TWO-PHASE NONISOTHERMAL HYDROLOGIC TRANSPORT STUDIES AT THE APACHE LEAP TUFF FIELD SITE

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ABSTRACT

Only limited investigations of hydrothermologic processes in unsaturated fractured rock related to the disposal of high-level radioactive waste in an underground repository have been conducted to date. To provide improved confidence in understanding nonisothermal processes, a field heater test is proposed in slightly welded tuff at the Apache Leap Tuff Site in Central Arizona. Previously, preliminary field and laboratory hydrothermologic experiments have been conducted to identify specific components associated with nonisothermal process. Additional laboratory nonisothermal experiments are currently being conducted to provide supplemental data sets. TOUGH (a multi-phase, nonisothermal computer simulation program) is being used as part of the experimental design phase for the purpose of determining the optimal heater size and heating duration, as well as the location and number of monitoring intervals surrounding the heater. The monitoring equipment will be employed to obtain temperature, water saturation, matric potentials, solute concentrations and other variables critical to the understanding of thermally induced hydrologic transport on field scales.

INTRODUCTION

A field-scale heater test is proposed for investigating hydrothermologic processes in unsaturated fractured rock related to the disposal of high-level radioactive waste in an underground repository. The test will be conducted in slightly welded tuff at the Apache Leap Tuff Site in Central Arizona (Fig. 1). The data collected from the experiment will be provided to the INTRAVAL program which is an internationally sponsored effort to validate hydrologic transport models.

An earlier heater test by Davies (1) was conducted near the proposed heater site in densely welded tuff and provides initial data sets which are being used to design the field-scale experiment (Figs. 2 and 3). Davies also conducted laboratory hydrothermologic experiments on unfractured drillcores which are interpreted by McCartin et al. (2). Additional laboratory nonisothermal experiments are currently being conducted to provide supplemental data sets.

TOUGH (a multi-phase, nonisothermal computer simulation program) is used as part of the experimental design phase for the purpose of determining the optimal heater size and heating duration, as well as the location and number of monitoring intervals surrounding the heater. The monitoring equipment will be employed to obtain temperature, water saturation, matric potentials, solute concentrations and other variables critical to the understanding of thermally induced hydrologic transport on field scales.

Described here are the salient features of thermally induced flow and transport as determined from experimental experience with previous laboratory and field nonisothermal tests. Also presented is a discussion of ongoing simulation efforts used to guide the experimental design. Due to the paucity of experience related to thermal disturbances at depth in unsaturated, fractured media, the experimental design has evolved as more data and monitoring tools have become available.

IMPORTANT PROCESSES

The processes which may affect non-isothermal flow and transport include thermal, liquid, solute, vapor, gas movement, and thermomechanical changes which can be described by coupled nonlinear partial differential equations (PDE's). Of special interest is the coupling between processes which causes complex interactions. The PDE's must be solved using theoretical or observed phenomenological coefficients. Some of the coefficients are highly nonlinear and hysteretic functions of fluid potential and water content.

Predictions based on the solution of the equations described above must be tempered by observations. Experience from laboratory experiments indicate a number of important phenomena which substantially affect fluid flow and solute transport. Laboratory experimental results indicate:

- Latent heat transport in the vapor phase, with sensible heat transport in the solid, liquid, and gas phases;
- A strong heat-pipe effect arising from countercurrent liquid-vapor flows which causes desiccation near the heat source and a concomitant accumulation of water away from the source;
- The possibility for osmotic potential to reduce the magnitude of the heat-pipe effect due to solute concentration effects on vapor pressure reduction and osmotic potential near the heater; and
- The dissolution and precipitation of silica in fractures which can alter the physical properties of the bulk rock.

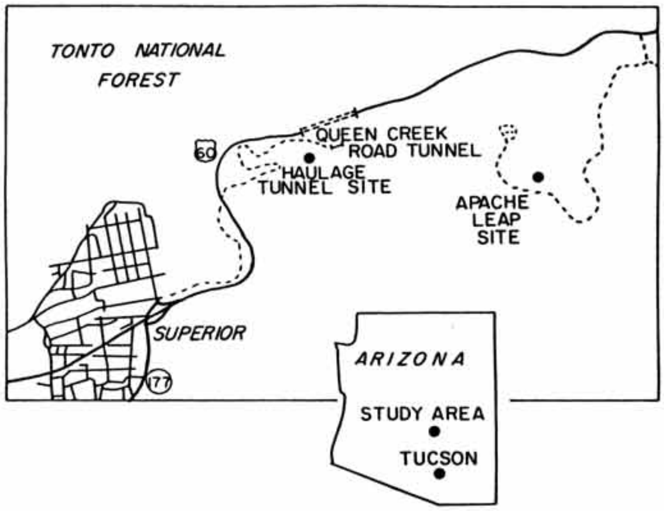

Fig. 1. Proposed location of field heater test at the Apache Leap Tuff site.

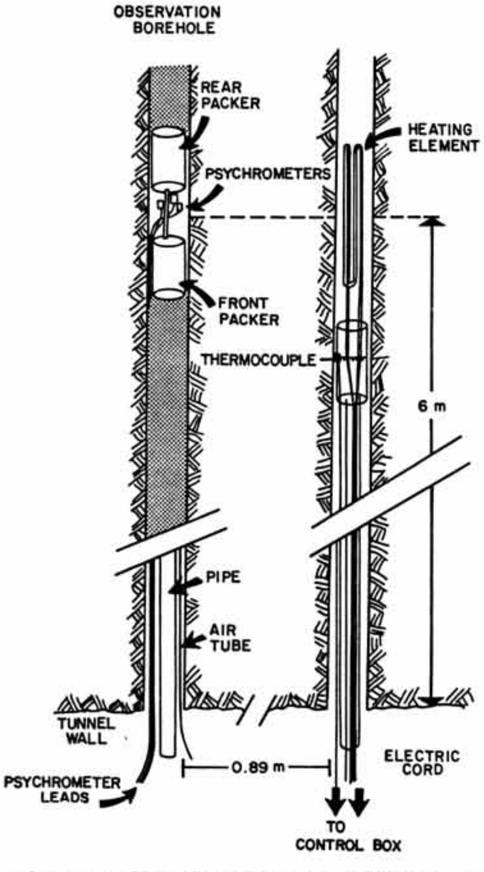

Fig. 2. Diagram of heating element and thermocouple located behind packer (right borehole) and packers isolating psychrometers (left borehole) at Queen Creek road tunnel site.

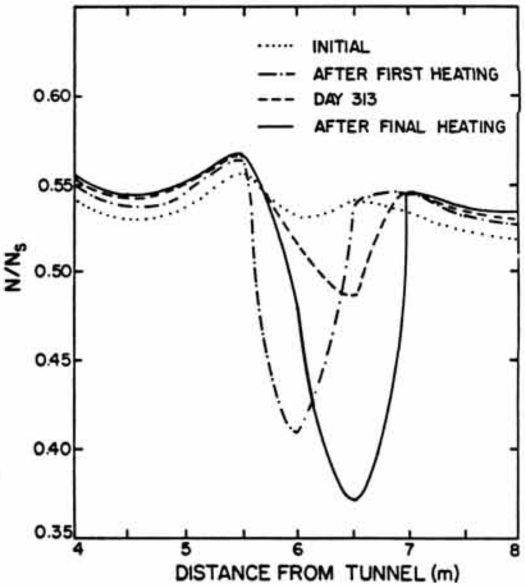

Fig. 3. Observed water content in tuff around the heater borehole as a function of time for heating experiment in the Queen Creek road tunnel.

These laboratory findings must be balanced by experimental evidence conducted over field scales using less artificial boundary conditions. The field scale findings include:

- Heat transport occurs from the source as sensible and latent heat, causing a desiccation of the rock near the source which expands over time.
- Liquid water accumulates in boreholes and openings near the heat source, with little water accumulation in the rock matrix.
- Substantial air movement occurs through fracture networks due to orographic and barometric gradients.

The nonwaste portion of the waste-repository structure will undoubtedly affect the hydrothermologic regime as well. The placement of shafts, seals, drifts, boreholes, ventilation ducts, and drains will have an impact on fluid flow and solute transport. In particular, the operation of the ventilation system will affect the transport in the vapor phase by:

- The injection of dry, cooler exterior air which will be circulated through the open repository;
- The resultant transport of water through the repository as vapor;
- The discharge of warm, humid air to the atmosphere; and
- The alteration of the existing orographic and barometric circulation within the subsurface.

By circulating air through the repository, substantial quantities of water will be removed and discharged to the atmosphere, thus causing the desiccation and cooling of interior repository surfaces. For isolated chambers within the repository, substantial condensation may or may not occur depending upon the moisture and thermal gradients across the chamber.

SIMULATION OBJECTIVES

The proposed field-scale experiment is being designed with the above-described hydrothermologic features in mind so that important aspects of coupled heat, liquid, gas and solute transport can be observed. Knowing what kind of monitoring equipment to install, where to place the monitoring equipment, and where and how the heater should be placed and operated requires that a simulation model be employed which incorporates as many of the processes as possible.

Simulations will be used to identify the important features of the heater experiment including zones of saturation, regions where fracture flows are expected, and accumulation of high salinity waters near the evaporation front. Once the size and location of these zones have been identified, various monitoring and sampling strategies will be examined and tested prior to conducting the field-scale heater experiment. The effects of gravity, fracture properties, initial water saturation, initial solute concentration, and material heterogeneities will be examined using sensitivity analyses. The types and locations of sensors to be installed will also be simulated to determine the required sensor sensitivities and the regions where the greatest changes are expected.

SIMULATION INPUTS

Inputs to the simulation model include physical properties of the rock matrix as well as fracture properties. To obtain the physical properties, laboratory tests of rock cores obtained near the proposed heater site are used to provide preliminary estimates of rock matrix parameters, such as the rock thermal, hydraulic, pneumatic, and solute transport properties (3). Coupling between processes are also estimated using laboratory experiments conducted under non-isothermal conditions in a closed system, and monitored using a dual-source gamma ray attenuation device. The fracture network at the field site has been inventoried by Thornburg (4) and is presented as Fig. 4. The location of the heater with respect to the fracture network is an essential component of the experimental design.

Other necessary simulation inputs are the boundary conditions. An important requirement for boundary conditions in the unsaturated zone is the ability to impose constant gradient, as opposed to constant flux, boundary conditions. For saturated media both conditions are interchangeable, but for this application the coefficient relating the gradient to the flux is a nonlinear function of water content. The proposed modification consists of allowing a constant gradient boundary condition to be prescribed, which is equivalent to a constant flux boundary condition only when the hydraulic, pneumatic or thermal conductivities remain constant as a function of matric suction. Additionally, model inputs of borehole surfaces must be considered. Rather than treating the borehole walls as no flow boundaries, transport into and along boreholes must be considered.

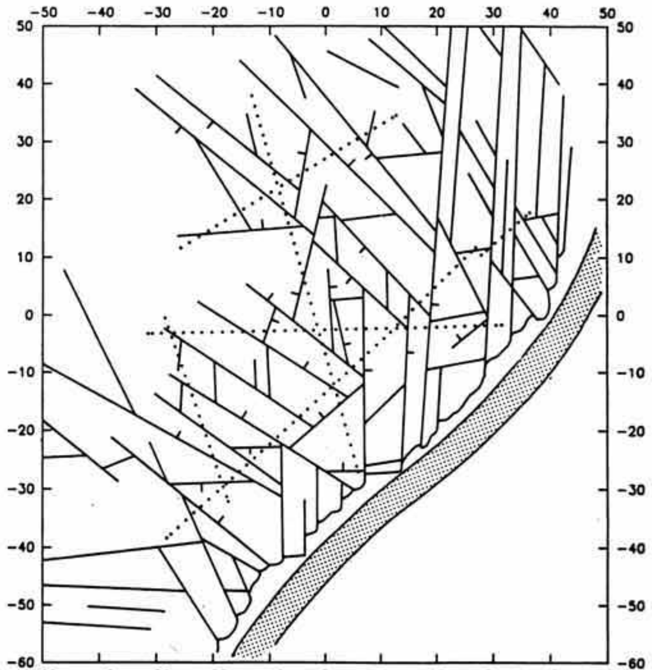

Fig. 4. Structural lineaments interpreted from aerial photographs of fracture planes exposed in outcrop at heater site.

SIMULATION RESULTS

The proposed field heater experiment is simulated by TOUGH using two-dimensional cylindrical space coordinates. The heater is initially placed at a depth of twenty meters. As an example of the use of TOUGH for experimental design purposes, Fig. 5 presents simulation output at 1000 days following the initiation of the heat pulse. The simulation assumes uniform material properties (no fractures or boreholes). Drying around the heat source is evident, and a zone of saturation is not observed away from the heat source.

SUMMARY

Once the expected conditions during the heating test at the field site have been adequately simulated, locations of monitoring boreholes will be selected to determine the optimal position for confirming simulation predictions. The heater will be operated to obtain significant information regarding the distribution of fluid movement, solute

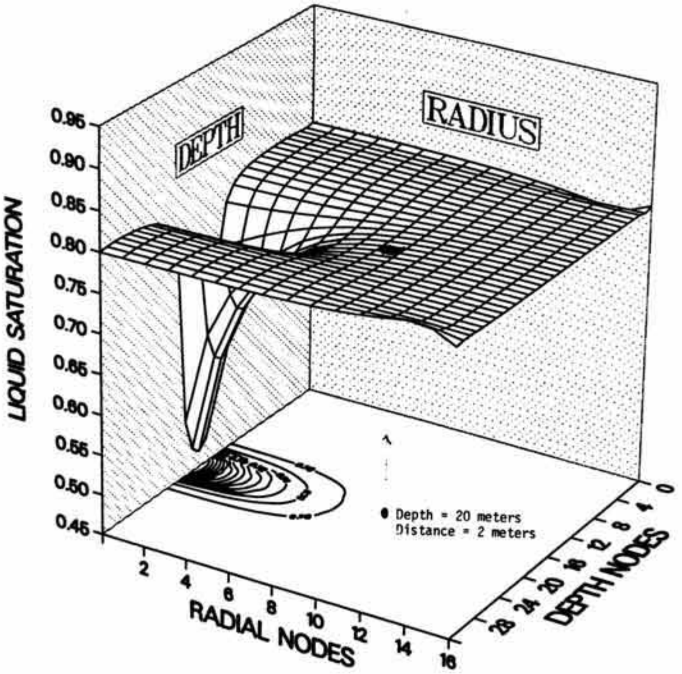

Fig. 5. Simulated liquid saturation distribution around heat source after 1000 days.

transport, gas and vapor movement, rock stress changes, and thermal alteration of the rock.

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