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The Effects of Infiltration on the Thermo-Hydrologic Behavior of the Potential Repository at Yucca Mountain

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Abstract

The thermo-hydrologic behavior of the potential repository at Yucca Mountain, Nevada, has been simulated to investigate the effects of infiltration. Transient temperatures, liquid saturations, and liquid mass flow rates through the fractures and matrix were simulated using several different steady infiltration rates ranging from 0.3 to 30 mm/year. The lower infiltration rates resulted in higher temperatures near the repository element, but the overall transient temperature profiles were similar. The hydrologic response near the repository (liquid saturations and fluxes) was found to be very sensitive to the infiltration rate. Increased infiltration rates reduced the time to re-wet the simulated repository during cooling, and an infiltration rate of 10 mm/year was sufficient to completely eliminate the dry-out zone around the repository.

Introduction

The integrity of high-level radioactive waste packages emplaced at the potential repository at Yucca Mountain, Nevada, will depend, in part, on the thermo-hydrologic response of the system surrounding the waste. Thermodynamic variables such as temperature and relative humidity will play an important factor in the rate of corrosion and degradation of the waste packages as liquid, gas, and heat are mobilized by the waste-generated heat. Although previous investigators have simulated the non-isothermal, multiphase response of the potential repository at Yucca Mountain (Tsang and Pruess, 1987; Buscheck and Nitao, 1993; Wu et al., 1995), few, if any, have rigorously considered the effects of infiltration on the thermo-hydrologic response. This paper identifies significant effects of infiltration on the thermo-hydrologic response of the potential repository through simulations of temperatures, saturations, and fluxes using various steady infiltration rates.

Numerical Modeling

The numerical code TOUGH2[2] (Transport Of Unsaturated Groundwater and Heat; Pruess, 1991, 1987) is used in the thermo-hydrologic analyses in the unsaturated

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[2] TOUGH2 (v. 3.2) has been qualified under the YMP quality assurance program.

zone (UZ). TOUGH2 is a multidimensional, multiphase, nonisothermal simulator that is used extensively in geothermal, environmental restoration, and nuclear waste management areas (Pruess, 1995). Mass and energy balances are solved simultaneously using the integral finite-difference method for air and water in porous media. The air and water components can partition freely between the gas and liquid phases. Sensible heat is transferred through the gas, liquid, and solid phases, while latent heat transfer can occur as a result of condensation or evaporation of water. Local thermodynamic equilibrium is assumed throughout the system. A complete description of the formulation and numerical implementation can be found in Pruess (1991, 1987).

Model Domain and Boundary Conditions

For the UZ thermo-hydrologic analyses presented in this report, a one-dimensional model is extracted from an east-west vertical cross-section of Yucca Mountain corresponding to section A-A in Altman et al. (1996). The northing coordinate of the one-dimensional domain is approximately 233,400 m, and the easting coordinate is approximately 170,650 m. Each finite-volume element is 10 m wide and 1 m thick. The height of each element varies as shown in the discretization of Figure 1. The discretization is finer near the repository and other geologic features. The mesh is comprised of 33 matrix elements and 33 fracture elements using the dual-permeability model (DKM). A relatively small number of elements is used in these analyses to provide consistency with concurrent two- and three-dimensional studies.[3]

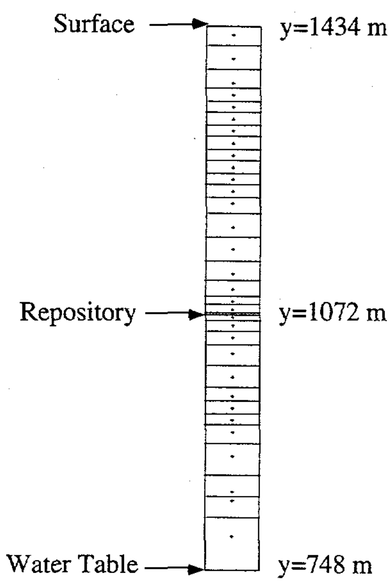

Figure 1. One-dimensional mesh used in TOUGH2 simulations (not to scale).

At the bottom of the domain, an element is added to simulate a water table with prescribed temperature, pressure, and saturation. The temperature at the bottom is fixed at a temperature of 32°C (Fridrich et al., 1994) and a pressure of 0.91×10^5 Pa (Pruess and Tsang, 1993). Infiltration is introduced in the top element of the modeled domain at steady rates ranging from 0.3 to 30 mm/year, which are based on distributions from Altman et al. (1996) and Hudson and Flint (1996). An additional element is added on top of the domain to impose surface temperatures, pressures, and air mass fractions. The surface temperature is fixed at 19°C (Sass et al., 1988), and the gas pressure is calculated based on hydrostatic conditions above the water table. The air mass fraction at the surface is calculated from the surface gas pressure, temperature, and an assumed relative humidity of 50%. An initial heat load of 3.36×10^5 kW/m^2 (83 MTU/acre) is assumed for the

[3]The one-dimensional simulations were found to be consistent with multi-dimensional simulations, and the one-dimensional results are adequate for the objectives of this paper.

repository. Based on this heat load and the total repository output power[4], the heat generation for the repository element can be calculated as a function of time.

Conceptual Model

The dual-permeability model (DKM) is used for the thermo-hydrologic analyses in this study. In this conceptual model, the fractures and matrix are modeled explicitly as separate, overlapping continua. This formulation allows water to flow through the fractures while the matrix remains unsaturated. Non-equilibrium behavior between the fractures and matrix has been evidenced by field experiments and numerical simulations (Eaton et al., 1996). The behavior of liquid flux and condensate drainage, which are expected to play a significant role in the performance of the repository during heating, can then be modeled and compared for different ambient infiltration rates. The reader is referred to Ho et al. (1995) for more specific details of the DKM.

Thermal and Hydrologic Parameters

The hydrologic parameters used in this study are taken from Altman et al. (1996). One difference between the parameters used in Altman et al. (1996) and the parameters used in this study is that the fracture van Genuchten beta parameter (β) is set equal to the value of the matrix beta parameter (1.6) in this study. In Altman et al. (1996), the fracture beta parameter was set equal to 3.0. While this worked well for the ambient simulations in that study, the high value of beta caused sharp gradients in the fracture capillary pressure curve near residual saturation and prevented convergence in the present simulations.

The thermal properties required for these simulations are rock grain density (kg/m^3), wet thermal conductivity (W/m-K) at saturation of 1.0, dry thermal conductivity (W/m-K) at saturation of 0.0, and rock-grain specific heat (J/kg-K). Values for these parameters are obtained from Ho et al. (1996)[5]. The fracture continuum thermal properties are assumed to be consistent with air properties at 77°C (Incropera and DeWitt, 1985). The thermal and hydrologic parameters vary between elements, especially near the non-welded PTn unit at y ~ 1300 m. The PTn exhibits higher matrix porosities and matrix permeabilities but lower fracture porosities and fracture permeabilities because of the reduced number of fractures present in that unit. The thermal conductivity in that unit is also lower than in other units.

Simulation Procedure

The single-phase module of TOUGH2 (EOS9) is first used to simulate steady-state saturations without the influence of heat or the gas phase (infiltration is applied). A preprocessor is then used to calculate the temperatures and pressures in the domain assuming a linear temperature distribution and hydrostatic pressure distribution between the water table and surface boundaries. The resulting saturations,

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[4] Controlled Design Assumptions Document, B00000000-01717-4600-00032, Rev. 02C, December 13, 1995.

[5] Ho, C.K., N.D. Francis, B.W. Arnold, Y. Xiang, S.A. McKenna, S. Mishra, G.E. Barr, S.J. Altman, X.H. Yang, R.R. Eaton, 1996, Thermo-Hydrologic Modeling of the Potential Repository at Yucca Mountain Including the Effects of Heterogeneities and Alternative Conceptual Models of Fractured Porous Media, W.B.S. 1.2.5.4.4, WA-210 Rev.00, Level 3 Milestone T6536, M&O, SNL.

temperatures, and pressures are then used as initial conditions in a two-phase simulation using TOUGH2 (EOS3). The two-phase simulations are run for $1x10^6$ years to further equilibrate the primary variables. The predicted saturations, temperatures, and pressures are then used as the initial conditions for the simulations with heat. A table of heat output as a function of time for the repository element is added to the TOUGH2 input file, and the simulations are run for 100,000 years. This procedure is followed for five different runs using infiltration rates of 0.3, 1, 3, 10, and 30 mm/year. In each of the simulations, temperatures, saturations, and flux variables are processed at various times during the thermal perturbation.

Results

For each infiltration rate, the fracture-matrix connection area of all the elements in the DKM is varied by a constant amount to yield steady-state matrix saturations that are consistent between simulations and observed borehole saturations at the repository horizon. As the infiltration increases, the fracture-matrix connection area is reduced. The exact amount of reduction for each infiltration is shown in Figure 2 as a factor, F, that is multiplied by the geometric connection area (Ho et al., 1995) between the fractures and matrix[6]. Figure 2 also shows the steady-state matrix saturations for each infiltration rate. The saturations are fairly consistent throughout most of the domain. Near the top, however, the matrix saturations are lower for the higher infiltrations because less water is imbibed into the matrix from the fractures (where the infiltration is introduced) at highly reduced fracture-matrix connection areas.

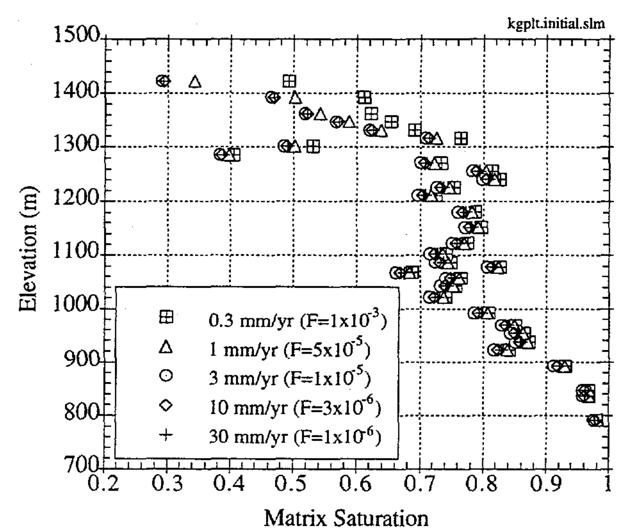

Figure 2. Ambient steady-state matrix liquid-saturations using DKM simulations with different infiltration rates. The fracture-matrix connection areas were multiplied by different factors (F) to obtain similar matrix saturations in the vicinity of the repository.

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[6]The reduction in fracture-matrix connection area is applied ubiquitously to all elements, but future studies will investigate its appropriateness for heat, gas, and liquid flows.

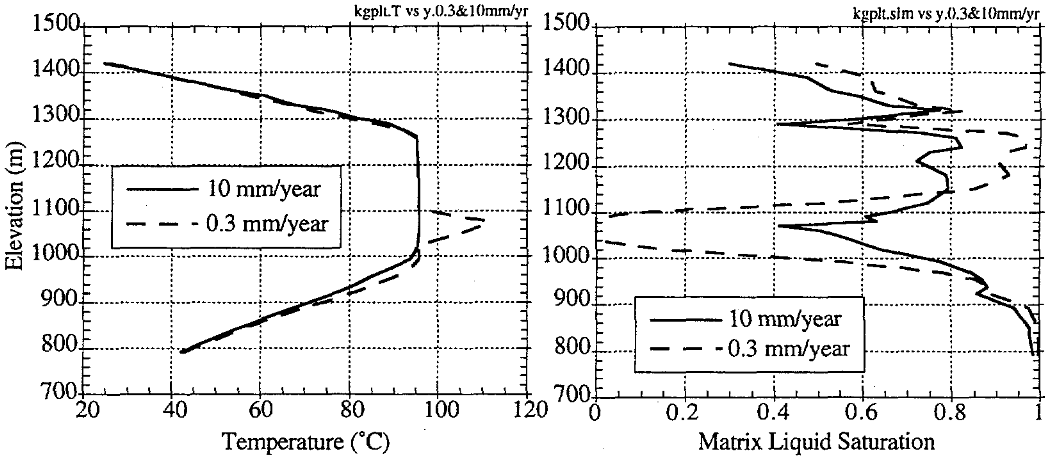

Figure 3. Temperature and matrix liquid-saturation distributions after 1000 years of heating for two different infiltration rates.

Each of the different infiltration simulations is equilibrated as described earlier and continued out to 100,000 years after the initiation of heat. Figure 3 shows the temperature and matrix liquid-saturation distribution after 1000 years of heating for infiltration rates of 0.3 and 10 mm/year. The lower infiltration rate results in a "dry-out" zone around the repository as indicated by the reduced matrix liquid-saturations and increased temperature. The lower infiltration rate also yields higher matrix saturations in a region above the repository because of imbibition of the condensate into the matrix. The higher infiltration rate simulation inhibits imbibition of the condensate because of reduced fracture-matrix connection areas (which are used to maintain ambient matrix liquid-saturations near observed values).

Figure 4 shows the percolation flux directly above the repository element as a function of time for simulations using infiltration rates of 0.3 and 10 mm/year. The low infiltration simulation shows a tremendous increase in fracture flow during the first hundred years of heating because of condensate drainage, but the generated heat is greater than the latent heat exchange caused by vaporization of the incoming liquid. Therefore, dry-out occurs around the repository and the percolation flux is zero for several thousand years. In the 10 mm/year infiltration case, the condensate drainage combined

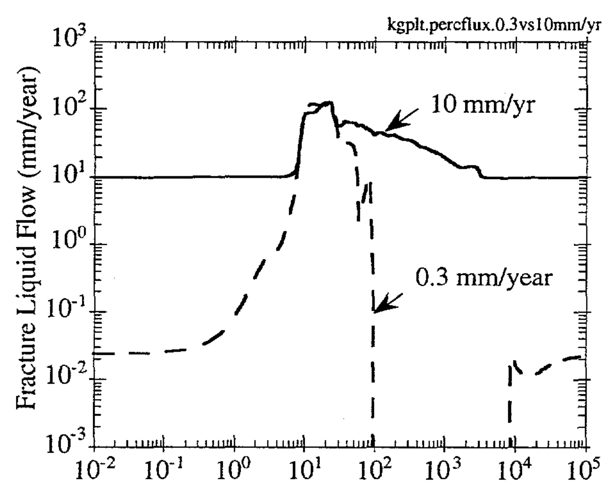

Figure 4. Percolation flux between the fracture element directly above the repository and the fracture element at the repository for steady infiltration rates of 0.3 and 10 mm/year.

with the large infiltration supplies sufficient latent heat exchange to offset the generated heat from the repository element. Therefore, no dry-out occurs, and the liquid flux through the fractures remains above ambient levels during the entire thermal perturbation.

Figure 5 shows the re-wetting and re-fluxing times for each of the infiltration rates. The re-wetting time is defined as the time it takes for the fracture saturation of the element above the repository to rise above 0.03 (the residual saturation) after being dried. If the fracture saturation does not decrease below 0.03, then the re-wetting time is specified as zero. The re-flux time is defined as the time it takes for the mass flow between the fracture element above the repository and the fracture element at the repository to return to the ambient mass flow. If the mass flow does not decrease below the ambient rate, then the re-flux time is specified as zero for that infiltration rate. As the infiltration rate is increased, the re-wetting and re-fluxing times decrease. For infiltrations exceeding 10 mm/year, a dry-out zone never develops, and the re-wetting and re-fluxing times are zero. These results indicate that the extent and duration of the dry-out zone is highly dependent on the infiltration rate.

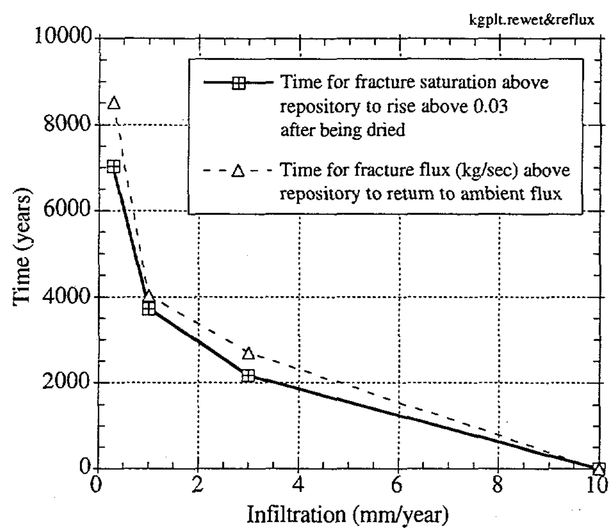

Figure 5. Re-wetting and re-fluxing times for the element directly above the repository for various infiltration rates. Note: a zero time indicates that either the fracture saturation did not decrease below 0.03 or that the fracture flux remained above ambient values.

Conclusions

A one-dimensional thermo-hydrologic analysis of the potential repository at Yucca Mountain has been performed using the dual-permeability model (DKM) to investigate the effects of infiltration. Based on the results of this study , the following conclusions can be drawn:

- The thermal response was similar for all infiltration rates, although the peak temperature near the repository was higher (up to 15°C higher) in lower infiltration rate simulations (0.3 mm/year) than in higher infiltration rate simulations (10 and 30 mm/year).

- The matrix liquid-saturations near the repository were higher in low infiltration simulations because of greater retention of condensate. The high infiltration simulations produced greater liquid flow through the fractures because of the higher infiltration rate and reduced fracture-matrix connection areas, which inhibited imbibition of the condensate into the matrix. All infiltration rates yielded significantly increased flow through the fractures (up to several order of magnitude greater than ambient levels) during the first hundred years because of condensate drainage.

- The infiltration rate influenced both the re-fluxing and re-wetting behavior of the elements near the repository during cooling. Higher infiltration rates reduced the re-wetting and re-fluxing times, and an infiltration rate of 10 mm/year was sufficient to completely eliminate the dry-out zone.

Acknowledgments

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