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A heated large block test for high level nuclear waste management

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ABSTRACT: The radioactive decay heat from high-level nuclear waste may, depending on the thermal load, create coupled thermal-mechanical-hydrological-chemical (TMHC) processes in the host rock of a repository. A heated large block test (LBT) is designed to understand some of the TMHC processes. A block of Topopah Spring tuff of about 3 x 3 x 4.5 m was isolated at Fran Ridge, Nevada Test Site. Small blocks of the rock adjacent to the large block were collected for laboratory testing of some individual thermal-mechanical, thermal-hydrological, and thermal-chemical processes. The large block will be heated by heaters within so that a dry-out zone and a condensate zone will exist simultaneously. Guard heaters on the block sides will be used to minimize horizontal heat losses. A constant load of about 4 MPa will be applied to the top and sides of the large block. The sides will be sealed with moisture and thermal barriers. Temperature, moisture content, pore pressure, chemical composition, stress, displacement, electrical resistivity, acoustic emissions, and acoustic velocities will be measured throughout the block during the heating and cool-down phases. The results from the experiments on small blocks and the tests on the large block will provide a better understanding of some concepts of the coupled TMHC processes. The progress of the project is presented in this paper.

INTRODUCTION

A major concern for the disposal of high level nuclear wastes in deep geological formations is the quantity and quality of water that may contact waste packages. The Yucca Mountain Site Characterization Project (YMP) is investigating the Topopah Spring tuff at Yucca Mountain, Nevada, for its suitability as a host rock for the disposal of high level nuclear wastes. The host rock at the potential repository horizon is a partially saturated, fractured, densely welded, nonlithophysal tuff. Therefore, the pores of the host rock are filled with both air and liquid water.

The radioactive decay heat from waste packages will heat up the rock mass in the near field of the repository. The temperature in the rock mass depends on the thermal load in the repository. Results from a heater test in G-Tunnel, Nevada Test Site[1] and model calculations[2] indicate that, above an areal power density threshold, the heat from the waste packages is enough to create a drier zone and a wetter zone in the near field. Laboratory studies[3] and a field investigation[4] indicate that fractures are the main flow path for vapor/steam. The thermal load may change the fracture porosity and connectivity. Most of the water vapor will condense where temperatures are sufficiently low. A region of increased saturation is expected to form around the drier region due to this condensation. In regions above the heater the condensate may reflux[2]. In regions to the sides of the heaters, the condensed water may be shed[5]. In the condensate region and in the refluxing zone, enhanced rock-water interaction may occur. The rock-water interaction will cause dissolution and re-deposition of certain minerals, which, in turn, will affect the movement of fluids within the rock mass[3,6]. These coupled thermal-mechanical-hydrological-chemical (TMHC) processes have to be understood before models can provide a meaningful description of the near-field environment and predictions of the quantity and quality of water in the waste package environment.

Laboratory and field experiments are being designed to test some model concepts of the TMHC processes. Laboratory tests on small intact samples and samples with single fracture are being conducted to study individual processes, such as dehydration and rehydration behavior, vapor diffusion, and liquid water imbibition. Larger-scale tests that can incorporate more fractures and inhomogeneities are needed to confirm and validate conceptual and numerical models. Eventually, in situ field tests in the Exploratory Study Facility (ESF) will be performed to confirm models that will be used to predict the performance of a repository. This paper presents a progress report of the large block test (LBT). Previous block tests investigated partially coupled processes with partially controlled boundary conditions[7,8]. The LBT is designed to study some of the TMHC processes under controlled boundary conditions[9]. Therefore, it will provide results that are easier to model and understand some concepts related to the coupled TMHC processes.

PURPOSE OF THE LBT

The LBT is designed to create controlled boundary conditions so that some of the coupled TMHC processes can be observed and tested. We will determine: 1) dominant heat transfer mechanism, 2) if there is coincidence of the dry-out zone and the boiling-point isotherm, 3) the relationship between re-wetting and cooling of the dry-out zone , 4) refluxing of the condensate water above the heated zone, 5) the change of water chemistry in the condensate zone, and 6) the mechanical responses of the block.

The LBT will provide tests on a block of rock which is closer in scale to the repository than previous heater test blocks [8]. The rock mass can be characterized from five exposed surfaces and multiple boreholes, and will be dismantled after testing for further characterization, especially for studying rock-water interactions. The LBT will also provide an opportunity for testing the performance of waste package materials in the heated rock block. In this case, coupons of certain candidate waste package materials will be placed in the block. The coupons will be examined before and after the test for their response to the environment.

DESCRIPTION OF THE LBT

The LBT consists of two parts: (1) laboratory tests on small blocks of intact rock and blocks with single fractures, quarried from the region adjacent to the large block, to study the thermal hydrological, mechanical, and chemical processes, and (2) a field test involving integrated macroscopic simulation and evaluation of the coupled TMHC processes in a large block, which includes multiple fractures.

Excavation of the Large Block

A block of 3 x 3 x 4.5 m was isolated at Fran Ridge, Nevada Test Site. The dimensions were chosen so that sufficient number of fractures are included in it. Pre-test thermal-hydrological and thermal-mechanical calculations have been performed to verify that the block size is suitable. The site at Fran Ridge was selected for the large block due to its desirable rock type, fracture characteristics, and accessibility.

A belt saw was used to saw four vertical slots that form the boundary of the large block. A hydraulic jack hammer was used to excavate the surrounding rocks. Vertical instrument holes within the block were drilled and cored before the sawing and excavation. A commercial wire saw was used to trim the top of the block. Some smaller blocks of rock, about 30 cm in size, were collected within a 1 m region around the large block for laboratory tests.

Characterization of the Block

Block characterization is in progress. Characterizations will include measurement of the distribution of fractures, mineralogical composition of the matrix and the fracture coating, mechanical and hydrological properties, and the initial moisture content. The properties of the matrix to be determined include porosity, permeability, moisture retention curves, electrical resistivity vs. moisture content, stress-strain curves, and acoustic wave velocity. The average porosity of the block was determined to be $11.55 \pm 2.28\%$. The fracture traces on the five surfaces and on the drill cores from the instrument holes were mapped. Figure 1 shows the fractures on top of the block and the vertical borehole locations. Most of the linear features are major fractures, which are near-vertical, west-dipping. The aperture of the fractures range from barely visible to a few mm.

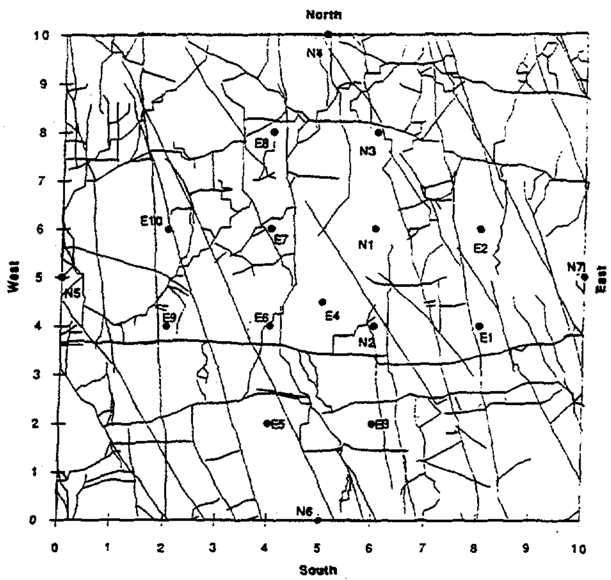

Fig. 1 The fractures on top of the block. The dots are the location of the vertical holes. The diameters of the holes are 3.8 cm for the E-holes and 7.6 cm for the N-holes.

Air injection tests were conducted after the first vertical hole (N1) was drilled, to estimate bulk permeability. Figure 2 shows the air permeability as a function of depth. Most of the sampled depths have a permeability above 1 m Darcy (10^{-15} m^2). It should be noted that the permeability is dominated by the fractures that intersect the injection hole. Due to the high fracture density in the block, the bulk permeability is likely to be more homogeneous.

Neutron logging was conducted in the E2, E3, E4, and E9 holes before and after the sawing to estimate the moisture content in the block. Figure 3 shows the water saturation as a function of depth, determined from neutron logging in E4 hole. The water saturation determined in other holes agrees well with these shown here. Neutron logging will be performed again to estimate the initial moisture content of the block before the experiment starts.

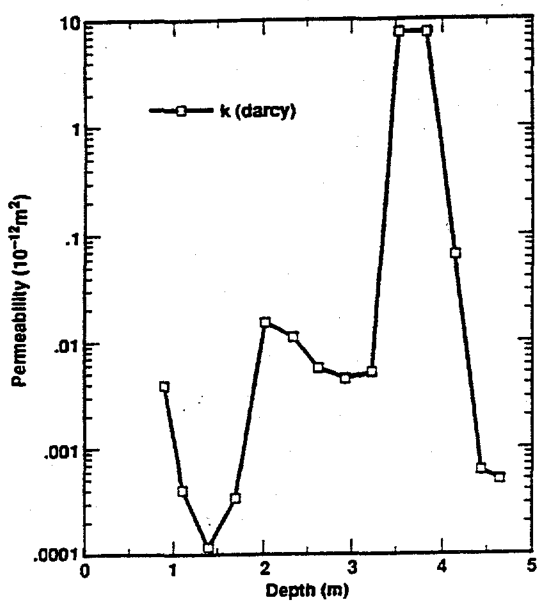

Fig. 2 Air permeability as a function of depth in the large block, obtained from a single hole air injection test.

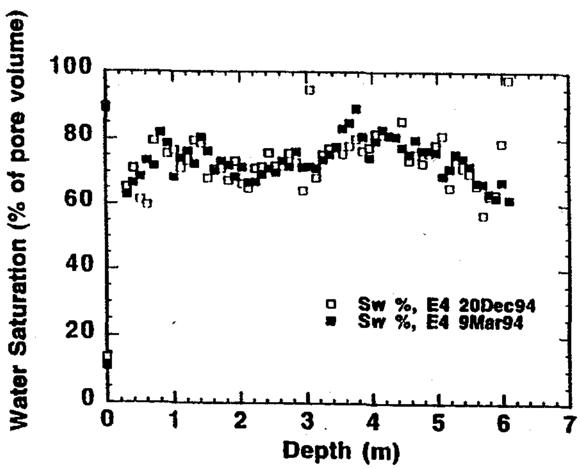

Fig. 3 Water saturation (percent of pore volume) in a vertical hole, near the middle of the block, as a function of depth, determined by neutron logging before and after the sawing.

Tests on Small Blocks

Blocks of Topopah Spring tuff collected during the excavation are being used for laboratory investigation of individual thermal-hydrological, thermal-chemical, and thermal-mechanical processes. These experiments include: fracture flow vs. matrix imbibition as a function of the fracture aperture, one-dimensional imbibition and dehydration, condensation along fractures, and geomechanical responses to heating. The thermal-hydrological experiments will be conducted for various fracture apertures, at elevated temperatures. Water that flowed through the fracture will be collected for chemical analysis. The fracture surfaces will be examined before and after the experiment for evidence of rock-water interaction. On-going experiments will determine relative humidity in the matrix as a function of water saturation, study condensation along a fracture and the movement of the condensate, and investigate fracture flow vs. matrix imbibition.

For the study of thermal-mechanical responses, a block will be put under constant triaxial loads and heated either uniformly or from one end. The load on each side of the block will be measured by load cells; deformation will be measured by strain gauges and/or displacement transducers. Stress-strain curves, displacement of the matrix and across fractures, and acoustic emissions will be measured. The fracture surfaces will be examined before and after heating, for evidence of changes in the fracture properties, using fracture surface profiling devices and a scanning electron microscope.

Large Block Tests of the Coupled TMHC Processes

The large block will first be characterized for its fracture intensity, location, and orientation, as described earlier. Horizontal heater holes and instrument holes will be drilled. Vertical and horizontal instrument holes will provide 3-dimensional coverage of the block. Instruments will also be installed outside the holes. Installation of instruments, data acquisition, test procedures, and data analyses are discussed below.

(1) Installation of Instruments

Resistance temperature devices (RTD) will be used to measure temperatures in the block. A bundle of RTDs will be grouted with cement in temperature holes. Some of the RTDs will be mounted in thin-walled stainless steel tubes so that they can be calibrated or replaced during the test. Other instruments to be installed in the boreholes include the following. The Rapid Evaluation of K and Alpha (REKA) thermal probe will be used to determine the thermal conductivity and thermal diffusivity[10] Extensometers, displacement transducers, stress transducers, and acoustic emission transducers will be either grouted or mounted on a SEAMIST membrane. Humidity sensors (Humicap), pressure transducers, and coupons of waste package materials will be installed in a packer system; the same holes will also be used to measure air permeability. Water sampling discs and microelectrode array sensors to monitor pH, Eh, and Cl^- will be mounted on the outer surface of a SEAMIST membrane. Coupons of the waste package material, such as carbon steel and copper, will also be instrumented with the microelectrode sensors. The neutron logging holes will be kept open by using a Teflon tube liner. The annular space between the liner and the borehole wall will be sealed with cement grout. One 2.44-m-long, 300-watt heating element will be installed in each of the five heater holes. Coupons of the waste package material will also be put in the heater holes. The opening of each heater hole will be plugged to prevent heat loss and to minimize moisture movement along the opening. Some of the electrical resistivity tomography (ERT) electrodes will be grouted in the ERT holes.

In addition to the instruments in the holes, the following devices will be mounted on the block surface: a temperature control/moisture collecting system at the top, and ERT electrodes, acoustic transducers, and guard heaters, all on the sides of the block. The guard heaters will be used to maintain a boundary condition as close to adiabatic as possible.

After installation of the instruments and heaters, the block will be sealed with thermal and moisture barriers on its four sides. Bladders will be used to load the sides and the top of the block. A hydraulic system will be used to keep the pressure in the bladders constant throughout the tests so that the block will be under a constant load. A prefabricated load-retaining frame will be assembled around the block, section by section. The electrical wires of instrument and high pressure lines for the bladders will be brought out through pre-drilled holes in the load-retaining frame and also through trenches under the frame.

(2) Data Acquisition

There are two data acquisition modes: automated data acquisition by a data acquisition system (DAS) and manual data acquisition. The data to be acquired by the DAS include temperature, pressure, displacement, heater power, voltage output from chemical sensors and Humicaps, and ERT. Data to be collected manually include neutron logging, REKA, acoustic emission and velocity, and air permeability. Water sampling will also be conducted manually.

(3) Test Procedures

The DAS will start collecting data at least one week before loads are applied to the block. The DAS will continue to operate throughout the test duration. During this period, at least one set of the manual data will be obtained. Then, the block will be loaded with a peak stress of about 4 MPa, both vertically and horizontally, at ambient temperature. At least one set of the manual data will be acquired after the block has reached equilibrium. Also during this period, the stress-strain behavior of the block will be determined. Then, the heaters within the block will be energized according to a heating strategy determined by scoping calculations. The heating phase will be followed by a natural cool-down period, during which the heater powers are zero. The block is considered cooled when its maximum temperature decreases to within 5°C above the ambient temperature. The natural cool-down phase may take several months. During the initial heating phase, the temperature at the top of the block will be allowed to rise along with the temperature in the block; then during the steady state the temperature at the top will be maintained at about 60°C. The maximum temperature in the heater zone will be kept at about 140°C. One of the criteria for determining the heating duration, the maximum temperature, and the temperature at the top of the block is to establish a dry-out region, a condensate region, and a relatively undisturbed region simultaneously for at least 2 months, so that enough data and samples can be acquired. During the heating phase, a constant load will be maintained on the block. The manual data and water samples will be collected once every two weeks. Vapor that exits the top of the block will be collected for measuring its amount and chemistry. The external loads on the block will be released when the block is cooled.

After the test, the block will be mechanically dismantled so that the fracture surfaces and some portions of the matrix can be examined for evidence of chemical processes and alterations during the experiment. Instruments that can be recovered will be re-calibrated.

(4) Data Analyses

Data reduction and analysis will begin when the data are available and will continue throughout the testing duration. The chemical effect of all man-made materials on the test will be studied and included in the data analyses. Post-test model calculations will also be performed to analyze the test results. In this case, V-TOUGH and NUFT will be used to model thermal-hydrological processes. The results of this experiment will also be used for model concept development and to verify model calculations using thermal-hydrological-chemical codes, such as NUFT, EQ3/6, BASIN II, and PRECIP. A thermal-mechanical model, such as Fast Lagrangian Analysis of Continua (FLAC), will be used to analyze the observed thermal-mechanical responses. A physical model will be set up to interpret the coupled processes.

CURRENT STATUS

The load-retaining steel frame is under construction. All vertical instrument holes have been drilled. Air injection tests indicate that the permeability of the block will be sufficient for generating a dry-out zone in the time frame of the experiment, based on the pre-test model calculations. The block was excavated and its top has been trimmed. Fractures on the surface of the block have been mapped in detail. Tests on smaller blocks in the laboratory are underway. Procurement of instruments is underway. Pre-test scoping calculations are being conducted. A tentative schedule is to start the tests on the large block in June of 1996.

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