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Prototype Heater Test of the Environment

Around a Simulated Waste Package

Abelardo L. Ramirez, Thomas A. Buscheck, Richard Carlson, William Daily,
V. Robert Latorre, Kenrick Lee, Wunan Lin, Nai-hsien Mao, Donald Towse,
Tzou-Shin Ueng, and Donald Watwood

Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, California 94550
415/422-6909

ABSTRACT

This paper presents selected results obtained during the 301 day duration of the Prototype Engineered Barrier System Field Test (PEBSFT) performed in G-Tunnel within the Nevada Test Site. The test described is a precursor to the Engineered Barrier Systems Field Tests (EBSFT) planned for the Exploratory Shaft Facility in Yucca Mountain. 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 paper discusses the evolution of hydrothermal behavior during the prototype test, including rock temperatures, changes in rock moisture content, air permeability of fractures, and gas-phase humidity in the heater borehole.

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INTRODUCTION

The Engineered Barrier Systems Field Tests (EBSFT) consist of in situ tests of the geohydrologic environment near heaters emplaced in welded tuff. As part of the Yucca Mountain Project (YMP) testing program in the Exploratory Shaft Facility (ESF), a series of 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 evaluate the

evolution of the post-closure repository environment with which the waste packages must interact. The information on the post-closure environment will be used as boundary conditions in designing the waste packages and in assessing their performance.

Prototype tests have been conducted in G-Tunnel (Nevada Test Site) prior to beginning field tests in the Exploratory Shaft Facility. The prototype tests were 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 (Zimmerman and Finley, 1985). These prototype tests were designed to evaluate the performance of measurement techniques and hardware under conditions similar to those expected in the ESF. This report will describe briefly the results of a prototype test that studied 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 heating and cooling during a thermal pulse which lasted approximately 195 days.

The hydrologic environment expected to develop around a heater during thermal loading is shown schematically in Fig. 1. With time, the heat will dry the partially saturated rock near the emplacement borehole. The steam 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 laboratory work performed by Daily et al. (1986). Steam will condense where the temperatures are sufficiently cool. Part of this water might move into the matrix due to capillary tension; the remainder might stay in the fracture held by capillary forces or it

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Figure 1. Schematic vertical cross-section of a probable hydrologic scenario in partially saturated welded tuff subjected to a thermal load.

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 re-wet due to the pore pressure and saturation gradients that develop in the rock around the heater.

PARAMETERS MEASURED

The following parameters were measured to characterize the behavior of the rock mass within a few meters of the heater before, during, and after the thermal cycle. The paper will briefly discuss results for a subset of the following parameters, and present interpretations pertaining to the evolution of the near field environment around a simulated waste package.

- Rock mass temperatures were 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 were used in reconstructing the flow regime of the air and water vapor in the rock mass.

Figure 2. Heater power schedule used for the test.

- Cross borehole measurements of the relative dielectric constant of the rock, and single borehole measurements of thermal neutron counts were used to infer the spatial and temporal changes in the moisture content of the rock mass.
- Air humidity measurements in the rock mass were 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 were 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 were 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 the other boreholes were drilled and sealed. The measurements were repeated after the heating sequence was completed and the heater was removed from the borehole.
- Fracture locations and orientations were measured in all the boreholes by borescope and/or borehole TV surveys performed before the heater was energized. The measurements were repeated along the heater emplacement borehole after heating was completed. This information was needed to understand the

effects of heating on the stability of the emplacement borehole walls, and to help interpret the changes in fracture permeability caused by the heating and cooling cycle. It also aids 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 was measured to estimate how much gas phase humidity flows towards the heater borehole.

This paper provides a small sample of all the data collected to illustrate some of the key observations. Other investigations related to the PEBSFT study are described by Daily et. al., 1989 (changes in moisture content using cross hole electromagnetic measurements), by Latorre, 1989 (use of a microwave resonator for in situ measurements of water vapor pressure), and by Nitao and Buscheck, 1989 (infiltration of a liquid front in an unsaturated, fractured porous medium).

TEST DESCRIPTION

An underground facility called the G-Tunnel Underground Facility (GTUF) has been constructed by the Sandia National Laboratories for the Yucca Mountain Project (YMP). The GTUF consists of drifts driven in welded tuff under Rainier Mesa, Nevada Test Site.

Figure 3. Plan view of the as-built borehole layout. The various line patterns identify the type of measurement made in each borehole. The locations of the Rock Mechanics Incline and the Small Diameter Heater Alcove in G-Tunnel are shown for reference.

Figure 4. Side view of the as-built borehole layout as viewed from the Rock Mechanics Incline. The various line patterns identify the type of measurement made in each borehole.

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 power schedule used for the test. The initial thermal loading for the 3-m (9.8-ft.) heater was approximately 3.3 kW (1.1 kW per meter of heater length). This initial thermal load per unit length of emplacement borehole was 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 disturbed volume of rock within the relatively short period available for prototype testing, and to create rock temperatures high enough to drive two-phase fluid flow. The duration of heating was based on the criteria of heating the rock mass such that the boiling point isotherm moved approximately 0.6-0.7 m (2.0-2.3 ft.) radially from the heater borehole wall. Another criteria was to achieve emplacement heater borehole temperatures similar to those expected for the repository (235° C). The spatial extent of heating affected 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 Figure 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 12 in. (30.5 cm).

The remaining 12 boreholes were 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 in order to provide better coverage of the

Figure 5. Changes in moisture content plotted against radial distance after 70 days of heating (approximately midway through the maximum power phase). The right hand plot shows an enlarged view of a subset of the curves on the left plot. Changes are calculated relative to pre-heating moisture conditions.

response that develops radially around the emplacement borehole. This arrangement allowed 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 ends of the heater.

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 were used to monitor changes in rock moisture content during the test. The techniques chosen included neutron logging in single boreholes and high frequency electromagnetic measurements performed between boreholes. Daily et al (1989) described the electromagnetic measurement results. This paper will interpret 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 repeated frequently 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 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 ± 0.003 grams per cubic centimeter (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 radial profiles of changes in moisture content during the drying and re-wetting phases of the test. Figures 5 and 6 show the difference traces calculated from day 70 data (heater energized on day 0) and for day 301 (last set of data collected 106 days after the heater was de-energized). Boreholes NE-2A, NE-6 and NE-7 are three coplanar boreholes located above and below the center of the heater as shown in Figure 4. The data collected along these boreholes were combined and plotted as a function of radial distance to the center point of the heater assembly. The changes shown were calculated relative to pre-heating

Figure 6. Changes in moisture content plotted against radial distance for the next to last day of maximum power heating. The right hand plot shows an enlarged view of a subset of the curves on the left plot. Changes are relative to pre-heating moisture conditions.

Figure 7. Changes in moisture content plotted against radial distance 301 days after start of heating (106 days after heater was de-energized). The right hand plot shows an enlarged view of a subset of the curves on the left plot. Changes are calculated relative to pre-heating moisture conditions.

moisture measurements. Each figure consists of two plots which show the same data at two different scales so that the smaller changes which occur at the more distant locations can be observed.

Figure 5 shows a radial profile of moisture content change seventy days after the heater was energized. This data set was collected midway through the maximum power phase of the test. As expected, the rock closest to the heater is losing substantial amounts of moisture. However, the rock near borehole NE-2A is drying at a faster rate than the rock near NE-6. Fracture maps of the test region suggest that a higher concentration of fractures mapped along NE-2A may be one cause for this

faster rate of drying. Also note that rock located between 1.75 and 2.25 m radii shows an increased moisture content as a result of condensation of steam generated in hotter regions closer to the heater.

Between days 70 and 127 (data not shown due to space limitations) the NE-2A profile showed very little additional drying when compared to Figure 5, while the NE-6 profile showed significant additional drying. Both profiles were now closely matched with the caveat that the width of the drying region appeared to be slightly wider near NE-2A. The closely matched profiles suggest that the rock near NE-2A and NE-6 was almost completely dry because very little additional drying occurred near

Figure 7. Changes in moisture content plotted against radial distance 301 days after start of heating (106 days after heater was de-energized). The right hand plot shows an enlarged view of a subset of the curves on the left plot. Changes are calculated relative to pre-heating moisture conditions.

NE-2A during a 57 day period when the heater continued operating at maximum power. The radius of the dry zone achieved was approximately 0.7 m; this is consistent with the test objective of achieving boiling conditions within a 0.6-0.7 m radius.

The radial profile of changes in moisture content for day 301 are shown in Figure 7. This data set was collected during the post heating phase of the test, 106 days after the heater was de-energized. The data show that the rock near the heater has changed relatively little during the power ramp-down and post-heating phase of the test. It also shows that the rock above the heater (borehole NE-6) is re-wetting faster than the rock below the heater (borehole NE-2A). This suggests that gravity-driven flow is playing a role in the re-wetting process.

Further insights into the re-wetting process can be gained by calculating changes in moisture content relative to the last day of full power heating. Figure 8 presents changes in moisture in borehole NE-2A, where "after" minus "before" changes are calculated relative to day 127 (i.e., the "before" data corresponds to day 127 which was the next to last day of maximum power heating as shown in Figure 2). The data were obtained during the power ramp-down and post heating phases of the test when the rock was cooling and re-wetting. Also shown are fractures mapped along the boreholes. Note that the rock regions that show the largest re-wetting are clustered around the fractures in NE-2A. The high degree of correlation between fracture locations and high re-wetting suggests that fractures play a dominant role in the re-wetting process. It is suggested that a mechanism for re-wetting along

fractures is capillary condensation of air humidity in the fractures because humid air (found in the wetter portions of the rock mass) can travel with relative ease along the fractures. Another mechanism that may play a role in the re-wetting process is water drips (i.e., gravity-driven flow) along fractures; Figure 7 shows evidence consistent with this argument in that the re-wetting front is penetrating faster above the heater (borehole NE-6) than below the heater (NE-2A).

TEMPERATURE MEASUREMENTS

Temperatures were measured to understand the thermal response of the medium around the heater. A total of 112 thermocouples were used in this test. All of these thermocouples were chromel-alumel (Type K) with an accuracy of $\pm 1^\circ \text{C}$ (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 boreholes TC-1, TC-2, P-1, P-2, and P-3.

Figure 8 shows the temperatures measured in all boreholes during the last day of the maximum power phase (day 128). The temperatures are plotted as a function of the natural log of radial distance to observe the degree of linearity of the temperature profiles. Note that with the exception of the P-3 profile, all profiles are fairly linear. This indicates that thermal conduction is the dominant heat transfer mechanism for the regions sampled. There are a few temperature values (in both P-2 and P-3) that deviate from a straight line for values of the

Figure 8. Changes in moisture content mapped along borehole NE-2A. Changes are calculated relative to the last day of full power heating. Fractures mapped are shown for comparison.

Figure 9. Temperatures in various boreholes measured during the last day of full power heating

Figure 10 shows thermocouple locations relative to the heater. Data for thermocouples 86 to 89 are shown in Figure 11.

radial distance less than 1 m (natural log less than 0). 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 within the boiling region 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 P-3 is lower in elevation than P-2. The matrix adjacent to these fractures might have imbibed some of the drill water, thereby increasing the initial saturation near the fractures. This elevated saturation would also tend to depress the local temperature for the same reason as stated in explanation 1.

The temperatures along borehole TC-2 are generally cooler than those in other boreholes at the same radial distance. The temperatures in P-2 are the highest among the five boreholes. TC-1, P-1, and P-3 registered about the same temperatures. These differences in temperature are probably due to the somewhat heterogeneous thermal properties of the rock mass. The almost linear portion of these curves at the longer radial distances indicates that conduction is probably the main heat transfer mechanism. Also, the TC-2 profile shows a more

shallow slope, which implies that the thermal conductivity of the rock around TC-2 is higher than at other locations.

A comparison of the P-2 and P-3 temperature profiles in Figure 9 will show that the temperatures in P-3 are consistently lower than those in P-2. This is probably due to the hotter temperatures which were measured at the top of the container. Air circulation within the heater container (i.e., hotter air going to the top of the container) may have caused the asymmetry in temperatures.

Figure 11 shows the temperatures for thermocouples 86 through 89 as a function of time. These thermocouples are located below and to the side of the heater, as shown in Figure 10. Thermocouples 86 and 87 show typical profiles of temperatures within the boiling region. 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 change 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 may be attributed to the latent heat capacity of the water as the water boils or condenses in the rock mass.

Thermocouples 88 and 89 in Figure 11 show very atypical temperature profiles. Note that the maximum temperature for both profiles is

Figure 11. Evolution of selected temperatures in P-3 borehole as a function of time. Thermocouples 88 and 89 show a flattening of the profiles between days 50 and 150 which may be due to the movement of condensed water in this region.

approximately 97° C. Also the profiles remain near the maximum temperature for a period of 70 or more days even though the rest of the rock mass continues to increase in temperature during this period (maximum power phase). In addition, the slope on the left side of the flattened portions of these two profiles rapidly increases before the flattening occurred. This indicates that additional energy is being deposited at these locations. It is postulated that condensed water with near-boiling temperature is moving into this region from regions above the heater as illustrated by the conceptual model presented in Figure 12. The possibility that this type of temperature signature is due to a heat pipe effect is recognized, but it is considered unlikely based on the rapid increase in slope observed prior to the flattening.

CHANGES IN AIR PERMEABILITY

Air permeability testing was conducted along sections of the heater emplacement borehole before heating and at the end of the power ramp-down phase of the test. The objectives of these tests were to characterize the in-situ permeability of the fractured tuff around the heater borehole and to determine the effect of a heating and cooling cycle on rock mass permeability.

Steady-state air injection testing was the method used to measure permeability. Through the use of inflatable packers, pre-selected sections of the borehole were isolated for testing. Pre-heating and post-heating permeability values are compared in

Figure 12. Conceptual model proposed as an explanation for the atypical temperatures shown by thermocouples 88 and 89 (shown in Figure 10). Also shown is the increased region of the drying and wetting fronts along the fracture.

Figure 13. Equivalent porous medium permeabilities along the heater borehole are also compared with mapped fracture locations. The permeabilities shown here were measured at a nominal pressure of 34 KPa (5 psi). The permeability of a 36-cm (14.2-in.) long test zone varies from a minimum of 0.04 Darcy to a maximum of 150 Darcies. The higher permeability value corresponds to a highly fractured zone, a few inches thick, at a depth of about 7.7 m (25.3 ft.) from the collar.

A comparison of the pre- and post-heating profiles in Figure 13 shows that portions of the measured region had increases in gas permeability as a result of the heating cycle. Note that the largest percent change occurred near the center of the heater element location. This is also the portion of the borehole with fewest fractures mapped. It is postulated that the increase in permeability is due to an increase in the number of small fractures (micro cracks) intercepting the heater borehole. Television surveys of the borehole showed no change in the visible fractures relative to the pre-heating survey. This implies that any new fractures created would have to be small enough to escape detection. Given that the smallest permeabilities were measured in the region of greatest change, increases in micro fractures would have a relatively larger effect than in regions with a higher pre-heating permeability. Note that the increases in permeability are small when compared to the natural heterogeneity in air permeability along the borehole.

STEAM INVADING HEATER BOREHOLE

The thermal loading exerted by the heater dries the partially saturated rock surrounding the emplacement borehole. Vapor pressure gradients drive steam into pressure sinks such as the emplacement borehole and fractures (refer to Figure

Figure 13. Gas permeability measurements made along the heater borehole before and after heating.

1). Steam may also move along the fractures toward the emplacement hole or move outward and condense where the temperatures are sufficiently cool. The moisture entering the heater emplacement borehole was collected to provide a measure of the resistance to vapor transport towards 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 using a high-temperature inflatable packer fitted to a 51-mm (2-in.) I. D. aluminum pipe. The packer sealed the borehole 50 cm (19.7 in.) outward (i.e., towards the collar) 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 isolated section remained unpressurized at all times). The heater emplacement borehole is sloping 5 degrees downward to the collar to facilitate the collection of the condensed moisture.

Figure 14 presents the results of water collection rate during the test. Also shown for comparison is the partial pressure of water within 15 cm of the intake for the water collection system; the partial pressure values are calculated based on relative humidity and air temperature measurements. The data show that: an insignificant volume of water was collected within the first two weeks of the experiment. Thereafter, the rate of water collection reached a maximum of approximately 0.1 liters per

Figure 14. Moisture collection rate and partial pressure of water in the heater borehole air as function of time.

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. Temperatures at some points on the packer suggest that packer surfaces could have acted as condensation 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.

The water collection rate in Figure 14 peaked at about day 50 and then decreased between day 50 and 90. This decrease in moisture collection rate was unexpected and is not understood at the time of writing. Note that the partial pressure of water in the air remained approximately constant between days 50 and 125. All other conditions being equal, it was expected that the moisture collection rate should have remained constant if the partial pressure of the air in the heater borehole remained constant. The partial pressure of water started to decrease as expected on day 125 when the power ramp-down phase began. Another unexplained aspect of the moisture collection rate is the abrupt rate decrease

Figure 15. Proposed conceptual model of mechanisms which affect the re-wetting process of rock around a heater.

at about day 90. This signature may be an indication of problems with the sensor; however, post-test calibration of the sensor did not indicate that the sensor was flawed.

SUMMARY

This paper presents a brief overview of results obtained during the first Prototype Engineered Barrier System Field Test (PEBSFT), recently completed in G-Tunnel within the Nevada Test Site. The PEBSFT described in this report has provided valuable experience that improves our ability to conduct the Engineered Barrier System Field Tests planned for the Exploratory Shaft Facility in Yucca Mountain. The results to date from the PEBSFT have shown that many environmental conditions expected to develop around a heater in welded tuff are as described in Figure 1 (see Yow, 1985 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 included an accelerated thermal cycle to examine the effects of the heating and cooling sides of a thermal pulse. The initial thermal loading for the 3-m (9.8-ft.) heater was approximately 3 kW (1 kW/m) and lasted 127 days. This initial thermal load per unit length of emplacement borehole was 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 this heating period was based on the criteria of heating the rock mass such that the boiling point isotherm

moved approximately 0.6-0.7 m (2.0-2.3 ft) radially from the heater borehole wall. This spatial extent of heating affected a volume of rock large enough to include several fractures. Subsequently, the heater power was gradually decreased to 0.0 kW over a 68 day period. The total duration of the heating cycle was 195 days.

The test described here has provided valuable experience that improves our ability to conduct the Engineered Barrier System Field Tests planned for the Exploratory Shaft Facility in Yucca Mountain. The test confirmed elements of the conceptual model of predicted environmental conditions. Test results confirm that a dry zone develops around the heater borehole (refer to conceptual model in Figure 12), 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. During the portions of the test when the heater power was gradually reduced and eventually turned off the dry region around the heater cooled off and slowly regained water (refer to conceptual model in Figure 15). A suction pressure gradient formed between regions depleted of water and regions further from the heater that contained more water. Re-wetting of the dry region occurs fastest in rock above the heater and in rock adjacent to fractures (fracture dominated re-wetting has been previously reported by Daily and Ramirez, 1989). It is suggested that fractures accelerate re-wetting by one or more of the following mechanisms: a) provide flowpaths for humid air to come in contact with the dry region so that capillary condensation occurs along the fracture face, b) allow binary diffusion of

the air humidity from the fracture to the dry matrix and, c) provide flow paths for water drips coming from saturated regions above the heater. Measurements of air permeability made along the heater borehole prior to heating show that the fracture system exhibits a strong heterogeneity in fracture permeability. Measurements made after the heater was turned off show that there was a general (but small) increase in air permeability for the rock that reached the hottest temperatures.

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 caused by an air convection cell established within the container; it may 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 clearly understood; it might be a consequence of an inadequate system used to collect and condense the steam or an indication of invalid assumptions used in the scoping calculations.

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REFERENCES

- Buscheck, T. A. and J. J. Nitao (1987), "Fluid Flow Modeling," in Institutional Research and Development, FY86 Annual Report, UCRL-53689-86, Lawrence Livermore National Laboratory, Livermore, CA, pp. 48-49.
- Daily, W., W. Lin, and T. Buscheck (1989), "Hydrology of Topopah Spring Tuff -- Laboratory Measurements," J. Geophys. Res., Vol. 92, No. B8, pp. 7854-7864.
- Daily, W., A. Ramirez, and T. Ueng, (1989), "High Frequency Electromagnetic Tomography to Study Near Field Hydrology", UCRL-101866, Lawrence Livermore National Laboratory, Livermore, CA.
- Daily, W., and A. Ramirez, (1989), "Evaluation of Electromagnetic Tomography to Map In Situ Water in

Heated Welded Tuff", Water Resources Research, vol. 25, no. 6, pp. 1083-1096, June 1983.

Latorre, V. R. (1989), "Microwave Measurements of Water Vapor Partial Pressure at Temperatures up to 350 C," UCRL-101866, Lawrence Livermore National Laboratory, Livermore, CA.

Ramirez, A. L., J. Beatty, T. A. Buscheck, R. Carlson, W. Daily, V. R. Latorre, K. Lee, W. Lin, N. Mao, J. J. Nitao, D. Towse, T. Ueng, D. Watwood, and D. Wilder (1989), "Prototype Engineered Barrier System Field Test Progress Report", UCRL-101615, Lawrence Livermore National Laboratory, Livermore, CA.

Yow, J. Jr. (1985), "Concept for Waste Package Environment Tests in the Yucca Mountain Exploratory Shaft," UCID-20450, Lawrence Livermore National Laboratory, Livermore, CA.

Zimmerman, R. M. and R. E. Finley (1986) "Summary of Geomechanical Measurements Taken in and Around the G-Tunnel Underground Facility, NTS," SAND86-1015, Sandia National Laboratories, Albuquerque, NM, 143p.