Available online at www.sciencedirect.com

SCIENCE DIRECT®

Physics and Chemistry of the Earth 31 (2006) 626–633

PHYSICS and CHEMISTRY of the EARTH

www.elsevier.com/locate/pce

Modeling coupled thermal–hydrological–chemical processes in the unsaturated fractured rock of Yucca Mountain, Nevada: Heterogeneity and seepage

S. Mukhopadhyay *, E.L. Sonnenthal, N. Spycher

Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

Received 11 August 2005; received in revised form 24 January 2006
Available online 3 July 2006

Abstract

An accurate understanding of processes affecting seepage into emplacement tunnels is required for correctly predicting the performance of underground radioactive waste repositories. It has been previously estimated that the capillary and vaporization barriers in the unsaturated fractured rock of Yucca Mountain are enough to prevent seepage under present day infiltration conditions. It has also been thought that a substantially elevated infiltration flux will be required to cause seepage after the thermal period is over. While coupled thermal–hydrological–chemical (THC) changes in Yucca Mountain host rock due to repository heating has been previously investigated, those THC models did not incorporate elements of the seepage model. In this paper, we combine the THC processes in unsaturated fractured rock with the processes affecting seepage. We observe that these THC processes alter the hydrological properties of the fractured rock through mineral precipitation and dissolution. We show that such alteration in the hydrological properties of the rock often leads to local flow channeling. We conclude that such local flow channeling may result in seepage under certain conditions, even with non-elevated infiltration fluxes.

Keywords: Seepage; THC processes; Unsaturated zone; Yucca Mountain

1. Introduction

In the context of radioactive waste emplacement in an underground repository, *seepage* refers to flow of liquid water into the emplacement tunnels. Scientists have recently made substantial efforts towards understanding and predicting seepage in the unsaturated fractured rock of Yucca Mountain, Nevada. Both experimental and modeling analyses (Trautz and Wang, 2002; Finsterle et al., 2003) have been performed to determine the amount of seepage under ambient conditions, i.e., when no thermal effect is present. In addition, predictive modeling studies, based on stochastic continuum models, have been carried out to predict the probability and magnitude of seepage under ambient conditions at Yucca Mountain (Tsang et al., 2004).

Those ambient seepage studies concluded that seepage under ambient conditions is prevented by the difference in the capillary pressure between the rock formation and a large underground opening (i.e., the emplacement tunnel), which is commonly referred to as the "capillary barrier." As a result, water is mostly diverted around the tunnels rather than flowing into them. Those previous investigations also concluded that the amount of ambient seepage, if any, is controlled by the magnitude of surface infiltration fluxes, the heterogeneities in the fracture permeability field, and the magnitude of the fracture capillary strength parameter (see below) of the host rock.

* Corresponding author. Tel.: +1 510 486 5686.
E-mail addresses: Smukhopadhyay@lbl.gov (S. Mukhopadhyay), ELSonnenthal@lbl.gov (E.L. Sonnenthal), Nspycher@lbl.gov (N. Spycher).

1474-7065/$ - see front matter
doi:10.1016/j.pce.2006.04.018

Heat generated by the emplaced radioactive waste causes the unsaturated rock at Yucca Mountain to stay above ambient temperatures for a long period of time. Thus, Birkholzer et al. (2004) investigated seepage during and after the thermal period at Yucca Mountain by simulating the thermal–hydrologic (TH) conditions in the unsaturated fractured rock surrounding the emplacement tunnels. Birkholzer et al. (2004) found that the quantity of seepage under thermal conditions is always smaller than ambient seepage, a result arising out of the presence of vaporization barrier (see Section 2), in addition to the capillary barrier. The other key finding from Birkholzer et al. (2004) is that the surface infiltration fluxes at Yucca Mountain are not sufficient to cause seepage into the emplacement tunnels. They further concluded that a substantially elevated background infiltration flux would be required to overcome the capillary and vaporization barriers at Yucca Mountain. While Birkholzer et al. (2004) estimate the transient pattern of seepage by analyzing the TH processes, the chemical changes in the host rock resulting from the elevated temperatures are not included in their conceptual model. It is our hypothesis that those chemical changes in the rock are pertinent for seepage. The objective of this paper is thus to investigate the combined effects of thermal–hydrological–chemical (THC) changes in hot, unsaturated fractured rock on seepage. Note that flow around an emplacement tunnel may also be influenced by coupled thermal–hydrological–mechanical (THM) processes as reported in Rutqvist and Tsang (2003) and Tsang et al. (2004), however, these THM models (similar to previous THC models) have not been explicitly coupled to the seepage models.

Seepage in heterogeneous fractured rock like that at Yucca Mountain is the result of two competing processes. The capillary forces of the fractured rock tend to prevent water from entering the emplacement tunnels. On the other hand, heterogeneity in the rock permeability leads to flow channeling in certain locations (zones of higher permeability) in preference to other locations (adjacent zones of lower permeability). If the flow channeling is so significant that the saturation builds up beyond a certain threshold, the capillary barrier is broken, and water begins to seep into the tunnels. Thus, heterogeneity in the hydrological properties of the rock plays a key role in influencing seepage.

For accurate prediction of seepage, two kinds of heterogeneities need to be considered in any conceptual model. The first type is the heterogeneity that is present in the rock before emplacement of wastes, i.e., the "ambient" or "geological" heterogeneities, resulting from physical and chemical changes occurring over geological time scales. All the previous ambient and thermal seepage analyses, including those of Birkholzer et al. (2004), considered only these ambient or geological heterogeneities. However, a second type of heterogeneity needs to be considered for accurate prediction of seepage. The elevated host rock temperatures, and subsequent moisture redistribution through boiling and condensation of pore water (see Section 2), cause varying spatial and temporal degrees of mineral precipitation and dissolution. These processes of precipitation and dissolution in turn change the hydrological properties (such as porosity, permeability, and even the capillary characteristics) of the rock, introducing additional chemical and hydrological heterogeneity in the rock. In the rest of the paper, we will show how these THC-induced "dynamic" heterogeneities lead to different transient patterns of seepage compared to seepage prediction excluding the chemical changes of the rock.

2. THC processes

To understand the coupled THC processes arising from repository heating, we must first understand the associated TH processes. Heat conduction from the drift wall into the rock matrix results in vaporization and boiling, with vapor migration out of matrix blocks into fractures. The vapor moves away from the tunnel through the permeable fracture network by buoyancy, by the increased vapor pressure caused by heating and boiling, and through local convection. In cooler regions, the vapor condenses on fracture walls, where it drains through the fracture network, either down toward the heat source from above or away from the drift into the zone underlying the heat source. Slow imbibition of water from fractures into the matrix gradually leads to increases in the liquid saturation of the rock matrix. Under conditions of continuous heating, a *dryout* zone (Fig. 1) may develop closest to the heat source, separated from the condensation zone by a nearly isothermal zone maintained at about the boiling temperature. This nearly isothermal zone is characterized by a continuous process of boiling, vapor transport, condensation, and migration of water back to the heat source, and is often termed a *heat pipe* (Pruess et al., 1990). The dryout zone, by exposing any incoming water to vigorous boiling, retards and reduces the flow of water towards the emplacement tunnel. It is thus often called a *vaporization barrier* (Birkholzer et al., 2004).

The chemical evolution of waters, gases, and minerals is intimately coupled to the TH processes discussed above. The distribution of condensate in the fracture system determines where mineral dissolution and precipitation can occur in the fractures and where direct interaction (via diffusion) can occur between matrix pore waters and fracture waters. Fig. 1 schematically shows the relationships between TH and chemical processes in the zones of boiling, condensation, and drainage in the rock mass, at the fracture-matrix interface outside of the emplacement tunnel and above the heat source. Zonation in the distribution of mineral phases can occur as a result of differences in mineral solubility as a function of temperature. The inverse relation between temperature and calcite solubility (as opposed to the silica phases, which are more soluble at higher temperatures) can cause zonation in the distribution of calcite and silica phases in both the condensation and boiling zones.