fracturematrix surface area to compute heat flux into the liquid (as is currently the case) overestimates the potential for vaporization of liquid on the fracture-matrix surface. Such a model underestimates the potential for liquid flowing rapidly in narrow fingers along the surface of the fracture to penetrate the thermal barrier and possibly seep into drifts. In this study, we account for the narrow area in fingering flow of liquid by scaling the fracture-matrix thermal conductivity according to the liquid saturation in the fracture (SL_f). The new effective fracture-matrix thermal conductivity (CONI) is equal to the greater of the matrix thermal conductivity (CONI_m) times the fracture liquid saturation (SL_f) or the thermal conductivity of air/vapor-filled fracture (CON_v) . If the fractures are not fully saturated with liquid, then this effective fracture-matrix thermal conductivity is smaller than the matrix thermal conductivity, resulting in a lower potential for vaporization of fracture liquid seeping towards the drift, due to reduced fracture-matrix heat conduction. Therefore, in this new model, liquid moving through fractures will seep closer to the drift, and has increased potential for seepage before complete vaporization. This modeling approach is expected to have little effect during the drying phase because both the fracture-matrix continua are dry, but may have significant contribution on the rewetting phase, allowing for increased seepage of liquid condensate flowing through fractures past relatively hot matrix continua.

4.3. Vapor diffusion

In previous TH models, the diffusive flux has generally been neglected. However, diffusive vapor flux resulting from high-temperature gradients between the heat source and the model boundaries can significantly alter the net mass flux and the liquid saturation of the rocks near the heat source (over the thermal load period). This is because a high-temperature gradient can result in drying by vapor diffusion, even in the absence of boiling and advective flux. In fractured media, this diffusive vapor flux occurs mainly through the low-saturation fracture system, where the total flux is:

Total fracture flux = Advective flux + Diffusive flux.
$$(2)$$

Enhanced vapor diffusion due to vapor pressure gradients is not modeled because it is considered to have little effect on the high-permeability (and hence, high-advective flux) system modeled in the UZ TH model.

The total diffusive mass flux between adjacent continua as computed above is proportional to the interface area between the continua. However, in the dual-k numerical grid convention, fracture–fracture (f–f) area and matrix–matrix (m–m) interface areas for any two adjacent nodes are treated as equal for fluid flow calculation (although in real



Fig. 2. Distribution of measured fracture permeability.

fractured media, the f-f interface areas are much smaller than m-m interface areas). Such a convention still correctly computes the advective component of the total fluid flux, because this flux depends on the calibrated permeability and Van Genuchten



Fig. 3. Stochastic fracture permeability (field case #1).

parameters (Van Genuchten, 1980), which are generated based on this convention. However, for f-f vapor diffusion flux, the convention is not valid because the molecular vapor diffusion coefficient is not a calibrated parameter. Computation of vapor diffusion, using molecular diffusion coefficients and the f-f areas as currently implemented in dualk numerical grids, will grossly overestimate the vapor diffusion through the fractures and lead to unrealistic prediction of drying potential by vapor diffusion. To correct the computed diffusive vapor flux, the TOUGH2 code was modified to include an effective f-f area for vapor diffusion $A_{\rm ffd}$:

$$A_{\rm ffd} = A_{\rm ff} * \rm PHI_{\rm f} \tag{3}$$

where $A_{\rm ff}$ = fracture – fracture interface area in the numerical grid and PHI_f is the average fracture porosity for the two adjacent continua.

4.4. Material properties

The fracture-matrix material properties for each element are explicitly assigned, based on the elevation of each element node and the corresponding calibrated flow properties of the UZ hydrogeological units at the center of the proposed repository. These flow



Fig. 4. Liquid saturation at 1000 years, uniform fracture permeability.

properties are taken from the calibrated properties model. In addition to these uniform properties, we develop geostatistically variable fracture permeabilities within the TSw units.

Fig. 2 shows the variation in measured fracture permeability in the lower lithophysal tuff in the Topopah Spring nonwelded unit (TSw33), the location of the potential repository. This unit covers 78% of the total repository area and shows a range of four orders of magnitude in fracture permeability. This large variation in fracture permeability will lead to corresponding variation in seepage potential. The heterogeneous fracture permeability may lead to faster transport of radionuclides below the potential repository level through preferential pathways. On the other hand, in the low-permeability areas, heterogeneous fracture permeability will delay the transport due to ponding and increased matrix diffusion. Note also that the presence of a large number of fractures influences seepage and transport not only by increasing hydraulic conductivity, but also by increasing fracture–matrix interface area.

To model the measured variation in fracture permeability, a geostatistical simulator SISIM (Deutsch and Journel, 1992) is used to generate fields of permeability multipliers over the TSw, using the statistical parameters defined by the distribution of measured fracture permeability. Fig. 2 shows the cumulative distribution of fracture permeability used with SISIM. The field has a range of 10^{-2} to 10^{+2} of the mean fracture permeability. The SISIM statistical multipliers generated using the measured permeability



Fig. 5. Liquid saturation at 1000 years, stochastic fracture permeability (case #1).

518

distribution are applied to the uniform fracture permeability (from the calibrated properties model) in each TSw unit to produce a spatially heterogeneous fracture permeability field. Although these statistical parameters are only valid for the TSw33, they are applied to all the TSw units to investigate the effect of spatial variability in TSw fracture permeability on seepage flux near the drifts. Fig. 3 shows the distribution of stochastic fracture permeability generated for one realization. The map in this case is an uncorrelated (random) field, but with statistical parameters given by the cumulative distribution of the measured fractured permeability shown in Fig. 2. Although smaller grid spacing would capture the spatial correlation, it was not used for this study because it is computationally intensive, owing to the large number of small elements. Note that in this study, only spatial variability in fracture permeability is considered and no corresponding adjustment of Van Genuchten parameters by Leverett scaling is performed.

To investigate the impact of high-permeability fractures/faults, the fracture permeability of a column of fracture elements intercepting the drift was increased by a factor of 100 and TH simulations, with one realization of stochastic fracture permeability conducted. The effects of increased liquid flux (due to focusing) on TH simulations were investigated by injecting liquid water at 10 times the present-day ambient infiltration rate at 10 m above the drift.



Fig. 6. Fracture liquid flux at drift centerline, uniform fracture permeability.

4.5. Boundary conditions and thermal load

The boundary conditions used are consistent with those used for the mountain-scale UZ TH simulations (Haukwa et al., 1996, 1999, 2003). These are (1) constant saturation of 0.99 at the water table corresponding to capillary fringe liquid saturation and saturation of 0.01 at the top boundary; (2) a 65 °C temperature boundary at 1000 m below the water table; (3) a 17 °C temperature at the top boundary; and (4) constant mass injection of water at the top boundary (infiltration condition), at rates determined by the average mountain-scale infiltration rates for the climate (4.79 mm/year present day, 11.27 mm/year monsoon) at the location modeled. The lateral sides are closed boundaries corresponding to zero-flow symmetry planes at the drift center and the midpillar between the drifts. A time-dependent heat source (with decay; Francis, 1997) applied to the drift corresponds to an initial thermal load of 67.7 kW/acre (1.35 kW/m). To account for the effects of preclosure ventilation, 70% of the heat is removed during the first 50 years.

5. Results

The results of the TH simulations are discussed in terms of moisture mobilization and liquid flux changes over a simulated period of 100,000 years. Ideally, many realizations and corresponding TH simulations would be done to perform a statistical evaluation of the



Fig. 7. Fracture liquid flux at drift centerline, spatially variable fracture permeability (case #1).

corresponding predictions. However, because the drying near the drift leads to small numerical time steps, 2 or 3 weeks are needed to conduct each TH simulation. Because of this time constraint, only three realizations of stochastic permeability field TH simulations were completed.

Results are analyzed using contour and line plots of liquid saturation and flux. A plot of the liquid saturation gives a measure of the extent of moisture mobilization. A plot of the fracture liquid flux at the elevation of the drift centerline and within the condensation zone at 5 m above the drift is used to evaluate the potential for liquid seepage into a heated drift. Fracture liquid flux accounts for over 95% of total liquid flux at the repository horizon, and is therefore the only route for potential seepage of liquid in/out of drifts. The fracture liquid flux at drift centerline represents the amount of liquid predicted to seep below the drift during the thermal loading period. The fracture liquid flux within the condensation zone (5 m above the drift) represents the amount of liquid that could potentially seep into drifts from accumulated condensate during the thermal period.

5.1. Liquid saturation

520

Fig. 4 shows the liquid saturation in the fracture continuum after 1000 years of thermal loading, for the uniform fracture permeability case. Dry-out is predicted in both the



Fig. 8. Fracture liquid flux at drift centerline, spatially variable fracture permeability (case #1), high fracture permeability into drift.

fracture and matrix, resulting from liquid vaporization and vapor diffusion effects. The presence of the heated drift creates a shadow effect in which liquid is diverted around the drift by the combined effect of the capillary barrier and vaporization. The resulting shadow effect leads to further drying of the matrix and fracture continuum directly below the drifts. The fractures dry out more rapidly than the matrix because of low initial liquid saturation and high-fluid mobility. This dry-out zone, which develops after waste emplacement, is maintained for 1000-2000 years. At 1000 years, the dry-out zone extends to 5 m above and 25 m below the drift and only 8 m laterally. A condensate and refluxing zone (return of liquid water through capillary suction and gravity drainage) develops above the dry-out zone and within the drift pillar. In this uniform permeability case, fracture saturation in the condensate zone above the drift rises from the ambient of about 1.0% to about 1.5-2.0%. Some of this liquid is laterally diverted, increasing the fracture liquid saturation in the drift pillar (between drifts) 10-15 m from the drift. Fig. 5 shows fracture saturation at 1000 years for one realization of spatially variable fracture permeability. The other stochastic fracture permeability cases predict similar conditions and are not discussed. In all these cases, liquid condensate may accumulate in the low-fracture-permeability areas above the drift and within the drift pillars, where fracture liquid saturation may increase to 7-10%. However, the models predict completely dry drifts (no seepage) for all realizations of



Fig. 9. Fracture liquid flux at drift centerline, spatially variable fracture permeability (case #1), high liquid flux 10 m above drift (simulated perched water case).

fracture permeability. Completely dry-drift conditions are also predicted for the highpermeability fracture and the simulated perched water cases for up to 1000 years after thermal loading.

As expected, a smaller dry-out zone is predicted for the drifts where focused flow results in substantially higher liquid flux than that predicted by present-day infiltration models. However, even when the increased flux is up to 10 times the ambient flux, evaporation, vapor diffusion, and capillary barrier effects can still maintain dry-drift conditions for up to 1000 years. The model further predicts that the presence of high-permeability fractures will promote drying of the drifts, except where such structures intercept large perched water bodies, which may promote liquid influx.

5.2. Liquid flux

Fig. 6 shows the evolution of liquid flux at the drift centerline for the uniform permeability case. The model predicts that no liquid seeps below the drift for over 1000 years of thermal loading, because the drifts are completely dry with zero relative permeability. At 100 years after thermal loading started, drainage of liquid condensate is primarily through the drift pillar and is laterally centered 12 m from the drift center, but extends from 10 to 15 m from the drift. At this time, the maximum fracture liquid flux is 100 mm/year. The liquid flux drops to an average of 20 mm/year after 500 years, but



Fig. 10. Fracture liquid flux 5 m above drift uniform fracture permeability.

increases to 25-30 mm/year at 1000 years because of climate change (the higher monsoon climate infiltration). At 2000 years, average liquid flux is 10-15 mm/year and is controlled primarily by ambient infiltration rates, and only the capillary barrier effects will limit flow through the drift. In this case, no substantial change in fracture liquid flux is predicted beyond 20 m from the drift center.

For the variable permeability cases, the large contrast in permeability causes corresponding variations in flux between realizations, but the average flux is similar to the uniform fracture permeability case. Fig. 7 shows the resulting liquid flux at the drift centerline for one realization of spatially stochastic fracture permeability. As in the case of uniform fracture permeability, even with four orders of magnitude variation in fracture permeability, no liquid seeps into the drift for up to 1000 years. The model shows irregular space/time evolution of liquid flux resulting from permeability variability within the fracture continuum. The maximum liquid flux is predicted to occur after 100 years of thermal loading, and the refluxing zone is still centered about 12 m from the drift center. However, maximum liquid flux ranges from 100 to over 220 mm/year, and declines to less than 20 mm/year after 500 years.

Figs. 8 and 9 show the evolution of the fracture liquid flux for the high-permeability fracture case and the simulated perched water case, respectively. Both cases predict no liquid seepage into the drift for over 1000 years. For the high-permeability fracture case (Fig. 8), the maximum liquid flux is 125 mm/year within the drift pillar after 100 years, but



Fig. 11. Fracture liquid flux 5 m above drift, spatially variable fracture permeability (case #1).

524

declines to an average of 40-50 mm/year after 500 years. For the simulated perched water case (Fig. 9), the average ambient liquid flux in this case is 45-50 mm/year; the maximum liquid flux rises to 350 mm/year in the drainage zone after 100 years, but declines to 100-150 mm/year after 1000 years.

Figs. 10 and 11 show the simulated liquid flux through the fractures in the condensation zone 5 m above the drift for the uniform fracture permeability case and for one realization of stochastic fracture permeability. These plots give an indication of the liquid flux that could directly seep through the drift in the absence of capillary diversion or intense vaporization and typically have been used as an indication of the thermally induced liquid flux in the UZ. For the uniform fracture permeability case (Fig. 10), the dry-out zone is predicted to extend beyond 5 m above the drift, and hence, no liquid flux is predicted at this location for over 500 years. The liquid condensate is laterally diverted by a capillary barrier, and the predicted liquid flux after 100 years rises to 110 mm/year about 8 m laterally away from the drift center. After 500 years, the average flux is 25 mm/year at a location 8 m laterally from drift center. At 1000 years, the area 5 m directly above drift starts to rewet and flux rises to 25 mm/year and the condensation/refluxing zone is located 30–40 m above the drift. Similar evolution of flux is predicted for the stochastic permeability field case, as shown in Fig. 11. In this case and in other two realizations, the dry-out zone does not extend beyond 5 m above the drift. At 100 years, liquid



Fig. 12. Fracture liquid flux 5 m above drift, spatially variable fracture permeability (case #1), high liquid flux 10 m above drift (simulated perched water case).

condensate flux exceeds 150 mm/year at several locations for the first fracture permeability field and is 250–300 mm/year for the second and third permeability fields. For the high-permeability fracture, even though the maximum flux in the condensation zone is through the fracture and rises to over 300 mm/year at 100 years, this high flux does penetrate the thermal barrier (Fig. 8). In all these cases, the high liquid flux results from a high capillary pressure gradient at the drying front. Such flux represents liquid that can be completely vaporized at the dry front and cannot seep into the drifts.

Fig. 12 shows the liquid flux at 5 m above the drift for the simulated perched water case. For this case, the fractures 5 m above the drift remain partially saturated by liquid condensate throughout the thermal loading period. Therefore, a liquid flux is maintained at 5 m above drift, rising to over 200 mm/year at 100 years, but declining to 50–100 mm/ year at 1000 years.

6. Summary and conclusions

A numerical model of near- and far-field TH processes has been developed to evaluate the effect of heterogeneity in fracture permeability on liquid seepage in the vicinity of an emplacement drift and within the pillars. The model uses a refined 2D vertical cross-section over 1/2 drift spacing. A uniform fracture permeability model and three realizations of stochastic spatial variation in fracture permeability were used to evaluate the influence of variability in fracture permeability on the predicted seepage and moisture distribution. An enhanced fracture permeability column is used to evaluate the effects of a discrete permeable feature (e.g., fault/fracture) that intercepts a drift. Similarly, liquid injection above the drift is used to simulate the effects of perched water conditions above a drift.

The studies show that for the design conditions considered, the models predict no liquid flux out of the drift for over 1000 years, although predicted liquid flux above the drifts and within the drift pillars may increase by up to two orders of magnitude, above the ambient flux. This results from the intensity of vaporization and the capillary effects that combine to form a seepage barrier over the drift, preventing direct liquid percolation through the drift. The uniform and stochastic fracture permeability models show similar magnitude of liquid flux above the drift and within the drift pillars over this period. Even with high-permeability features or perched water conditions above the drifts, the models predict dry-drift conditions for over 1000 years.

In the stochastic fracture permeability cases, the simulations show a potential for buildup of perched water in the condensate zone above the drift and within the drift pillars. Vapor diffusion does not substantially change the predicted moisture distribution and mass flux despite the high-temperature gradient, because of the small fracture porosity and fracture–fracture interface areas. The results further show that even under fingering flow conditions, the model predicts that the liquid flux is not sufficient to break down the seepage barrier, because of continued vaporization caused by strong heating within the drift. However, fingering flow may increase seepage during the rewetting phase. This modeling study also confirms that for the thermal load considered, a uniform model for fracture permeability gives an adequate prediction of average liquid saturation and liquid flux, as well as of the long-term average response of the UZ to thermal loading.

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