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A Report on Laboratory Scale Thermally-Coupled Processes Experiments

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Introduction

Yucca Mountain Site Characterization Project (YMP) is studying Yucca Mountain, Nevada as a potential repository for high-level nuclear wastes. The studies include predictions of the quantity and quality of water in the repository near-field environment that will affect the release rate of radioactive nuclides from waste packages, and the transport of the nuclides through the rock mass adjacent to these packages. The radioactive decay heat from the high-level nuclear waste may increase the temperature in the rock mass to the extent that coupled thermal-mechanical-hydrological-chemical (TMHC) processes may exist in the originally partially-saturated Topopah Spring tuff—the host rock for the potential repository in Yucca Mountain. Modeling the coupled TMHC processes is necessary to predict the quantity and quality of water in the near-field environment for the entire life span of a repository (tens of thousands of years). In situ thermal tests are required to build up the confidence level of the coupled TMHC models.

The purposes of conducting the laboratory studies of the coupled TMHC processes are to enhance our understanding of those processes, and to assist the interpretation of the field test results. Laboratory experiments deal with controlled experimental and boundary conditions, smaller sample sizes, and simpler geometrical configurations (e.g., regular shape and single fracture). These characteristics make the laboratory results suitable for understanding the processes. This in turn will make incorporation of these processes in model calculations more manageable. However, it should be noted that small sample size and simple geometrical configuration make the results of the laboratory tests unsuitable for direct use in predicting behaviors of in situ rock mass. The laboratory tests included in this reporting period are summarized below, along with projection of future work. This report fullfils the level 4 Milestone ID: SPL7A5M4.

Fracture Flow Versus Matrix Imbibition

X-ray linear scanning was used to monitor the process of fracture flow and matrix imbibition. The tests were described by Roberts and Lin (1996), Lin and Roberts (1996), and Roberts and Lin (1997). Small blocks of 2.5 x 10 x 10 cm and 2.5 x 15 x 30 cm densely welded nonlithophasal Topopah Spring tuff from Fran Ridge, with a tensile fracture in the middle, were used in the tests. Water doped with KI was added to the top of the sample and radiographs were taken as a function of time to try to determine the distribution of water content. Two types of tests have been conducted: ambient temperature tests and elevated temperature tests.

Ambient Temperature Tests

Two tests have been conducted on a dry sample block of 2.5 x 10 x 10 cm. First the two halves of the block were put together well matched. Water was observed entering the fracture and the matrix very slowly. A v-shape imbibition front with its tip on the fracture was observed (Figure 1). More than one month after the experiment started the tip of the imbibition front had traveled only about half of the block height (about 5 cm). The block was flushed, dried, and reassembled with 25-micron gold shims on the fracture surfaces, after which the experiment was repeated. Water flowed along the fracture within a couple of hours. The water then imbibed into the matrix almost uniformly from the fracture (Figure 2). The lateral imbibition was rapid where there were lithic fragments (inclusions) and near-lateral microfractures. The images are being processed to determine saturation as a function of time, and the wetting front as a function of time. A video of the images of the second experiment was produced to show the fracture flow vs imbibition process.

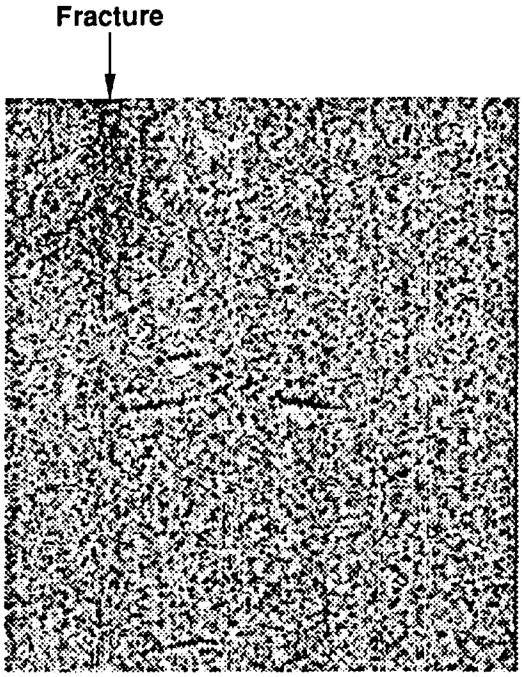

Figure 1. X-ray difference image of radiographs of tuff containing an unshimmed tensile fracture. The experiment was performed at room temperature. Water containing KI to enhance attenuation of x-rays was ponded on top of the sample. A roughly V-shaped wetting front was observed, this image was taken at 47.5 hours.

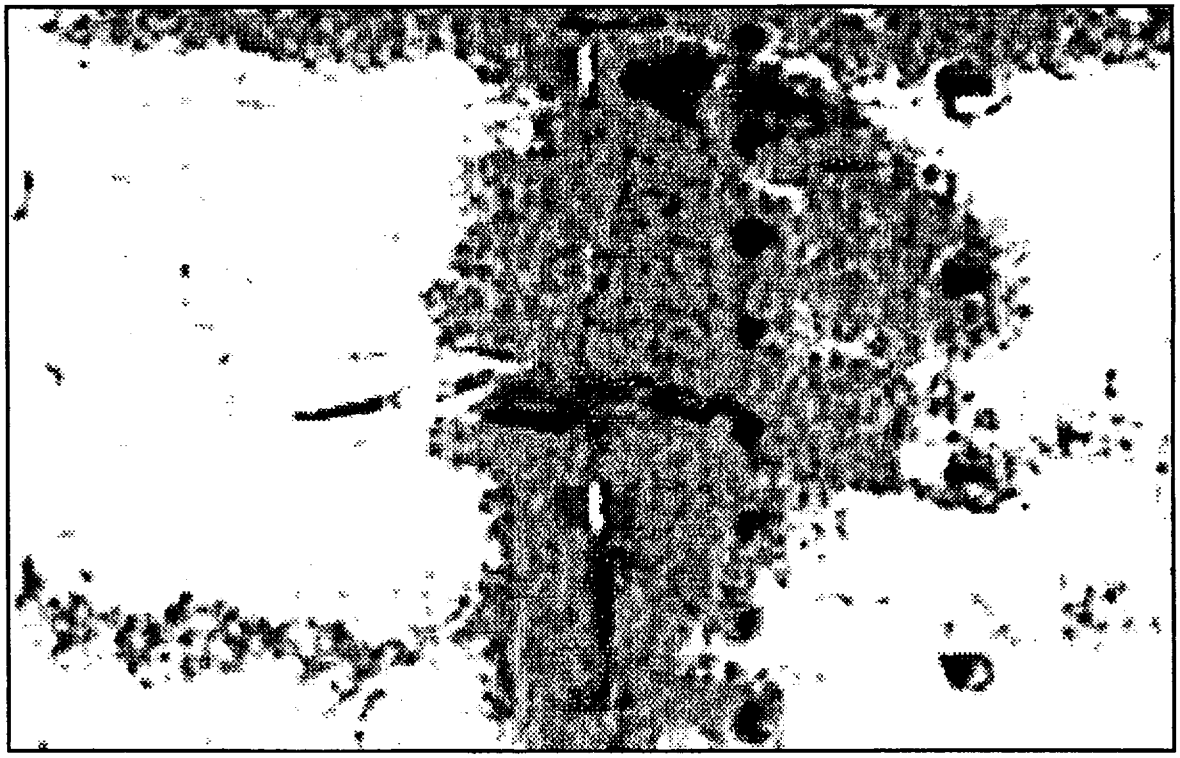

Figure 2. X-ray difference image of radiographs of tuff containing a tensile fracture. Four 25 μm shims held the fracture open. Experiment was performed at room temperature, elapsed time of the image is 70 hours after fracture flow was initiated.

Elevated Temperature Tests

After the second test at ambient temperature reported above (with 25μm shims), tape heaters were placed at the bottom of the block. The sample, in an initial state of near saturation, was heated from below. The temperature at the bottom was held at about 95°C for a few months. The temperature at the top of the block was not controlled. The dry-out process is not the reverse of the wetting process (Figure 3). The fracture was observed to rapidly dry-out. A high attenuation zone near the lower portion of the block subsequently developed. The high attenuation zone may be due to the deposit of KI after the water was evaporated.

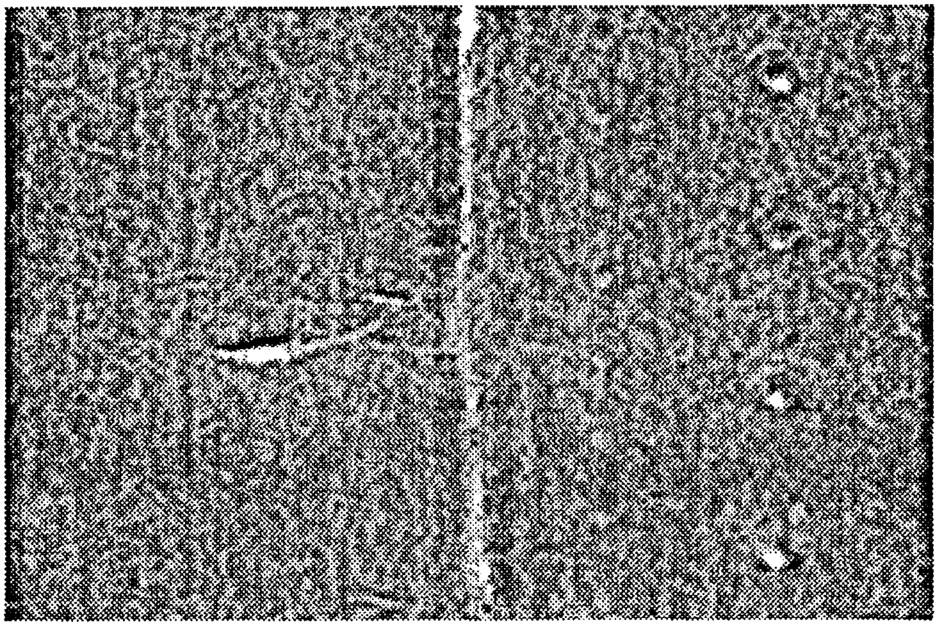

Figure 3. X-ray radiograph of the sample during heating from below to dry out. White area near the fracture indicates dry-out.

A small block of 2.6 x 15 x 23 cm Topopah Spring tuff from Fran Ridge, with a tensile fracture in the middle, was used to test the fracture flow and matrix imbibition against a thermal gradient. The sample preparation was similar to the previous experiment at room temperature. Three foil heaters were mounted at the bottom of the block. Four thermocouples were mounted along the vertical axis of the block, with the hot junction very close to the fracture surface. The temperature at the bottom of the block was maintained at about 110 °C, and the temperature at the top was about 28°C. Water doped with KI was added to the fracture at the top of the sample, with a water head of about 0.02 m, and radiographs were taken as a function of time to try to determine the distribution of water content. Preliminary results indicate that fracture flow against a thermal gradient is slower than that at room temperature. Water flowed in the fracture first, similar to the previous shimmed test at room temperature, before imbibition into the matrix takes place. Heterogeneity in the rock has strong influence on the water flow. Water in the fracture never flowed through the boiling zone, where KI deposit was observed (Figure 4). This phenomenon, if occurs in situ, could significantly impact repository performance by slowing rewetting of the repository environment.

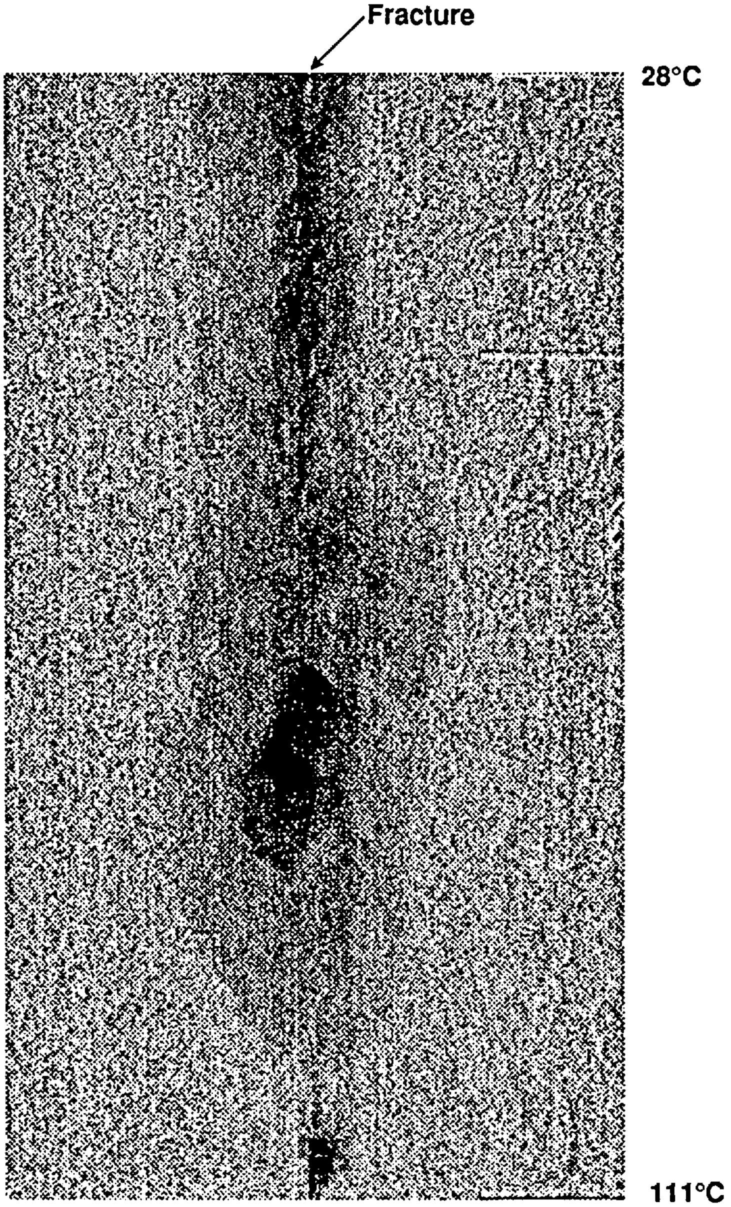

Figure 4. Difference radiograph of tuff containing a tensile fracture with 25 μm shims taken 73.5 hours after flow was initiated. The water head was about 0.02 m. This image shows progression of the wetting front past the highly porous region to the boiling zone.

Another test on the effect of infiltration flow rate on the fracture flow vs. matrix imbibition was conducted to evaluate the effect of a thicker dryout zone on the fracture flow and matrix imbibition. The same block of 2.6 x 15 x 23 cm used in the previous test was used in this test. The greater infiltration rate was simulated by increasing the water head above the top of the fracture from 0.02 to 1.45 m. In this test tape heaters were added to the side of the sample block mentioned above to increase the thickness of the zone in the sample, where temperatures are expected to be greater than 100°C, to be about 2.5 cm. The temperature at the top and bottom of the sample block were 80 and 148°C respectively. This created a larger boiling region than the previous test, and a slightly smaller thermal gradient. The fracture aperture, and the rock type in this test were the same as in the previous test. The water in the fracture flowed into the boiling zone, but did not pass through it (Figure 5). Imbibition into the matrix was observed.

The water head above the block sample was then increased to 2.92 m, while all of the other conditions were maintained the same as in the previous test. Water in the fracture was able to flow through the zone where temperature was above boiling within a few minutes, and no imibibtion into the matrix was observed (Figure 6). This preliminary result indicates that if water head can be built up, water can infiltrate through a fracture where temperature is above boiling.

Future experiments will further investigate the effect of fracture aperture and infiltration flow rate on the fracture flow vs. matrix imbibition in a heated block.

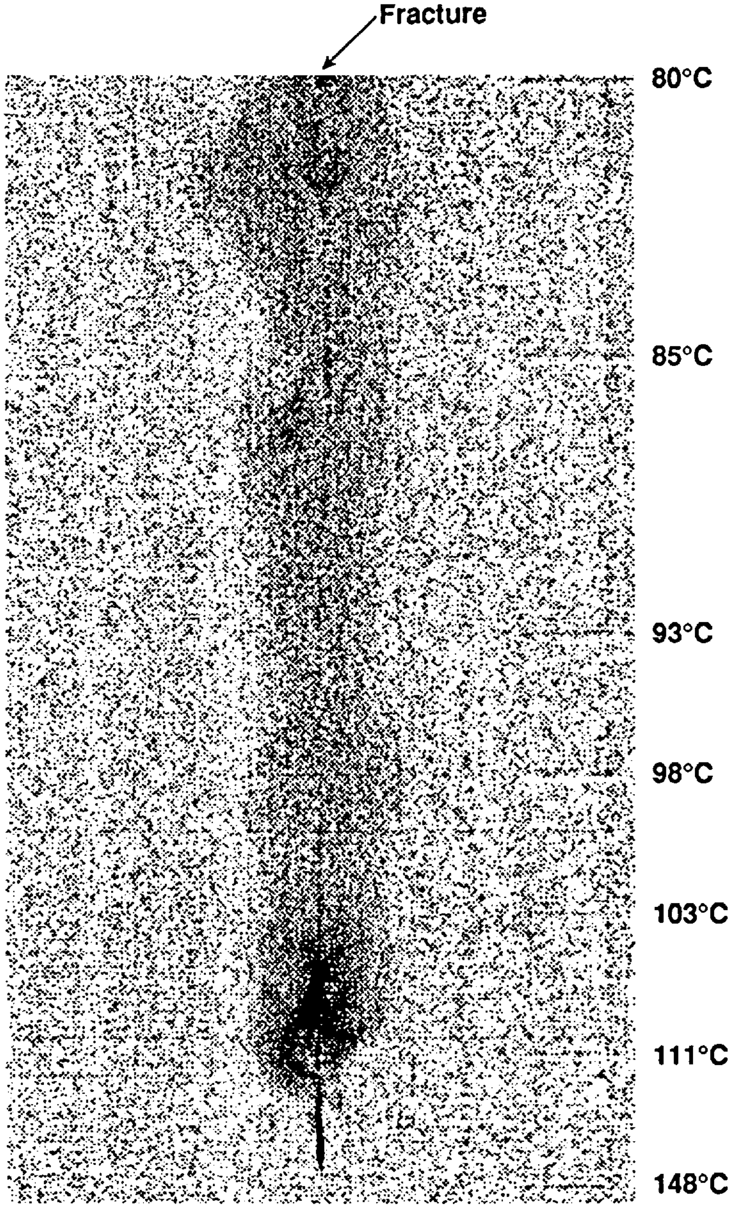

Figure 5. Difference image of radiograph of tuff containing a tensile fracture with four 25 μm shims, taken 7.2 hours after flow was initiated. Thermal gradient is indicated. The height of the water column was 1.45 m. Flow did not completely penetrate the boiling zone.

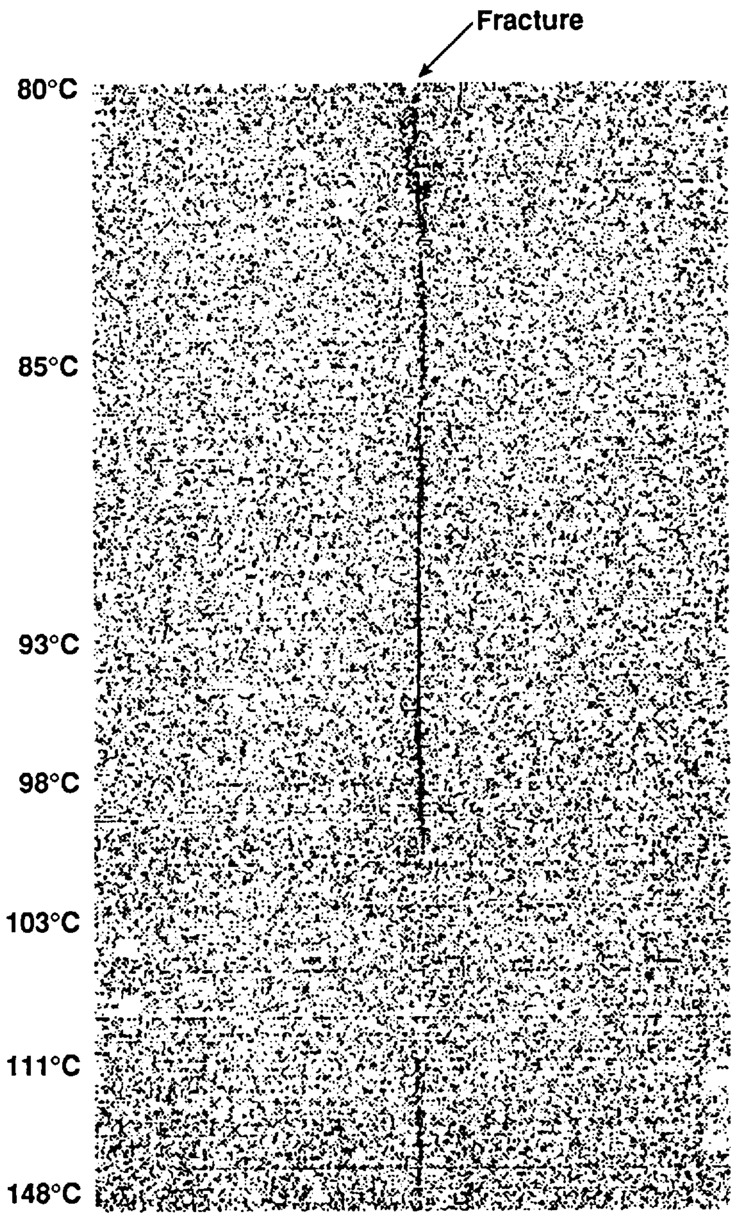

Figure 6. Difference image of radiograph of tuff containing a tensile fracture with four 25 µm shims, taken 0.67 hours after flow was initiated. Thermal gradient is indicated. The height of the water column was 2.92 m. Water flowed the length of the fracture through the boiling zone almost immediately upon ponding.

Fracture Healing

The experiment to determine the effect of confining pressure on the fracture healing, as observed previously by LLNL investigators (Lin and Daily, 1984; Daily et al., 1987; Lin and Daily, 1989; Lin and Daily, 1990; and Lin, 1991), has been completed. The experiment was reported by Lin et al., 1995). A fractured Topopah Spring tuff sample from G-4 hole was used. Saturated water permeability in the sample was measured as a function of temperature at various levels of confining pressure, from 10 Mpa to 5.0 Mpa, while the pore pressure was maintained at 0.5 MPa. The results are shown in Figure 7. At room temperature the water permeability was first measured as a function of confining pressure, from 1.0 to 5.0 MPa, then returned to 1.0 MPa. As expected, the permeability decreased as the confining pressure increased. The permeability recovered to its original value when the pressure decreased to the ambient level. This indicates that the maximum pressure in this test was not high enough to cause permanent deformation on the fracture surfaces of the sample. Then the pressures were raised to 1 MPa confining pressure and a pore pressure of 0.5 MPa, and the permeability was measured as a function of temperature to 150°C, and down to the room temperature. Then the confining pressure was increased to 2 MPa while the pore pressure was kept at 0.5 MPa, and the measurement of the permeability as a function of temperature was repeated. Next, the confining pressure was increased to 3 and 5 MPa and the measurements were repeated. Water that flowed through the sample was collected at every measurement for chemical analysis. The fracture surfaces of the sample were examined under SEM before and after the experiment to examine the mineralogical changes. The results are summarized in the next paragraph.

As shown in Figure 7, the overall permeability decrease during this 6100-hour experiment was from about 18 x 10^{-15} m^2 to about 2 x 10^{-15} m^2. About 69% of this permeability decrease occurred during the first temperature cycle at 1 MPa confining pressure. If the first temperature cycle was conducted at greater confining pressures the decrease in permeability may have been greater. The chemical analyses and SEM examinations indicated that deposition of silicate minerals may have happened during the first heating of the sample; dissolution and deposition may have occurred in the subsequent heating and cooling cycles. Freshness of the fracture surfaces may have stronger effect on the rock-water interaction than confining pressure. EQ3/6 calculations will be run to understand the rock-water interaction during the experiment.

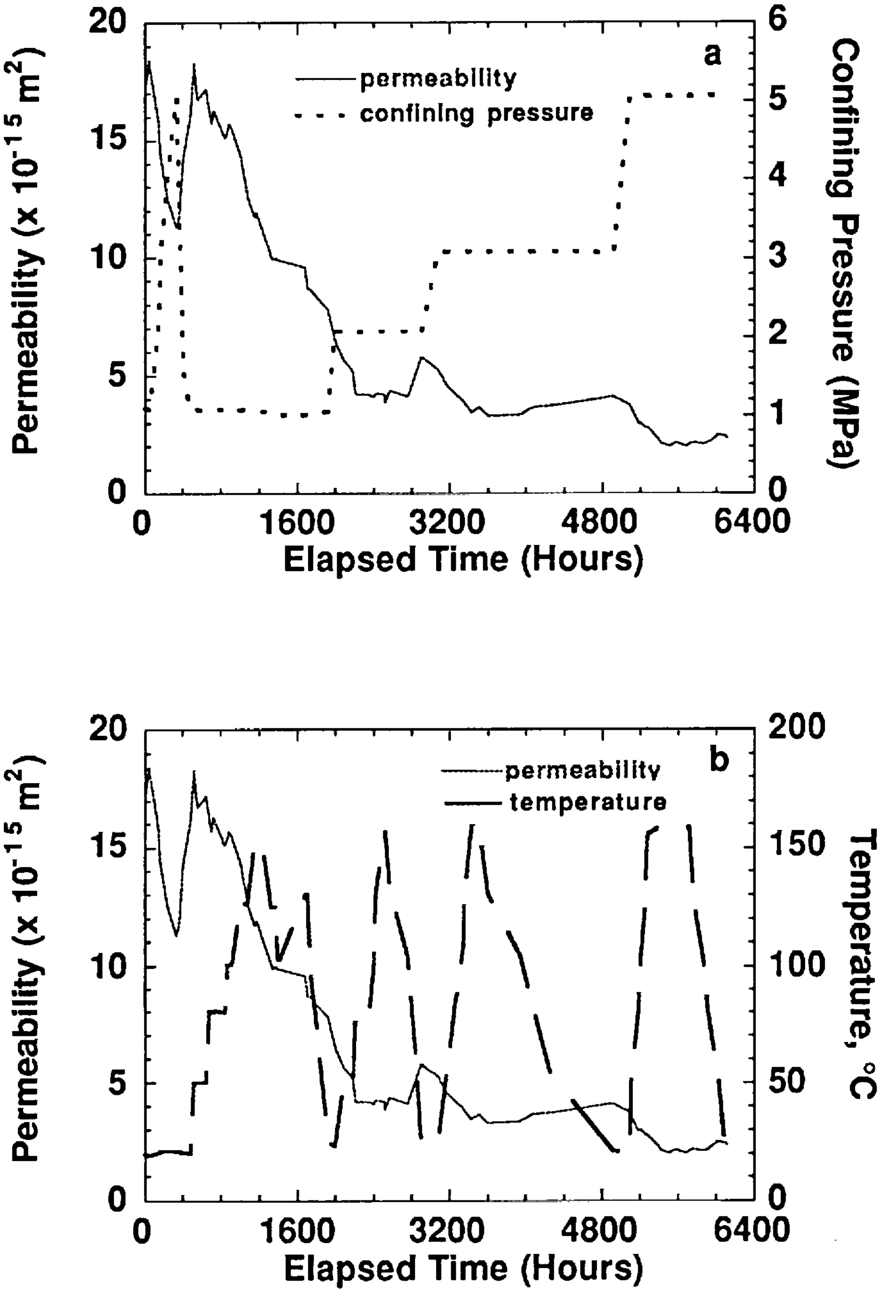

Figure 7. Permeability and confining pressure (a) and permeability and temperature (b) as functions of elapsed time. Pore pressure was maintained at 0.5 MPa.

Future tests will be focused on conditions that are more likely to occur in a repository. These include flowing hot vapor in partially-saturated fracture surfaces, flowing finite amounts of hot water in an unsaturated fracture, and refluxing of condensate in a fracture.

A fractured Topopah Spring tuff sample has been jacketed. The moisture content in the core was controlled to be about 70% saturation. The pressure transducers in the high-pressure-high-temperature system were calibrated. A syringe water sampling system will be installed so that the water samples will not contact air. This will permit a more accurate measurement of fluid pH. The experimental procedures for this test are as follows: Gas will be used as confining pressure medium. Gas permeability will be measured at ambient temperature. The temperature in the sample will be increased to about 150°C while a confining pressure of about 1.0 MPa will be maintained on the sample. During the heating the pore fluid lines will be open to prevent the pore pressure from rising, but the amount of vapor leaving the sample will be mornitored. When the temperature reaches 150°C, gas permeability will be measured again. Then an amount of water equal to about two pore volumes of the sample will be flowed through the sample. The water that leaves the sample will be collected for chemical analyses. The residual water in the pore pressure lines will be removed and weighed. The amount of water left in the sample will be estimated. Any extra water in the sample will be dried out. Then gas permeability will be measured again when the temperature is still at 150°C. The temperature will then be decreased to the ambient temperature, and gas permeability will be measured again. The gas permeabilities before and after the flow of hot water will be compared to evaulate the effect of flowing hot water on the gas permeability, which will indicate fracture healing. The sample will be removed from the pressure vessel, and the fracture surfaces will be examined for evidence of rock-water interaction.

Follow-on experiments will be performed to investigate the effect of other factors, such as the amount of water flowed through the sample, the flow rate of the water that flows through the sample, and refluxing of the pore water (alternating the water flow direction), on the fracture healing.

Enhanced Vapor Diffusion

Vapor diffusion is one of the mechanisms that can transport water through the matrix of partially-saturated rock. Vapor diffusion may be enhanced when the rock is in a thermal gradient. An experiment to investigate the conditions under which vapor diffusion may be enhanced, and to determine the magnitude of the enhancement is being designed. A related preliminary study is the measurement of relative humidity as a function of moisture content in a Topopah Spring tuff core.

This experiment was reported by Lin et al., (1996). An intact core sample of 6.95 cm in diameter and 14 cm in length was machined from one of the small blocks collected from Fran Ridge. The average porosity of the core is about 8%. A small hole of about 1.4 cm in diameter and 7.1 cm depth was drilled in the middle of the core for housing a Humicap, which measures relative humidity. The sample and the Humicap were placed in an air-tight sample holder. The core sample was dried in a vacuum oven first. The measurement started with the dry sample. Water was added to the sample for various levels of water saturation. Relative humidity was measured as a function of time after each increment of water saturation. When the measured relative humidity reached a constant level the sample was weighed to determine the water saturation associated with that level of relative humidity, and water was added to increase water saturation. The wetting phase of the experiment was completed, when the measured relative humidity reached about 99.6% and the water saturation level was about 41%. Figure 8 shows the relative humidity as a function of water saturation. This is a complete moisture retention curve when the relative humidity is converted to water potential.

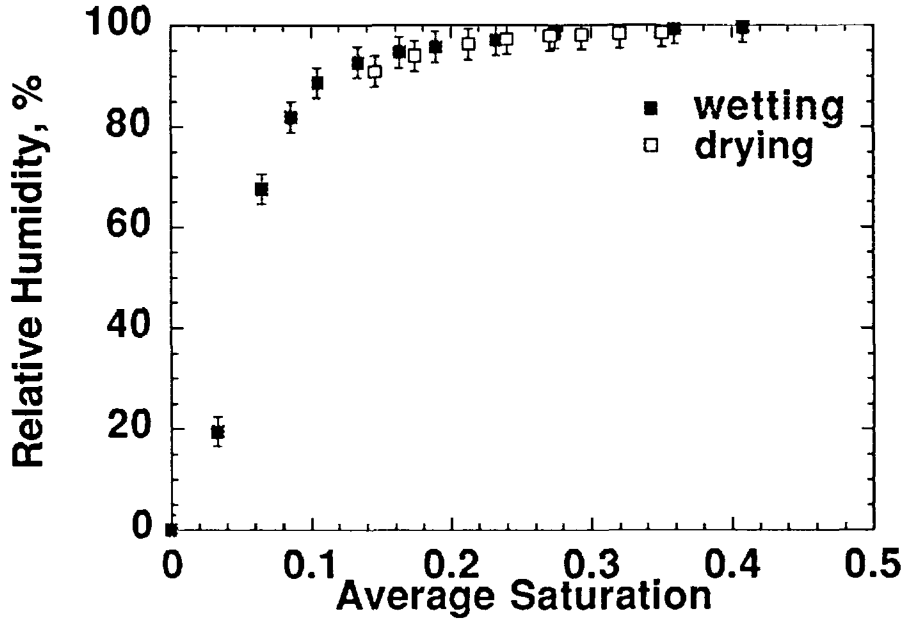

Figure 8. Relative humidity within a Topopah Spring tuff sample as a function of saturation. Filled squares represent wetting, open squares represent drying. Error bars are +/- 3% relative humidity.

In order to determine the effect of temperature on the relative humidity, at the end of the wetting phase measurement the sample assembly was placed in an oven at 95°C for about one week then at 65°C for a couple weeks. The relative humidity remained at 100% regardless of the temperature. It was expected that the relative humidity would decrease when the temperature increased. The Humicap was sent out for calibration. Another recently calibrated Humicap was installed in the sample. The humidity reading was about 98% whereas the saturation level was about 35%. The fact that the relative humidity did not decrease at elevated temperatures is still under investigation. The relative humidity as a function of water saturation in the drying phase is now being determined. As shown in Figure 8, the water saturation level is down to about 14%. The results of these tests will be used to design a test of the enhanced vapor diffusion. Additional sample holders have been constructed and the data collection hardware and software were modified so that two experiments can be performed simultaneously. The design of an experiment to investigate the enhancement of vapor diffusion has not yet been. It is likely that relative humidity at one end of a sample will be measured, while the other end is kept at a constant level of humidity, without a thermal gradient first. Then the same measurement will be repeated when a thermal gradient is imposed on the sample, while the temperature at the measuring point is kept at the same level as in the iso-thermal case. The time history of the two measurements will be compared to evaluate the effect of a thermal gradient on the vapor diffusion.

Acknowledgement

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