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PROTOTYPE ENGINEERED BARRIER SYSTEM FIELD TESTS—PROGRESS REPORT

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ABSTRACT

This paper presents selected preliminary results obtained during the first 54 days of the Prototype Engineered Barrier System Field Tests (PEBSFT) that are being performed in G-Tunnel within the Nevada Test Site. The test described is a precursor to the Engineered Barrier Systems Field Tests (EBSFT). The EBSFT will consist of in situ tests of the geohydrologic and geochemical environment in the near field (within a few meters) of heaters emplaced in welded tuff to simulate the thermal effects of waste packages. The PEBSFTs are being conducted to evaluate the applicability of measurement techniques, numerical models, and procedures for future investigations that will be conducted in the Exploratory Shaft Facilities of the Yucca Mountain Project (YMP). The paper discusses the evolution of hydrothermal behavior during the prototype test, including rock temperatures, changes in rock moisture content, air permeability of fractures, gas pressures, and rock mass gas-phase humidity.

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INTRODUCTION

The Engineered Barrier Systems Field Tests (EBSFT) in part consist of in situ tests of the geohydrologic environment near heaters emplaced in welded tuff. As part of the YMP testing program in the Exploratory Shaft Facility (ESF), field tests have been designed that simulate the emplacement of high-level radioactive waste containers. The results from EBSFT tests will be used together with laboratory studies and numerical modeling simulations to anticipate the evolution of the postclosure repository environment with which the waste packages must interact. Information on the postclosure environment will be used as boundary conditions in designing the waste packages and in assessing their performance.

Prototype tests are being conducted in G-Tunnel (Nevada Test Site) prior to beginning field tests in the ESF. The prototype tests are being conducted in the Grouse Canyon welded tuff layer, which has properties similar to those expected for the Topopah Springs welded tuff unit in Yucca Mountain.[1] These prototype tests are designed to evaluate the performance of measurement techniques and hardware under conditions similar to those expected in the ESF. This paper describes briefly the results of the first of two prototype tests, which study the hydrothermal perturbation of welded tuff near a horizontally oriented heater. The test measured several parameters as a function of location and time to examine the effects of the heating and cooling during a thermal pulse that lasted approximately 28 weeks.

The hydrologic environment expected to develop around a heater during thermal loading is shown schematically in Fig. 1. In time, the heat will dry the partially saturated rock near the emplacement borehole. The water vapor formed will be driven by vapor pressure gradients through the matrix until it intersects a fracture; it will then move down-gradient along the fracture, as noted in the laboratory work.[2] The water vapor will condense where the temperatures are sufficiently cool. Part of this water might

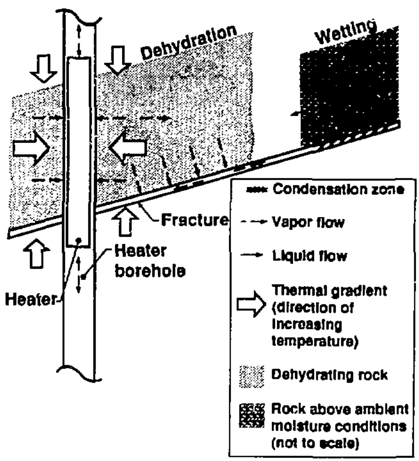

Figure 1. Schematic representation of a probable hydrologic scenario in partially saturated welded tuff subjected to a thermal load.

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move into the matrix due to capillary tension; the remainder might stay in the fracture held by capillary forces or it might flow along the fracture down-gradient. The percentage of water that moves into the matrix will depend on the degree of saturation of the matrix, the matrix hydraulic conductivity, and the contact time between fracture water and matrix. When the dried region is allowed to cool, it is expected to slowly rewet due to the pore pressure and saturation gradients that developed in the rock around the heater.

PARAMETERS MEASURED

The following parameters are being measured to characterize the behavior of the rock mass in the near field of a heater before, during, and after the thermal cycle. This paper briefly discusses results for a subset of the following parameters and presents interpretations pertaining to the evolution of the near-field environment around a simulated waste package.

- Rock mass temperatures will be used in reconstructing the thermal response of the rock and in evaluating the performance of the test equipment during the test.
- Rock mass gas pressure and atmospheric pressure are used in reconstructing the flow regime of the air and water vapor in the rock mass.
- Cross borehole measurements of the relative dielectric constant of the rock and single borehole measurements of thermal neutron counts are used to infer the spatial and temporal changes in the moisture content of the rock mass.
- Air humidity measurements in the rock mass are used to calculate the pore pressure gradients that drive the movement of liquid water within the rock mass. Changes in the moisture content and pore pressure information are used to reconstruct the flow regime of liquid water in the rock mass. The spatial variations in moisture content will be used to infer the flow paths of the liquid water and to define regions that are losing or gaining water as a function of time.
- The air permeability measurements are used to detect changes in the permeability of rock surrounding the emplacement borehole. These measurements were made along the heater borehole as soon as all other boreholes were drilled and sealed. The measurements will be repeated after the heating sequence is completed and the heater is removed from the borehole.
- Fracture locations and orientations have been measured in all the boreholes by borescope and/or borehole TV surveys performed before the heater was energized and will be repeated along the emplacement borehole after the test is completed. This information is needed to understand the effects of heating on the stability of the emplacement borehole walls, and to help intrepret the changes in fracture permeability caused by the heating and cooling cycle. It will also aid in interpreting the flow regime of vapor and liquid water in the rock mass as inferred from other measurements.
- The condensed volume of steam invading the heater borehole is being measured to obtain estimates of how much vapor flows toward the heater borehole.

This paper provides a summary of a much more detailed description of the test.[3] Other investigations related to the PEBSFT study presented at this conference are: changes in moisture content using cross-hole electromagnetic measurements[4]; use of a microwave resonator for in situ measurements of water vapor pressure[5]; and infiltration of a liquid front in unsaturated, fractured porous medium.[6]

TEST DESCRIPTION

An underground facility called the G-Tunnel Underground Facility (GTUF) has been constructed by the Sandia National Laboratories for the YMP. The GTUF consists of drifts in welded tuff under Rainier Mesa, Nevada Test Site. The prototype test was conducted in the rock mass between the Small Diameter Heater Alcove and the Rock Mechanics drifts.

The test includes an accelerated thermal cycle to examine the effects of the heating and cooling sides of a thermal pulse. Figure 2 shows the planned thermal loading history for the test. The initial thermal loading for the 3-m (9.8-ft) heater is approximately 3 kW (1 kW/m). This initial thermal load per unit length of emplacement borehole is set higher than the loading expected for a typical spent fuel container (0.4 to 0.7 kW/m) in an attempt to increase the volume of rock to be disturbed in the relatively short period available for prototype testing and to create sufficiently high rock temperatures to drive two-phase fluid flow. The duration of heating is based on the criteria of heating the rock mass such that the boiling point isotherm extends approximately 0.6–0.7 m (2.0–2.3 ft) radially from the heater borehole wall. This spatial extent of heating will affect a volume of rock large enough to include several fractures.

Figures 3 and 4 show the borehole layout and the measurement stations for the various instruments used. The test location within G-Tunnel is bounded by the Small Diameter Heater Alcove and the Rock Mechanics Incline, as shown in Fig. 3. The heater borehole is inclined slightly upward (elevation increases from the collar to the end of the borehole) from the Rock Mechanics Incline. The diameter of the heater borehole is 30.5 cm (12 in.).

The remaining 12 boreholes are used to monitor the rock response; all of these are near horizontal, inclined slightly downward. The majority of the boreholes are orthogonal to the emplacement hole axis, which provides better coverage of the spatial variations that develop parallel to the emplacement borehole radius. This arrangement allows measurements in the direction of expected maximum thermal and hydrologic gradients. Three boreholes were drilled parallel to the heater borehole axis to monitor rock response beyond the heater ends.

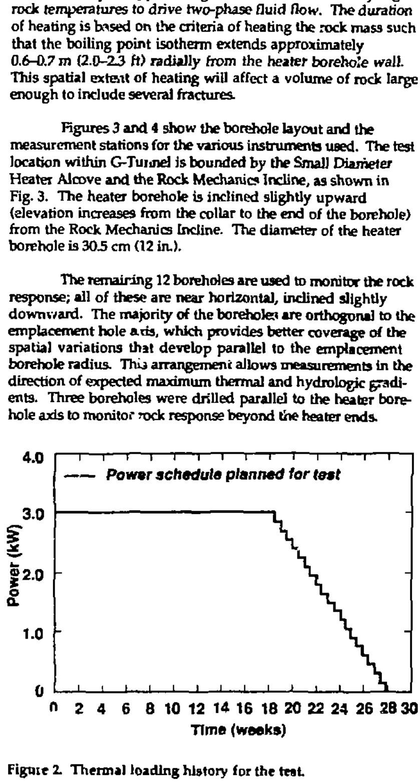

Figure 2. Thermal loading history for the test.

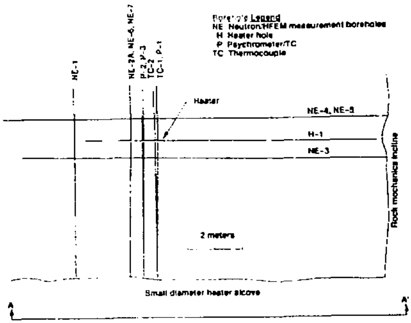

Figure 3. Plan view of the as-built borehole layout. The locations of the Rock Mechanics Incline and the Small Diameter Heater Alcove are shown for reference.

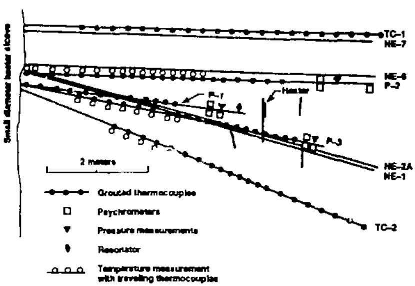

Figure 4. Cross-section view of the as-built borehole layout as viewed from the Rock Mechanics Incline. Also shown are the locations of various sensors grouted in place.

CHANGES IN ROCK MASS MOISTURE CONTENT

A thorough understanding of local hydrology over the package lifetime is central to understanding waste package performance. Geophysical techniques have been used to monitor changes in rock moisture content during the test to reduce the need for boreholes. The techniques chosen include neutron logging in single boreholes and high frequency electromagnetic measurements performed between boreholes. Daily et al.[4] describe the electromagnetic measurement results so this paper intreprets only the neutron log results.

The neutron logging probe contains a source of high-energy neutrons and a detector for slow (thermal) neutrons. Hydrogen present in water in the rock slows the neutrons for detection. Seven boreholes (NE1 through NE7) were sampled before the heater was turned on; the measurements were frequently repeated after the heater was energized to monitor temporal and spatial changes in moisture content. A paraffin shield included with the probe was sampled at the beginning and end of each logging day to verify that the tool was functioning properly.

For each borehole, we calculated the differences between the "before" and "after" measurements ("after" heating minus "before" heating) to produce a difference log. We have chosen to use differences rather than absolute values of moisture content because the effects of the borehole liners and grout within the survey boreholes have not been accounted for.

A spatial filter was applied to each difference log to smooth the spikes in the trace caused by the random fluctuations in the number of neutrons generated by the radioactive source in the probe. The precision for the filtered data is estimated to be ±0.0003 g/cc. This precision estimate means that for any one point on a difference trace that equals or exceeds ±0.003 g/cc, there is a 95% probability that the difference is caused by true changes in the measurement and a 5% probability that it is caused by random fluctuations in the neutron output of the radioactive source.

Figures 5 and 6 show the difference traces calculated from data obtained prior to November 1, 1988. Figure 5 shows the difference traces generated for borehole NE6. This borehole is orthogonal to the heater and above the heater approximately 0.7 m (2.3 ft) at the closest point of approach. Note that the September 12 trace (heater was energized September 7, 1988) shows that the moisture content above the heater slightly increased for 31 of the 32 points. The average value for the trace is approximately 0.002 g/cc, with an approximate error of ±0.0005 g/cc. The largest increases appear in rock that is above and to either side of the heater [the heater is located approximately below the 5-m (16.4-ft) mark], between the depths 3–4.1 m (9.8–13.4 ft) and 5.7–6.3 m (18.7–20.7 ft). This zone of increased saturation then decreases with time while the rock directly above the heater shows a drying trend (negative changes relative to preheating data).

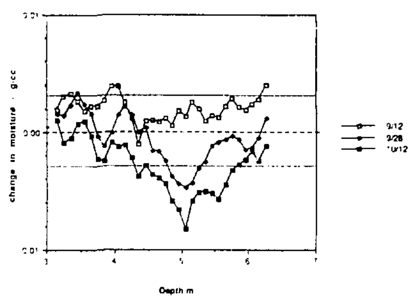

Figure 5. Changes in moisture content along borehole NE6.

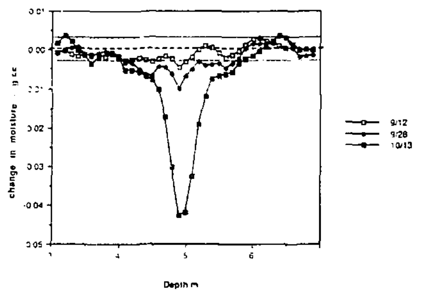

Figure 6. Changes in moisture content along borehole NE2a. Note differences in scale from Fig. 5.

Figure 6 shows that the difference traces for borehole NE2a tell a somewhat different story. This borehole is coplanar with boreholes NE6 and NE7 and is located approximately 0.55 m (1.8 ft) (at the closest point of approach) below the heater axis. Note that the September 12 trace does not show a general increase in moisture content like NE6 and NE7 showed. Instead, it shows an increase from 5.8 to 6.4 m (19 to 20 ft) and 5.3 to 5.4 m (17.4 to 17.7 ft), and a general decrease elsewhere. This drier region develops much faster than the drying zone near NE6 but has approximately the same width. The drying observed at this location is greater than that observed in NE6 by a factor of 4–5, and thus it is plotted at a smaller scale than the other figures.

Moisture content plotted versus radial distance (not shown due to space limitations) from the heater's center shows that, during the early stages of heating (5 days after start of heating), rock at higher elevations generally shows a higher increase in moisture content than rock below the heater at the same radial distance. This asymmetry in response was unexpected and the reason for it is unclear at present. It might be due to higher fracture density along NE2 than NE6. It might also be related to a higher initial moisture content (from drifting water) below the heater. It might also be an indication of the tendency of the steam to move upward preferentially due to buoyancy.

In summary, the neutron data for the rock directly above the heater shows an early wetting episode (i.e., increased moisture content), followed by slight drying episodes. The data from directly below the heater show evidence of a higher degree of drying early and then continues to dry with time. Rock to either side of the heater borehole, whether higher or lower in elevation than the heater, showed an early wetting episode that later dissipated. For locations closer to the heater, a drying episode followed, and for the rock farthest from the heater, continuing increases in moisture were observed.

TEMPERATURE MEASUREMENTS

The purpose of measuring temperature in this test was mostly to understand the thermal response of the medium around the heater. There are a total of 112 thermocouples used in this test. All of these thermocouples are chromel–alumel (Type K) with an accuracy of ±1°C (1.8°F).

Ten thermocouples were installed within the heated portion of the heater borehole to monitor container and borehole wall temperatures. The rest of the thermocouples (102 total) were in the thermocouple holes (TC1 and TC2) and the psychrometer holes (P1, P2, and P3). Figure 4 shows the distribution of thermocouples in the thermocouple holes and psychrometer holes. The thermocouples in each hole were bundled together and grouted in with a spacing of either 20 cm (7.9 in.) or 30 cm (11.8 in.), depending on the distance from the heater; shorter spacing was used where the thermocouples were within 1.5 m (4.9 ft) from the heater.

The temperature distribution around the heater hole and its variation as a function of time are presented in Figs. 7–9. Figure 7 shows the temperature distribution on a plane perpendicular to the heater at its midpoint on October 28, 1988. The contour lines are the interpolation of the temperature reading from the thermocouples. This set of data was taken at 1 p.m. on October 28, 1988. From Fig. 7, we see a greater thermal gradient region near the heater, which indicates heat transfer by conduction. The temperatures above the heater container are

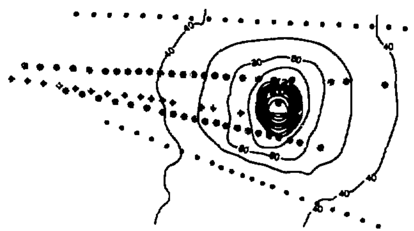

Figure 7. Temperature distribution on a plane perpendicular to the heater at its midpoint.

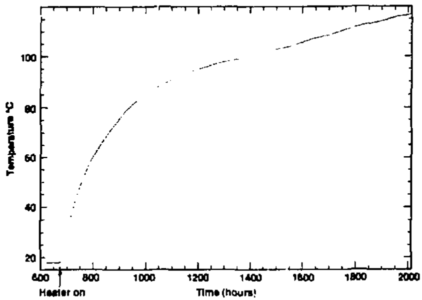

Figure 8. Temperature in the rock at a distance of about 0.4 m (1.3 ft) from the heater since the beginning of heating.

greater than those below the heater, which might be related to the temperature on top of the heater can being greater than that at the bottom. One should bear in mind that the contour diagram is for qualitative interpretation only, due to the limited number of data points and their uneven spatial distribution along the vertical direction.

Figure 8 shows the temperature in the rock at a distance about 0.4 m (1.3 ft) above the heater as a function of time. This thermocouple is in the rock and is closest to the heater. The temperature increased quickly at the beginning of heating, then became almost linear with time. At these later times, the temperature–time plot has no obvious increase of slope. A change in slope would indicate a change in the thermal conductivity and heat capacity of the rock. At later heating times, changes in slope might be attributed to the latent heat capacity of the water as the water boils or condenses in the rock mass. The subtle change in slope at a temperature just below 100°C might be due to boiling of water in the rock.

Another example of temperature evolution in time can be observed in Fig. 9. This figure shows how temperatures change in time and space. Temperatures in P3 (dotted lines) are consistently lower than those in P2 (solid lines). This is probably due to the hotter temperatures that developed at the top of the container. Air circulation within the heater container might have caused the asymmetry in temperatures.

There are a few temperature values (in both P2 and P3) that plot cooler than the remaining curve for values of the radial distance less than 1 m (3.3 ft). At these locations, fractures were mapped in close proximity (within a few centimeters) of the thermocouple locations. This close proximity suggests that the depressed temperature values near the heater borehole are caused by fractures. At least two explanations can be postulated. (1) The fractures create more permeable flow paths for vapor to escape the system. As water is converted to vapor and allowed to escape, energy is removed from these locations. This energy is therefore not available to elevate the rock temperatures. (2) The fractures also create flow paths along which drilling water moves downward. Borehole P3 is lower in elevation than P2. The matrix adjacent to these fractures might have imbibed some of the drill water, thereby increasing the initial saturation near the fractures.

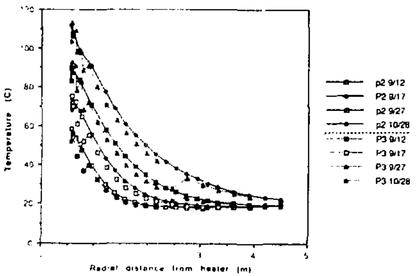

Figure 9. Evolution of temperature in P2 and P3 boreholes as a function of radial distance from the heater. Temperatures in P3 are systematically lower than in P2.

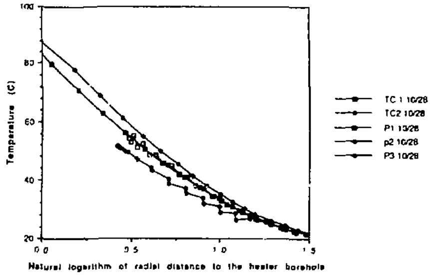

Figure 10. Temperature in various boreholes on October 28, 1989 as a function of radial distance from the heater.

This elevated saturation would also tend to depress the local temperature for the same reason stated in explanation 1.

Figure 10 compares temperature profiles for all boreholes 41 days after the heater was energized. The temperatures along borehole TC2 are generally cooler than those in other boreholes at the same radial distance. The temperatures in P2 are the highest among the five boreholes. TC1, P1, and P3 registered about the same temperatures. These differences in temperature are probably due to the heterogeneous thermal properties of the rock mass. The heterogeneity is also shown by the temperatures in TC2. There, the temperature difference from two thermocouples at similar radial distance is probably due to the two thermocouples monitoring different regions (i.e., adjacent thermocouples in Fig. 8 sample rock on opposing sides of the heater at approximately the same radial distance). The almost linear portion of these curves at small radial distances indicate that conduction is probably the main heat transfer mechanism. Also, the TC2 profile shows a more shallow slope, which implies that the thermal conductivity of the rock around TC2 is higher than at other locations.

A higher thermal conductivity might represent rock that has a higher initial saturation than surrounding areas. Supporting evidence for this hypothesis comes from cross-hole electromagnetic measurements that indicated a higher initial saturation below the heater than above.

STEAM INVADING HEATER BOREHOLE

The thermal loading exerted by the heater dries the partially saturated rock surrounding the emplacement borehole. Vapor pressure gradients drive water vapor into pressure sinks such as the emplacement borehole and fractures (refer to Fig. 1). The water vapor might also move along the fractures toward the emplacement hole or outward and condense where the temperatures are sufficiently cool. We are collecting the moisture entering the heater emplacement borehole to provide a measure of the resistance to vapor transport toward the heater relative to the resistance to transport away from the heater as a function of time.

The moisture migrating into the heater emplacement borehole was collected as shown in Fig. 11, using a high-temperature inflatable packer fitted to a 51-mm (2-in.) I. D.

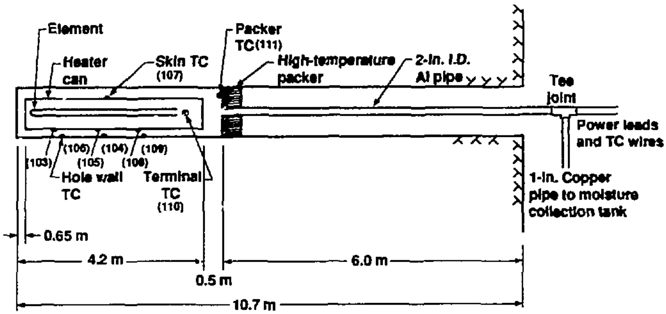

Figure 11. Moisture collection system and thermocouples in the heater borehole.

aluminum pipe. The packer sealed the borehole 50 cm (19.7 in.) outward from the heater and allowed the steam to flow through the aluminum center pipe, condense, and flow to the borehole collar and into a collection device. The heater emplacement borehole is sloping 5 degrees downward to the collar to facilitate the collection of the condensed moisture.

Figure 12 presents the results of water collection up to November 1, 1988, showing that an insignificant volume of water was collected within the first two weeks of the experiment. Thereafter, the rate of water collection is approximately 0.1 liter per day, which is less than the value predicted by the scoping calculation (approximately 0.5 liter per day).

The reasons for this discrepancy are unclear at present. One possible explanation is that the packer temperature at the intake point for the system is below the dew point. This might have caused some vapor to condense, pond, and possibly drain into fractures, instead of entering the center pipe at the packer. However, relative humidity measurements in the emplacement borehole using a sensor on the back surface of the packer show

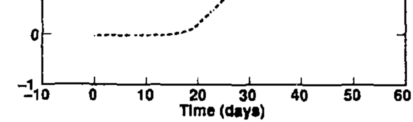

Figure 12. Moisture collection as function of time.

that the relative humidity remained below 100 percent, except during the first four days of heating. On the other hand, the temperatures measured directly on the packer near the borehole wall are generally about 9°C lower than the Humicap temperatures. These results suggest that (following the first four days of heating) no condensation occurred at the Humicap location, yet temperatures at some points on the packer were below the dew point, and condensation might have occurred at those points. Another possible reason for the discrepancy is that the scoping calculations assume an infinitely long heater. This assumption would cause a substantial overestimate of the steam produced. Additional work is in progress to evaluate the impact of this assumption.

PRELIMINARY SCOPING CALCULATIONS OF HYDROTHERMAL FLOW

The fractures in densely welded tuff have been observed to be major conduits for fluid flow and must be accounted for in the near-field hydrothermal model. Because of the low rate of surface recharge to the formation, the rock at the PEBSFT horizon is only partially saturated, and multiphase flow of air, water vapor, and liquid water is therefore possible. As shown in Fig. 1, heat generated by the waste package can lead to water vaporization and vapor flow in the matrix and fractures. Condensation of this vapor outside the boiling zone and capillary-driven flow of liquid water can result in the development of a "heat-pipe". To account for these conductive, convective, and latent heat transport mechanisms, we use the integral finite difference code TOUGH.[7,8,9]

We have conceptualized the physical medium as a discrete fracture/matrix system. As such, we utilize distinct fracture and matrix properties obtained from Topopah Springs tuff because it is similar to the formation found in G-Tunnel. This approach is well suited to small-scale systems in which the fracture spacing is large in comparison to the scale of the simulation domain. Because our calculations are to be used in assuring that the instruments surrounding the heater are adequately sensitive to the range of pressures, temperatures, and saturations to be encountered, our model must be sufficiently resolved to indicate small-scale variations.

All numerical calculations were done using LLNL's version of the TOUGH (transport of unsaturated groundwater and heat) code. TOUGH is a multidimensional numerical *simulator capable of modeling the coupled transport of water,* vapor, air, and heat in fractured porous media.

The following are key observations made during the PEBSFT scoping calculations study (details are presented by Buscheck and Nitao).[10]

- Fracture spacing strongly affects moisture redistribution; the volume of vaporized water as well as water in the condensation halo increase with fracture density.
- Hydrothermal flow is not sensitive to fracture permeability for the range of observed fracture apertures (and permeability).
- Rock temperatures during the heating cycle are inversely proportional to initial saturation until the water is boiled away.
- The spatial extent of boiling increase with matrix permeability.
- Heater borehole communication with the drift (i.e., venting) affects the volume of water vapor remaining within the PEBSFT.

DISCUSSION AND PRELIMINARY INTERPRETATIONS OF RESULTS

The PEBSFT has provided valuable experience that improves our ability to conduct the EBSFT for the ESF in Yucca Mountain. Results to date have shown that many environmental conditions expected to develop around a heater in welded tuff are as described in the Introduction (see Yow[10] for additional details on expected environmental conditions). The test has also shown which of the applied measurement techniques performed adequately under realistic environmental conditions and which techniques might need to be modified or replaced. The test has also realistically evaluated the effectiveness of Quality Assurance Procedures for use in the ESF.

WASTE PACKAGE ENVIRONMENT

The test confirmed elements of the conceptual model of predicted environmental conditions. Test results confirm that a dry zone develops around the heater borehole, and the degree of drying increases with proximity to the heater. A "halo" of increased saturation develops adjacent to the dry region and migrates away from the heater as rock temperatures increase. Some of the fractures intercepting the heater borehole increase the penetration of hot-dry conditions into the rock mass. A build-up of pore gas pressure develops in rock regions where vigorous evaporation is occurring. The air permeability of the fracture system exhibits a strong heterogeneity.

The test also yielded some surprises in terms of environmental conditions. The temperature above the heater container is approximately 30°C (54°F) higher than below the container. This condition might be a consequence of hotter air accumulating at the top of the container; it might also be related to the higher moisture content present below the heater borehole. The amount of steam predicted by scoping calculations to invade the heater borehole is much less than that expected. The reason(s) for this discrepancy is not known at present; it might be a consequence of an inadequate system used to collect and condense the steam or a result of the calculation's assumption that the heater was infinitely long.

INSTRUMENTATION PERFORMANCE TO DATE

The instrumentation performance for the various sensors *used exhibits considerable variability. As expected,* temperature measurements made with thermocouples and RTDs show that both types of sensors are sufficiently rugged and accurate. Similarly, the neutron and gamma ray tools were rugged enough to withstand temperatures up to 70°C (manufacturer's specification); in borehole locations where temperatures above 70°C exist, the probe is removed periodically to allow probe temperatures to drop below 70°C. Another sensor exhibiting reliable performance is the Humicap capacitance sensor used to measure air humidity in the heater borehole.

Laboratory measurements of air humidity made with the microwave resonator showed that, in principle, the technique is sufficiently sensitive. However, field results suggest that the calibration curves have shifted. The reason for these shifts is not well understood. These resonators will be recovered upon test completion for further evaluation and testing. Air humidity measurements made with thermocouple psychrometers appear to imply a hydrologic scenario consistent, in a qualitative sense, with that expected a priori. However, at present, it has not been demonstrated that these sensors can provide absolute measurements of suction over the range of relevant temperature conditions. Gas pressure transducers used during the early part of the test showed a significant change in calibration characteristics as the pressures changed. These sensors have been replaced with those from a different manufacturer and the problem appears to have been solved.

FUTURE PLANS

The test will continue at maximum heater output until rock temperatures 0.7 m (2.3 ft) radially from the heater container have reached approximately 120°C (248°F). At that time, the heater output will be gradually decreased to create "cool down" conditions. Measurements will continue for approximately 2–3 months after the heater has been turned off. After that, a few of the test boreholes will be overcored to recover sensors, grout/liner seals, and rock samples that might have been perturbed by the test for post-test examinations. The numerical simulations will be repeated assuming a heater of finite length. Upon the completion of the PEBSFT Horizontal Emplacement, a second prototype test will be conducted using a vertical borehole in welded tuff for heater emplacement.

ACKNOWLEDGEMENTS

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