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FIRST PHASE OF SMALL DIAMETER HEATER EXPERIMENTS IN TUFF

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ABSTRACT

As part of the Nevada Nuclear Waste Storage Investigations (NNWSI) project, we have undertaken small diameter heater experiments in the G-Tunnel Underground Facility on the Nevada Test Site (NTS). These experiments are to evaluate the thermal and hydrothermal behavior which might be encountered if heat producing nuclear waste were disposed of in welded and nonwelded tuffs. The two Phase I experiments discussed have focused on vertical borehole emplacements.

In each experiment, temperatures were measured along the surface of the 10.2 cm diameter heater and the 12.7 cm diameter boreholes. For each experiment, measurements were compared with computer model representations. Maximum temperatures reached were: 196°C for the welded tuff after 21 days of operations at 800W and 173°C for the nonwelded tuff after 35 days of operations at 500W. Computed results indicate that the same heat transfer model (includes conduction and radiation only) can describe the behavior of both tuffs using empirical techniques to describe pore water vaporization.

Hydrothermal measurements revealed heat-induced water migration. Results indicated that small amounts of liquid water migrated into the welded tuff borehole early in the heating period. Once the rock-wall temperatures exceeded 94°C, in both tuffs, there was mass transport of water vapor as evidence indicated condensation cooler regions. Borehole pressures remained essentially ambient during the thermal periods.

INTRODUCTION

Volcanic tuffs on and adjacent to the Nevada Test Site (NTS) are being considered by the Department of Energy (DOE) for the possible geologic disposal of commercial high level radioactive wastes. The Nevada Nuclear Waste Storage Investigations (NNWSI) project was established by DOE in 1977 to evaluate such disposal. Sandia National Laboratories, one of the participants in the NNWSI project, has as one of its responsibilities the development of the rock mechanics program to support the design of a repository in tuff. This program includes evaluations of the thermal, mechanical, and hydrothermal (heat-induced water migration) effects on the surrounding rock resulting from excavating the repository and emplacing the nuclear waste.

The rock mechanics field program has begun in the G-Tunnel Underground Facility; later experiments are to be incorporated into investigations in Yucca Mountain, the potential candidate repository site, when access can be provided. This paper reports on the results of the first two field experiments in the rock mechanics program, the Phase I small diameter heater experiments. These small diameter heater experiments are scheduled for G-tunnel, in two phases (Zimmerman 1982). Phase I experiments are intended to reveal the pertinent thermal (heat transfer) and hydrothermal behavior of welded tuffs (porosity< 25%, relatively unjointed, ductile rock) and nonwelded tuffs (porosity > 25%, relatively unjointed ductile rock). Both types of tuff are present in Yucca Mountain and determination of phenomena important to waste disposal are needed. At least one Phase II experiment is planned to evaluate emplacement concepts in welded tuff. All experiments are designed to define the thermal and hydrothermal behavior so findings can be incorporated into the design of more elaborate canister-scale experiments which emphasize thermomechanical responses. Results from these two phases of small diameter heater experiments also support NNWSI repository design efforts by providing preliminary field evaluations of heat transfer models. Thermal and hydrothermal data also aid in definition of the waste package environment.

SCOPE

Experiments were designed to evaluate the phenomena that occurred in a vertical waste emplacement borehole in a simulated nuclear waste repository-like setting. Temperature measurements were made along the length of the heater and borehole wall to evaluate the effects on heat transfer resulting from dewatering the partially initially saturated (~80 to 95%) tuffs. Hydrothermal measurements included determining the borehole pressure and the quantities of water in the bottom of the borehole as well as observing where vapor had condensed in the total system.

This paper summarizes the results for the Phase I experiments and evaluates the adequacy of available empirical heat transfer models. The emphasis is on the measurement results and evaluations rather than on instrumentation and hardware functioning, although components are described for completeness.

EXPERIMENTAL SETUP

Components

The experimental setup is shown in Figure 1. At the lower end is the stainless steel heater unit (HU), a self-contained unit made up of the heated section (1.2 m), insulated section (next 0.6 m), terminal section (for electrical connections), and the handling pipe. The heater unit is 10.2 cm in diameter. Immediately above the heater are aluminum honeycomb segments, 11.4 cm in diameter, used as a space filler to minimize convection.

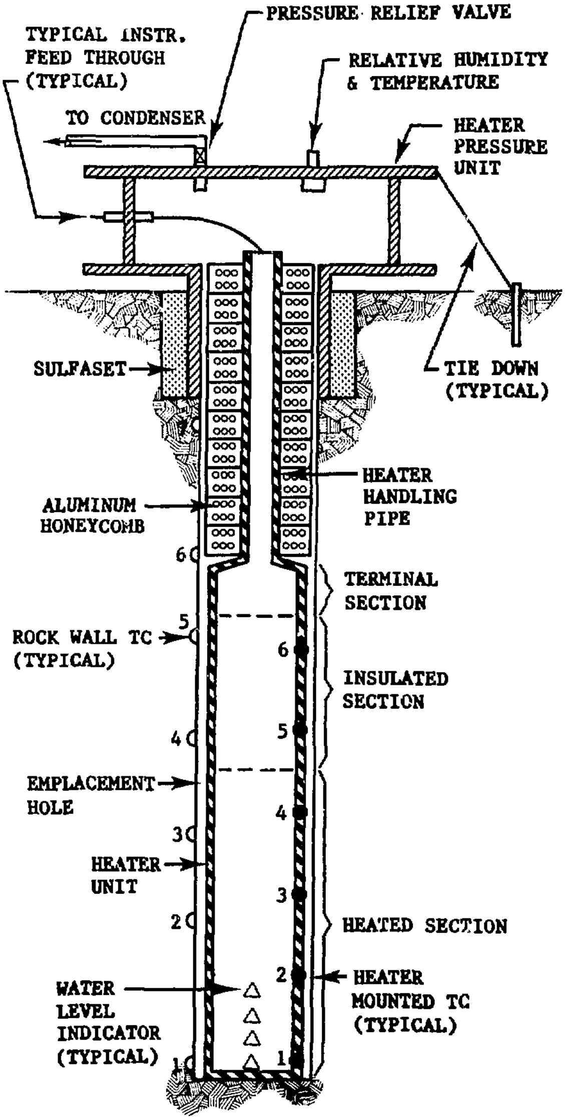

Figure 1. Small Diameter Heater Section

At the top is the heater pressure unit (HPU). This aluminum unit is attached to a collar, which is bonded to the emplacement hole with Sulfaset. The heater pressure unit contains feed-throughs for all borehole instrumentation so that a pressure seal can be maintained within the borehole.

Emplacement holes were slightly different for each of the experiments, but the diameters were a constant 12.7 cm. The hole in welded tuff was in a fractured, brittle material. A design requirement was that the bottom 0.3 m be in intact rock to minimize water loss through fractures. It was necessary to drill the hole 3.2 m deep to achieve this. The welded tuff hole was significantly fractured above this level. The hole in nonwelded tuff was 2.4 m deep. This hole was unfractured over the heated length.

Measurements

The heater unit contained three different measurement systems. Six thermocouples were located on each of three lines spaced at 120° around the periphery for the heater surface measurements. Vertical locations are provided in Table 1. Five thermocouples were placed inside the heater as part of the second system. The third measurement system consisted of surface water level sensors, placed along the lower 38 cm of the heater to measure water level accumulations in 2.5 cm increments.

The heater pressure unit contained a resistance temperature device (RTD), a digital humidity analyzer, and a pressure gage. The system was designed so that pressure could be released if it exceeded 0.7 MPa. The surrounding alcove had similar instrumentation so tunnel environment changes could be factored into evaluations.

There were two systems to measure rock-wall temperatures. Thermocouples were either heater mounted or bonded to the rock-wall in silicone rubber inserts that fit into pre-cut slots. The heater-mounted thermocouples were designed so that the spring action of the insulating sheath would hold the thermocouple against the rock wall. One of the objectives of these experiments was to evaluate the relative merits of the two thermocouple configurations, but this evaluation is unfinished and beyond the intended scope of this paper. Preliminary indications are that the heater-mounted thermocouples appeared to be influenced by direct radiation and sheath conduction so that recorded temperatures were about 20°C higher than those determined by the rock-mounted insert thermocouples. The heater-mounted thermocouples proved to be excellent sensors for evaluating borehole annulus heat transfer effects. For the purpose of this paper all rock-wall data are from the insert thermocouples except in one case (nonwelded, Level 1) where heater-mounted thermocouples were adjusted to the equivalent insert thermocouple value. Table 1 summarizes the location and type of thermocouples used at each level in the two experiments.

OPERATIONS

Heater

Table 2 summarizes the pertinent details for heater operations. There were two heating stages for the experiment in welded tuff. After the initial heating period and a seven-day cooldown, the borehole was flooded, with the heater in its initial position. The bottom 0.3 m of the hole was saturated for a full seven days, and the fractured tuff up to a height of 1.8 m was under water for a period of approximately 15 hours. A manually operated steady-state flow system was used to maintain the elevated water level for this shorter period of time. At the end of the flooding period, the free water was removed.

The heater power level chosen for the welded tuff experiment was similar to that used in the *Tuff In Situ Water Migration/Heater Experiment* (Johnstone, Hadley, 1980). Major differences in these experiments were orientations of the boreholes and water sampling schemes. In both experiments the heaters had similar shapes and dimensions. The wattage for the nonwelded experiment was selected so that the maximum tuff temperatures would be well into the zeolite dehydration range (>100°C) and thermal contraction would be expected (Lappin 1980). Heating periods were terminated when trends were apparent and little could be gained with additional heat and time.

One change was made after completing the experiment in welded tuff. The heater power reflected variations in the commercial electrical power that was distributed to G-tunnel. Influences of these variations could be seen in many of the thermocouples. The problem was corrected by operating the heater power on an uninterruptible power supply (UPS) for the experiment in nonwelded tuff.

Table 1. Thermocouple Details

		Welded Tuff		Nonwelded Tuff	
Location Function	Level	Thermo* Type	Height**	Thermo Type	Height
Heater Surface	1	H,H,H.	4.1cm	H,H,H.	4.1cm
	2	H,H,H.	41.0cm	H,H,H.	41.0cm
	3	H,H,H.	78.7cm	H,H,H.	78.7cm
	4	H,H,H.	116 cm	H,H,H.	116 cm
	5	H,H,H.	139 cm	H,H,H.	139 cm
	6	H,H,H.	168 cm	H,H,H.	168 cm
Rock Wall	1	R,T,T.	5 cm	T,T,T.	5 cm
	2	R,T,T.	59.7cm	R,R,T.	63.5cm
	3	R,T,T.	95.2cm	R,R,T.	117 cm
	4	R,T,T.	139 cm	R,T,T,T.	140 cm
	5	R,T,T.	176 cm	R,T,T,T.	168 cm
	6	R,R,R.	208 cm	R,R,R.	203 cm
	7	R,R,R.	254 cm	---	---

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* H - Heater Surface, R- Rock-Wall Insert,
T - Heater Mounted Tip-Out

**Height measured from bottom of hole

Table 2. Heater Operation

Experiment	Time Start	Time Stop	Duration	Wattage
Welded-Initial	Apr 12, '82-1600	May 4, '82-0900	21.67 days	800
Welded-Reheat	May 19, '82-0900	May 26, '82-1230	7.19 days	800
Nonwelded	Aug 31, '82-1100	Oct 5, '82-1100	35.00 days	500

Data System

The data acquisition system was designed around an HP 9845 desk top computer located underground. Data on all channels (80) were collected in periodic scans. The shortest scan interval of five minutes was used immediately before and after all changes in the heater power levels. As the thermal phenomena stabilized, the scan interval was lengthened to a maximum of 30 minutes. Most data were taken at the longer intervals.

Thermal Results

The thermal results for both experiments are summarized in Figures 2 and 3. Heater and rock-wall temperatures are displayed as the ratio of temperature change to power level so that common ordinates can be used. The temperature changes are normalized with the constant power level rather than with thermal diffusivity or conductivity because of the temperature dependence of the latter. To allow for curve initialization an initial temperature of 18°C was subtracted from all measured temperatures, except for the reheating data, before dividing by the power level. A temperature of 24°C was subtracted from the reheat data to factor out the residual temperature that existed when the heater power was turned on.

Heater Midplane

Maximum rock-wall temperatures were recorded near the heater midplane (Level 2 in Table 1). Maximum heater surface temperatures were measured above this midplane at Level 3. Results are displayed in Figure 2.

Let me present first the welded tuff heater and rock-wall thermal results. Irregularities in the curves at the later times are due to irregularities in the heater power. The peak at t = 3 x 10^4 minutes is due to a surge caused by the temporary substitution of power from the

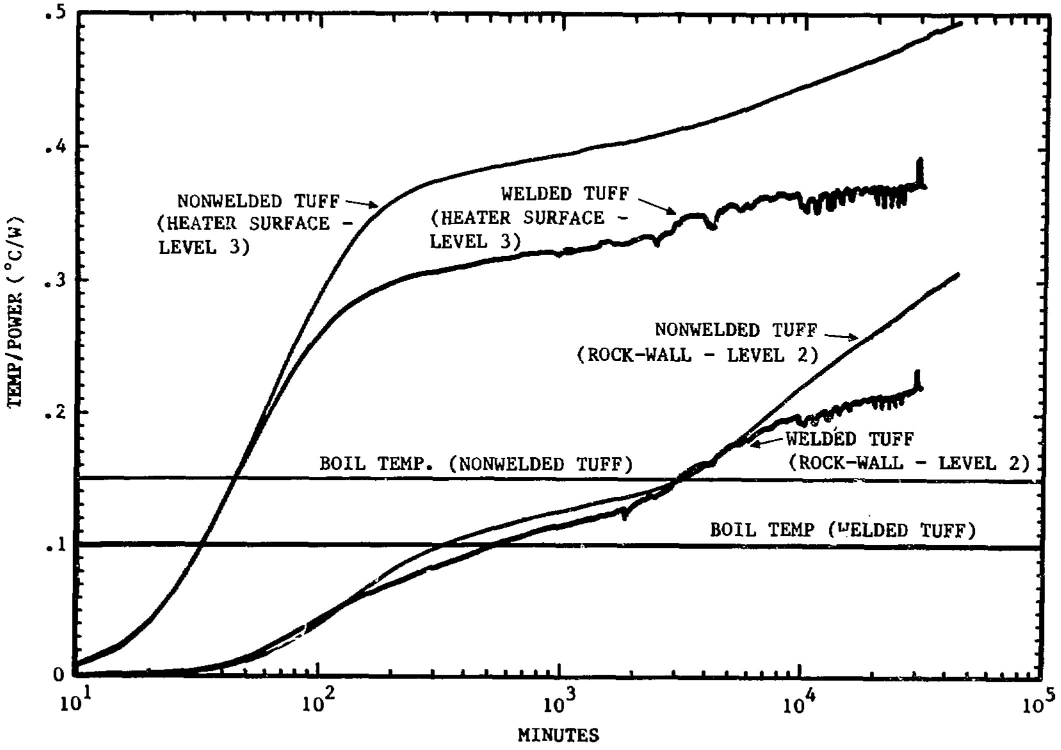

Figure 2. Maximum Rock-Wall and Heater-Surface Temperature Results

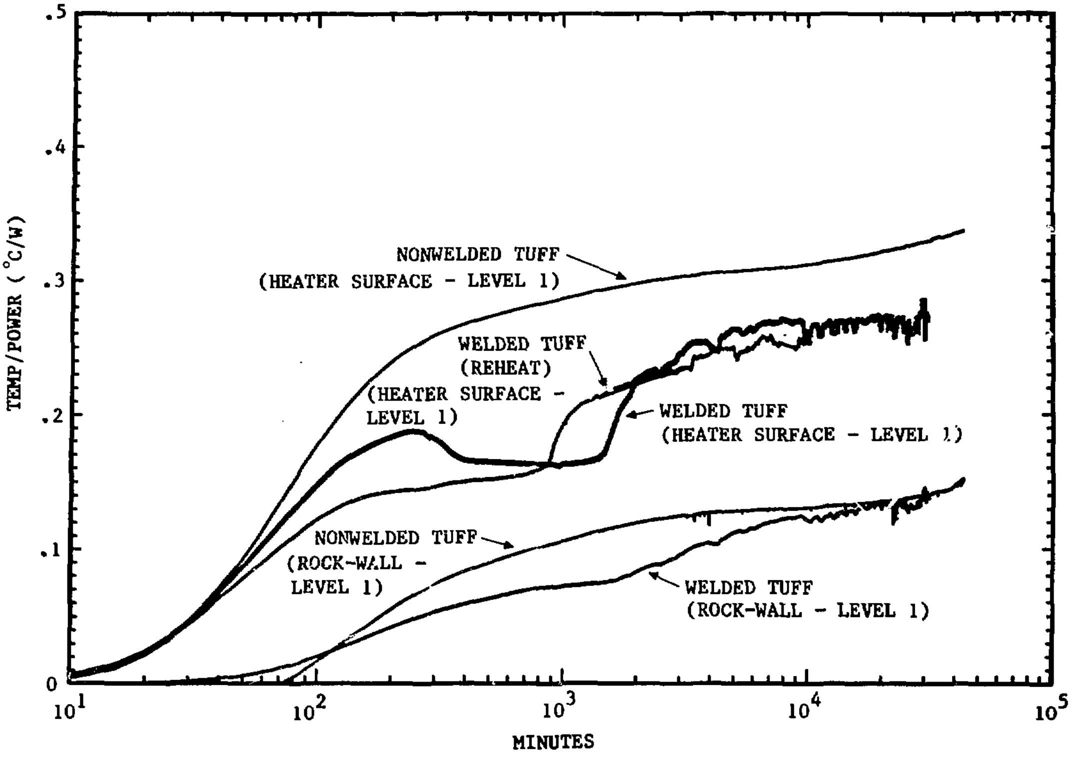

Figure 3. Level 1 Rock-Wall and Heater Surface Temperature Results

autostart diesel that was used for emergency power. The intersection of the horizontal line marked "boil temp. (welded)" and the normalized data curve for the rock wall represents the time when the rock-wall temperature exceeded the local boiling temperature of water (94-18 ÷ 800). At about $t = 1.8 \times 10^3$ min the slope for the rock-wall data increased slightly, suggesting a decrease in thermal conductivity. The latent heat of vaporization is a factor that would tend to flatten the curves, but its presence is not observed. The temperature difference between the heater surface and rock wall decreased after the vaporization started, a further indication of the decreasing heat transfer properties of the dewatered tuff.

The thermal results for the experiment in nonwelded tuff are more uniform because of the regulated power supply. The curves show that the changes in slopes after vaporization (94-18 ÷ 500) are much more profound, due to the higher porosity and water content in the nonwelded tuffs (relative properties are provided in the thermal modeling section). The significance of these changes in slopes is that heater and borehole temperatures rise significantly as a result of decreased rock thermal conductivity as pore water is vaporized.

Maximum temperatures reached in both experiments were:

Experiment	Max Rock Temp	Max. Heat Surf. Temp.
Welded Tuff	196°C	317°C
Nonwelded Tuff	173°C	265°C

The data in Figure 2 indicate that the nonwelded tuff was still increasing in temperature at a significant rate after 35 days of operation, whereas the welded tuff was nearing a maximum temperature after only 21 days of heating.

Post-experiment observations indicated that both heater holes appeared to be structurally stable and intact after the heater was removed. There was no evidence of borehole sloughing due to heating.

Lower Heater

Figure 3 shows the heater surface and rock-wall temperature changes for Level 1 (Table 1). Level 1 reheat data for the heater are also shown because this is the only level where there were perceptible differences.

The most significant phenomenological events are reflected in the curves for the heater surface for the welded tuff experiment. There was a dip in the temperature of the heater surface at times between 240 and 2000 min for the initial welded tuff heater experiment. The reheat experiment showed similar results with the exception that there was not the initial hump at t = 240 min and that the increase in slope started some 500 min earlier. The figure shows that the welded tuff rock-wall temperature was below the nominal boiling temperature (temp/power = 0.095) during this period. The dip in the heater temperatures is attributed to hydrothermal phenomena. It is hypothesized that pore water in the nearly saturated tuff migrated to the emplacement hole and collected there. This particular borehole had an irregular bottom after drilling, and approximately 1000 cc of crushed tuff were placed in the hole to provide a level surface. This crushed tuff would have a storage capacity estimated to be less than 0.2 ℓ. The possibility exists that liquid water collected in this void space and possibly around the bottom of the heater and increased the thermal conductivity in this region for the period when the rock wall temperatures were below boiling. Later discussions of hydrothermal phenomena provide additional data to support this hypothesis.

The reheat experiment data support the general trends, and the two differences can be explained. The absence of the hump at t = 240 min is attributed to the limitations in removing the water from the crushed tuff at the bottom of the hole with the heater in place. The hole was vacuumed dry before placing the heater initially. The earlier increase (t = 1×10^3 min) in the slope of the reheat curve is perhaps due to the limitations in resaturating the tuff above 0.3 m during the flooding periods. Possibly, the tuff in the initial heater experiment had more pore water available.

Heater Pressure Unit

Measurements in the heater pressure unit were enlightening. For the welded tuff experiment the HPU temperature increased by only 4°C over the entire experiment, indicating minimal convection to the top of the deeper borehole. For the experiment in nonwelded tuff, the HPU temperature increased by 15°C within 4800 min and reached a plateau. At t = 29,000 min the HPU was wrapped with insulating fiberglass and the HPU temperature increased by another 20°C. This indicated that the HPU was dissipating energy that was being carried upward by convection in the borehole annulus. The annulus was 0.6 cm wide around the aluminum honeycomb.

The data indicated that there was a strong convective driving force in the nonwelded tuff, whereas it was relatively minor for the welded tuff. The difference was posited as vapor transport into the fractures. This concept is supported with hydrothermal data discussed next.

HYDROTHERMAL RESULTS

Borehole Water Migration

Water migration into a heated borehole was much different than the earlier In Situ Heater/Water Migration Experiment in welded tuff (Johnstone, Hadley 1980). In that experiment over 60 ℓ of water was collected in 63 days of operation. The highest flow rate was in the first few days. A major difference in experimental setups was that the water collection sampling location for this earlier experiment was located beneath the heated region and remained cool. For both of the small diameter heater experiments the total amount of collected water was less than 1ℓ.

Hydrothermal phenomena were monitored with three different measurement systems. The accumulation of liquid water in the bottom of the borehole was monitored with the water level sensors. The presence of water vapor and the possible formation of refluxing cells in the borehole was monitored with the heater-mounted thermocouples. The evidence of water migration to the HPU was monitored by the environmental monitors located there.

The water level sensor was nonstandard and merits a description. It was formed by exposing the two leads for a sheathed thermocouple at a desired level along the heater surface. The thermocouple wires were energized with an alternating current so that a circuit could be completed by conduction through the air between the exposed leads. The sensitivity was set so that there would be an increase of 5-7 volts if any water containing ions were to come in contact with the exposed leads.

The only water level sensor that detected water was the one at the bottom of the heater. Figure 4 summarizes the responses of this water level sensor. The next potentially active sensor was 2.5 cm higher and no signal was recorded.

The two curves for the welded tuff have interesting similarities and differences. The similarities are that they have initial dips between 20 and 200 min, then relative increases through the next 400 min and then decreases to near zero. The significance of the behavior for the region between 240 and 2000 min is that this is the same time period that the Level 1 heater surface temperatures were lower (Figure 3). This apparently coupled phenomenon suggests that the water migrated into the borehole in liquid form. The earlier dip for t = 120 min is thought to be due to the initial dewatering of the bottom of the hole as the heater surface reached the boiling temperature at about t = 50 min.

The reason the initial voltage was higher for the reheat experiment is that the moisture in the crushed tuff could not be removed with the heater in place. A further possibility is that additional minerals collected during the initial heating phase and increased the conductivity of the water.

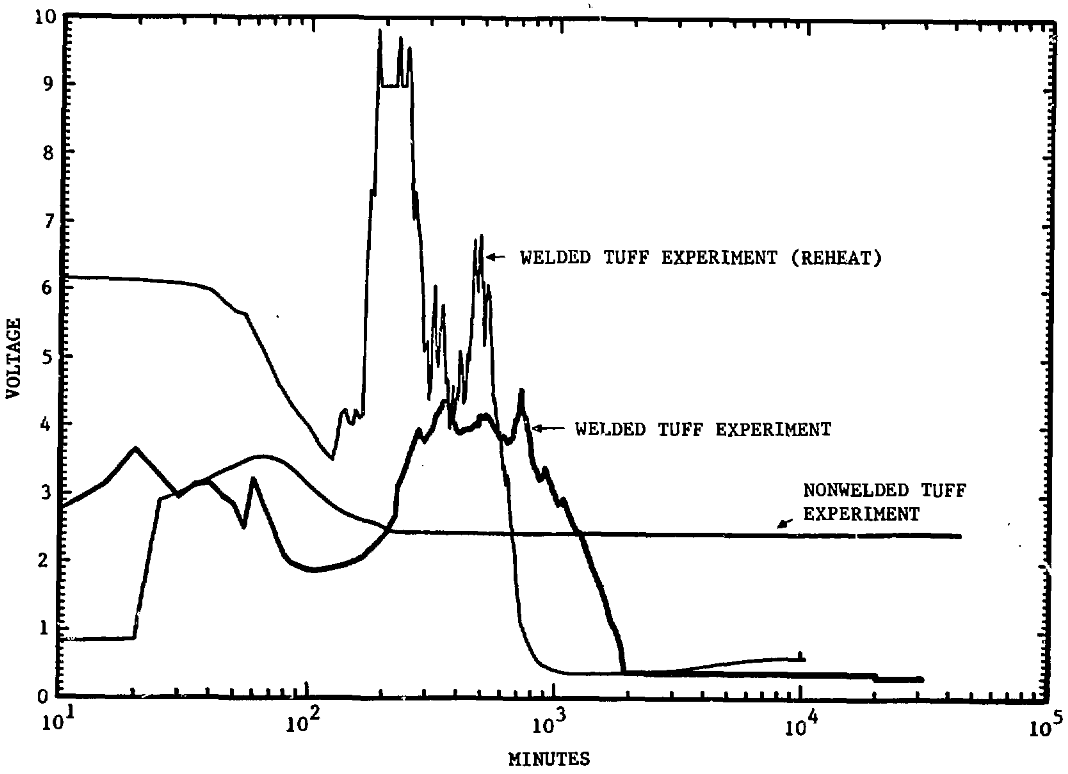

Figure 4. Lowest Water Level Sensor Results

The curve for the initial experiment in welded tuff shows that the water level sensor was exposed to water for a longer period. This supports the hypothesis that the pore space of the tuff was not fully recharged during the brief flooding period.

The water migration phenomena for the experiment in nonwelded tuff were somewhat different. The figure shows that there was some slight increase in voltage for the first 70 min and then a single decrease and stabilization. There were no apparent influences on the temperatures at the bottom of the heater. Only the water level sensor indicated that there might have been a trace of liquid water. The heater bottom reached a boiling temperature in about 100 min, and the decreasing magnitudes of the moisture curve after this time suggest this influence. The fact that the sensor stabilized above 2V is attributed to sensor variations because post-experiment analyses indicated that there would have been a significant voltage increase if liquid water were present.

Vapor appeared to migrate towards the warmer air and then to be transported upward by convection. This vapor-transporting air cooled in the HPU and the moisture condensed. This was particularly evidenced in the experiment in nonwelded tuff where more than 0.5ℓ of water was found in the handling pipe located above the heater. Water was found on the base plate of the HPU for this same experiment. By contrast, only droplets were found in a similar region for the welded tuff experiment. It is conceivable that water vapor was present in the annulus in the welded tuff, and that it was transported into the fractures where it condensed.

HPU Environmental Changes

Environmental conditions within the HPU and the surrounding alcoves were monitored for temperature, pressure, and relative humidity changes. The most pronounced changes occurred in the relative humidity in the HPU. Saturation was reached within 12 hours in both experiments. The temperature increases have already been discussed. Pressure changes were negligible for both the welded and nonwelded tuff experiments.

PRELIMINARY MODEL EVALUATIONS

Model Definition

The preparation of the experiments for the Phase II testing includes an evaluation of the state of the current models. While the preparation of a computer code for the analysis of two-phase flow in tuff is underway at Sandia National Laboratories, an empirical approach has been used to describe the effects of pore water vaporization on the conductive heat transfer process (Eaton et.al., in preparation). The techniques of this empirical approach have been applied to the conditions for the two heater experiments and model - data comparisons are presented here. These comparisons are used as a feedback mechanism for ongoing code and material property evaluations.

The design of the experiments allowed use of two-dimensional, axially symmetric, finite element techniques. The heater surface was modeled as a conductive and radiative surface with a volumetric heat generation over the heated volume. Components within the heater were modeled as equivalent parts of axial symmetry. No attempt was made to compare internal heater model and measured values. The emphasis was on the heater and rock-wall surfaces. The rock-wall surface was modeled for radiation and conduction.

The thermal conductivity and heat capacity values for welded tuff were specified for the temperature ranges according to the representative curves in Figure 5. The figure shows that the thermal conductivity is changed in two step decreases as the temperature is increased from 70 to 120°C. The first step represents the average of the saturated and dry conditions whereas the second represents the dry properties (dewatered). The figure shows that the heat of vaporization is added to the nominal volumetric heat capacities for the tuffs by distributing it over the 70 to 120°C range. This procedure allows for a more gradual transition for the vaporization phenomena.

Cores from the boreholes drilled for these experiments were subjected to laboratory analyses (see Table 3). These data were used in the material property definitions shown schematically in Figure 5. Other pertinent model data are included in the table.

Model/Data Comparisons

Figure 6 is organized so that the heater surface and rock-wall thermal profiles for both experiments can be shown together. Comparisons of the 1st and 21st days of operation illustrate the relative time independence of the trends. The major factor evidenced is that the overall heat transfer computer models appear to be adequate for tuffs having vastly different

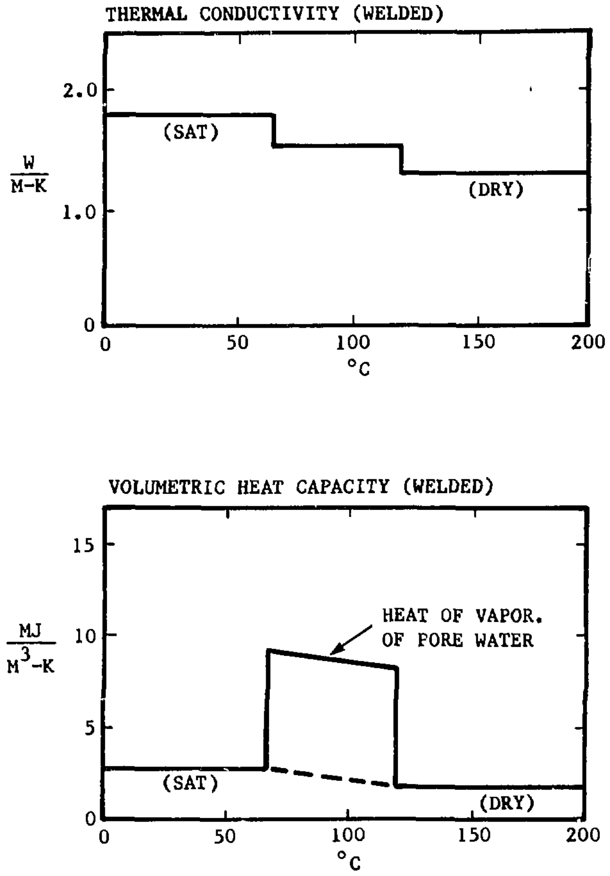

Figure 5. Thermal Model Representation

Table 3. Core and Model Material Properties

Property	Units	Welded Tuff	Nonwelded Tuff
Thermal Cond. (Sat.)	W/m°K	1.80	1.30
Thermal Cond. (Dry)	W/m°K	1.44	0.66
Heat Capacity (Sat.)	KJ/m^3°K	2478	2964
Heat Capacity (Dry)	KJ/m^3°K	1858	1105
Heat of Vaporization of Pore Water (70<T<120°C)	KJ/m^3°K	6550	19,650
Density (dry bulk)	KJ/m^3	2220	1320
Porosity		0.15	0.45
Saturation (measured)		0.85	0.90
Saturation (model value)		1.00	1.00
Emissivity - Heater Surf. (assumed)		0.6	0.6
Emissivity - Rock (assumed)		0.9	0.9

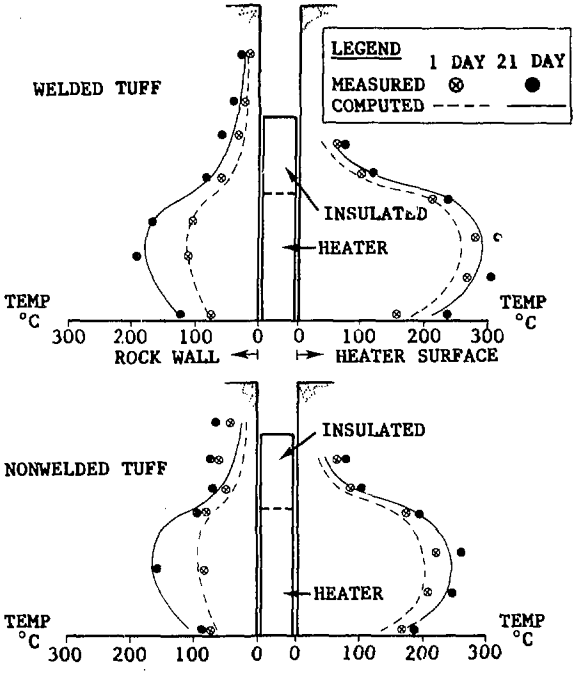

Figure 6. Measured and Predicted Temperature Distributions on the Heater Surface and Rock-Wall 1 and 21 Days After Heater Turn On

porosities and mineralogy.

The figure shows that the measured data for both heater surfaces are generally higher than the computed values. Deviations occur in two places. Differences in the heated region are attributed to assumed values for the heater and rock-wall emissivities, and planned emissivity measurements on these surfaces should reduce these differences. The figure also shows that there are differences above the heated zone. The differences are greater for the experiment in nonwelded tuff. These differences are attributed to convection in the borehole annulus. This phenomenon is even more pronounced in the rock-wall model comparisons in this same region.

An unexplained measurement trend in the figure is the apparent temperature increase at Level 5 as compared to Level 4 for the nonwelded tuff rock-wall data. This could be due to two reasons. First, the thermocouple at this level could have become dislodged and moved nearer the heater. Second, a refluxing cell could be influencing the temperatures at this level.

The convection phenomenon is present but less evident for the rock wall of the welded tuff experiment. Data show that convection may be important for modeling the very near field around the borehole, but that thermal impacts on thermomechanical behavior in the surrounding tuffs should be minimal.

As for differences in the rock-wall data/model values, measured maximum temperatures for the nonwelded tuff were approximately 6% less than the model values, whereas the similar values were approximately 5% higher for the welded tuff. Apparently, additional convection in the nonwelded tuff experiment caused the lower measured temperatures in the heated region.

CONCLUSIONS

These phenomenological evaluation experiments in welded and nonwelded tuffs have shown that:

1. The same heat transfer modeling technique can be used for tuffs having porosities of 0.15 and 0.45, and maximum temperature data/model comparisons were within 6%. Convection should be integrated into near field models if accuracies are to be improved.
2. Only small amounts of liquid water were detected in the bottom of the boreholes. Major water transport mechanisms appear to be the accumulation of vapor in the warmer air around the heater and later deposition as condensate in cooler regions away from the heater.
3. Borehole surfaces did not show structural degradation. While measurements were not taken in the rock outside of the borehole, results show that there is the potential for pore moisture vapor transport into the fractures and this could impact joint motion in the thermomechanical evaluations.

ACKNOWLEDGEMENTS

These experiments were performed by a team coordinated within Sandia National Laboratories. The analyses are those of the author, but the experiments could not have been performed without invaluable contributions from the remainder of the team. William Barrett prepared and operated the various facets of the data acquisition system. Carl Duimstra prepared the hardware and instrumentation. Both contributed to data evaluations. John Lindman helped field the experiments and monitored the equipment during the heater periods. Steve Winters helped fabricate the water level sensor. Dave Sanders and Jack Sutton of SAI helped prepare the experiment in nonwelded tuff. Finally, John Osnes of RE/SPEC performed the heat transfer calculations. Roger Eaton and Mark Blanford of SNL are thanked for their thorough reviews.

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