SCIENTIFIC NOTEBOOK
822E
Volume 1

by

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INITIAL ENTRIES

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This computerized electronic notebook is intended to address the criteria of CNWRA QAP-001.

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Description: Support Pre-licensing transition to License Application Review- UZ2 ISI Flow paths in the Unsaturated Zone

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Personnel Qualification: All collaborators involved with the tasks detailed in this scientific notebook are familiar with the principles of unsaturated flow and heat transfer processes.

The scope of work is to evaluate the results of thermal tests and examine test results for evidence of thermal refluxing of fluids with potential elevated concentrations of solutes. Thermal tests whose results will be evaluated include, but are not limited to, the following:

Section 1: 1977-83 Climax Mine heater tests by LLNL
- 1.1 1977-78 Climax small-diameter heater tests
- 1.2 1980-1983 Climax Spent Fuel Test

Section 2: 1982-84 G-Tunnel heater test series by SNL
- 2.1 1980 Borehole heater test – one test
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- 2.3 1981-84 Heated block test

Section 3: 1988-89 G-Tunnel borehole heater test by LLNL
Section 4: 1997 Fran Ridge Large-Block Test (LBT) by LLNL
Section 5: 1985 Superior Road Tunnel heater test by the U of AZ
Section 6: 1997 ESF Single-Heater Test (SHT) by LBNL
Section 7: 1997-2005 ESF Drift-Scale Heater Test (DST) by LBNL

This scientific notebook will contain information collected and considered as part of the evaluation of thermal tests results. Evaluation of each test will be documented in a separate section. Note that all text directly cited from published documents are denoted with "…". Bold print is meant to emphasis selected passages for ease in reading. No additional meaning is intended by the bold print. Text highlighted in the color red was directly taken from the documents that were cited. The color red was not added as part of this project. No additional meaning is intended by the color red.

The concern explored in this evaluation is that there may have been evidence from these heater (i.e., TH or thermohydrology) tests indicating the occurrence of refluxing fluids with elevated concentrations of solutes and that this evidence was not or has not been recognized or examined. Documents describing these heater tests will be reviewed to ascertain whether there is evidence of thermal refluxing.

Thermal refluxing, if present, would most likely occur in fractures. Thermal refluxing becomes a performance issue when: (i) refluxing occurs in fractures located above emplacement drifts, (ii) fractures are oriented toward waste packages such that refluxed fluids can potentially drip on the waste packages, and (iii) fractures have fluid transport properties that are conducive to transport of fluids to the waste packages.

Direct evidence of thermal refluxing is difficult to observe and quantify because of the spatial and temporal sparseness of the phenomenon. Direct observation of the phenomenon is further complicated because extraction of a fracture system from its *in situ* environment invariably alters the transport characteristics of the fracture system. Interpreting how this alteration affects thermal refluxing is further complicated because it is not clear in which way this alteration would bias the transport process exhibited by the fracture. Therefore, optimal insight on thermal refluxing would be gained by observing the phenomenon *in situ*.

Because of the difficulty in directly observing thermal refluxing, it is beneficial to identify indirect evidence that could or would be an indicator of the phenomenon. Indirect evidence includes:

1) Deposition of concentrated solutes within the air spaces or voids of heater tests. These airspaces include boreholes, fracture surfaces, and drifts.
2) Rapid temperature excursions that indicate liquid flow across a temperature sensor.
3) Liquid buildup with elevated solute, chemical, or mineral concentrations

Therefore, the objective of this study will be to examine heater test documents to determine whether there was evidence of thermal refluxing or the potential for thermal refluxing during the tests.

Date	Test	Evidence	Documentation
1977-78	Climax heater test 1, NTS, NV		UCRL report
1978-85	Climax heater test, NTS, NV	Dripping onto heater	Indirect, final report
1980-84	SNL G-Tunnel heater tests, NTS, NV	Temperature excursion	SAND reports
1988-89	LLNL G-Tunnel heater test, NTS, NV	Corrosive fluid build up on resonator	URCL reports
~1984	U of Arizona road tunnel heater test, Superior, AZ	Fluid build up in adjacent borehole	Personal communication
1994-95	Large Block Test, Fran Ridge, NV	Episodic dripping (temperature)	Reported
1996-97	Single Heater Test		
1997-2005	DST dripping into heated drift during experiment, ESF, NV	Dripping into heated drift	Observed, CNWRA staff
1996-97	CNWRA lab-scale tests	Dripping into drift	Reported

Section 1. Climax Stock Mine Heater Tests

References

Montan, D.N. and W.E. Bradkin. 1984. Heater Test 1, Climax Stock Granite, Nevada. UCRL-53496. Livermore, CA: Lawrence Livermore National Laboratory. 20p + appendices.

Montan, D.N. and W.C. Patrick. 1986. Post-thermal calculations and data analyses for the spent fuel test – Climax. UCRL-53728. Livermore, CA: Lawrence Livermore National Laboratory. 71p.

Patrick, W. 1986. Spent Fuel Test – Climax: an evaluation of the technical feasibility of geologic storage of spent nuclear fuel in granite. Final Report. UCRL-53702. Livermore, CA: Lawrence Livermore National Laboratory. 297p.

Patrick, W.C., R.C. Carlson, and N.L. Rector. 1981. Instrumentation report No. 2: Identification, evaluation, and remedial actions related to transducer failures at the Spent Fuel Test – Climax. UCRL-53251. Livermore, CA: Lawrence Livermore National Laboratory. 58p.

Patrick, W.C., N.L. Rector, and J.J. Scarafiotti. 1984. Instrumentation report No. 3: performance and reliability of instrumentation deployed at the Spent Fuel Test – Climax. UCRL-53637. Livermore, CA: Lawrence Livermore National Laboratory. 76p.

Weiss, H., R.A. Van Konynenburg, and R.D. Wright. 1985. Metallurgical analysis of a 304L stainless steel canister form the Spent Fuel Test – Climax. UCID-20436. Livermore, CA: Lawrence Livermore National Laboratory. 13p + attachments.

Test Documentation

The Climax mine is located in the Climax Stock quartz monzonite at the Nevada Test Site. There were two sets of *in situ* heater tests performed by LLNL in the Climax Stock: (i) a series of three tests performed in small-diameter vertical boreholes (Montan and Bradkin, 1984) and (ii) the Spent Fuel Test performed with 11 spent fuel assemblies and six electric heaters placed in vertical boreholes (Patrick, 1986 and Weiss et al., 1985). All test were conducted in the SFT-C facility at a depth of about 420 m below ground surface.

1.1 Climax Small-Diameter Borehole Heater Tests

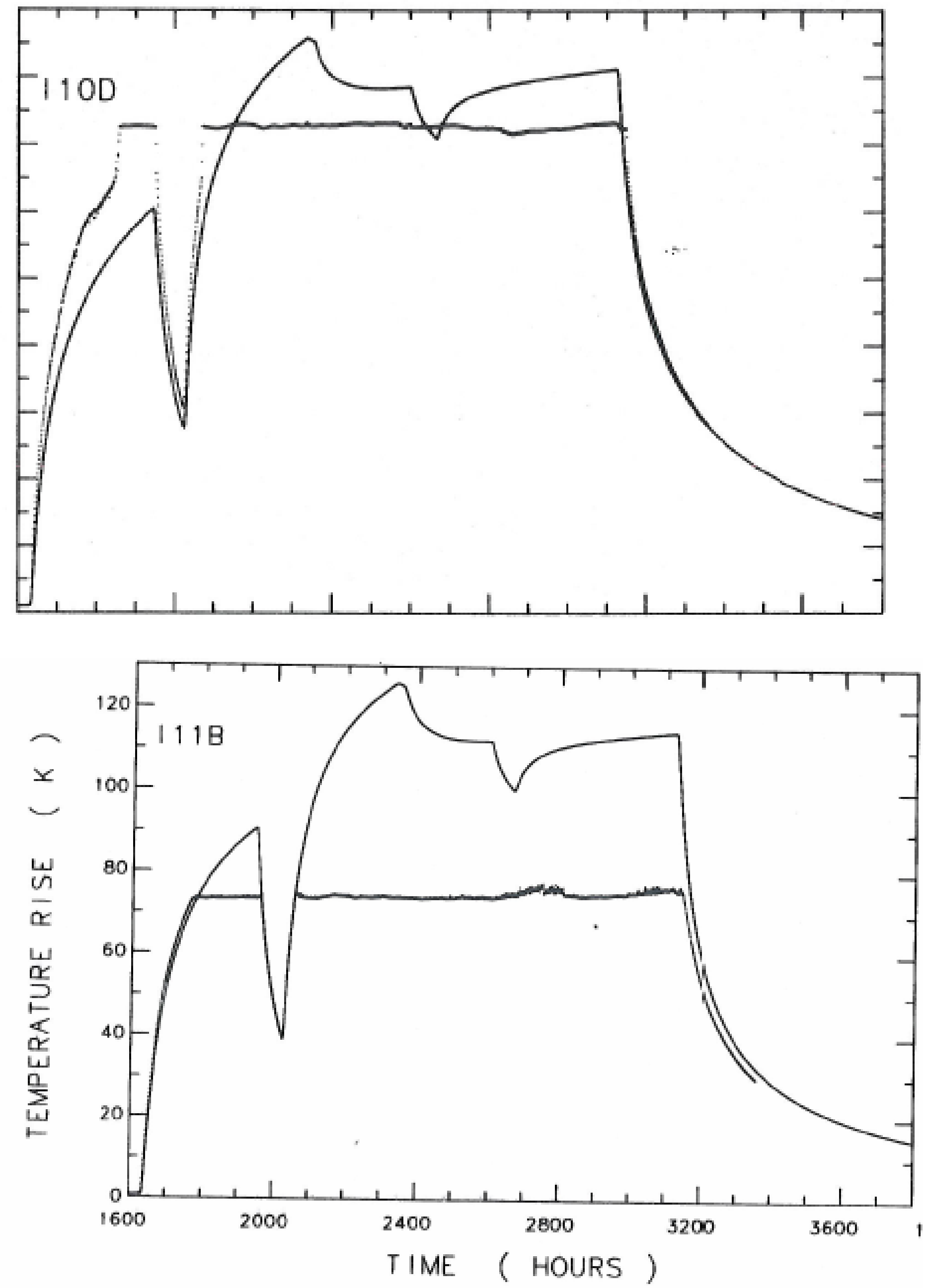
The three *in situ* tests were conducted in 1977-78 as part of series to obtain information on *in situ* thermal conductivity, thermal diffusivity, and permeability of granite (Montan and Bradkin, 1984). Of greater interest were the first two tests, test three was conducted to measure the effect of temperature changes on rock permeability. The tests were conducted in vertical boreholes which were 9 to 12-m in depth and varied in diameter from 48 to 76 mm. The thermocouples were spring activated to press them firmly against the rock wall. After thermocouple installation, the boreholes were backfilled with loose Perlite insulation.

The first heater test, H-1, operated for 68 days in late 1977. There were two outages in power and one equipment malfunction during the H-1. The first power outage occurred after nine days of heating. The project team ascertained that: "A small amount of water, probably circulating fluid lost to the fracture system during drilling, entered the heater hole as vapor and began refluxing in a region neat the top of the heater. This refluxing eventually caused a short circuit in the power leads…". Heating was discontinued for three days to repair the heater apparatus. After seven more days of heating, there was an apparent transient short circuit in a heater lead. No additional discussion on this event was provided by Montan and Bradkin (1984). Chemical analysis of refuxing water was not determined. There is little opportunity to discern whether there was any evidence that the refluxing waters had elevated ionic concentrations or that the refluxing waters were condensate. Montan and Bradkin (1984) noted "When and where boiling water effects were not important, the heater test data appear to fit with values near k = 3.1 W/m-K for thermal conductivity and $\kappa = 1.3\ mm^2/s$ for thermal diffusivity". The intent of the Climax small-borehole heater test was to determine the thermal properties of the host rock. Therefore, ancillary issues, such as chemistry of refluxing water, were not addressed.

Temperature was reported in figures in terms of temperature rise over ambient. The ambient temperature is reported as 23 C (Montan and Bradkin, 1984), therefore boiling would be a rise of about 73 C above ambient. Temperature recorded at four depths in six monitoring boreholes I-01 through I-05 and J-01. Evidence of a heat pipe was observed in three boreholes, I-01, I-02, and J-01. All three boreholes also had evidence of temperature excursions where temperatures above boiling were rapidly decreased to the boiling temperature. (Figures A-1, A-2, and A-3 in Montan and Bradkin, 1984). During test H-1, a temperature excursion was observed at the heater horizon in temperature monitoring borehole I-02 located 0.5 m from the heater borehole. The temperature excursions are evidenced by rapid decreases in temperature from temperatures as high as 130 C down to the temperature of boiling. Back filling the boreholes with loose Perlite insulation is apparently insufficient to prohibit the rapid downward flow of refluxing water

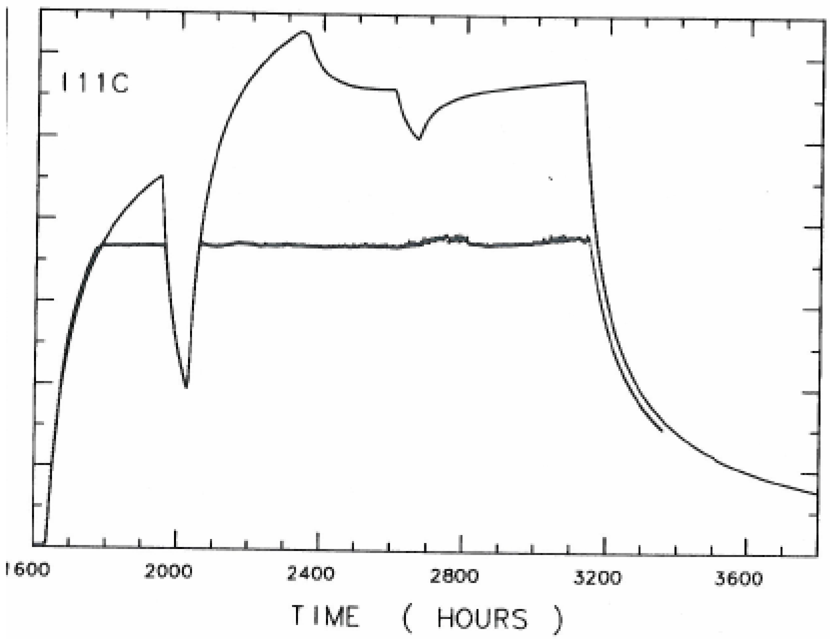
The second heater test, H-2, operated for 62 days in late 1977 and early 1978. Montan and Bradkin (1984) reported an unanticipated rise in temperature at the bottom of the heater during this test. However, figures A-7 through A-10 indicated the anomalous temperature rise occurred above the mid-plane of the heater. Regardless of the location, Montan and Bradkin (1984) attribute the temperature excursion to an accumulation of fine granite dust at the bottom of the heater and also noted there was indication of water refuxing above the heater. Evidence of a heat pipe was observed in three boreholes, I-10 (Figure A-9D), I-11 (Figure A-7B, C, D), and J-02 (Figure A-8B). [B and C denote that temperature was measured at the midplane. D was measured above the heater midplane.

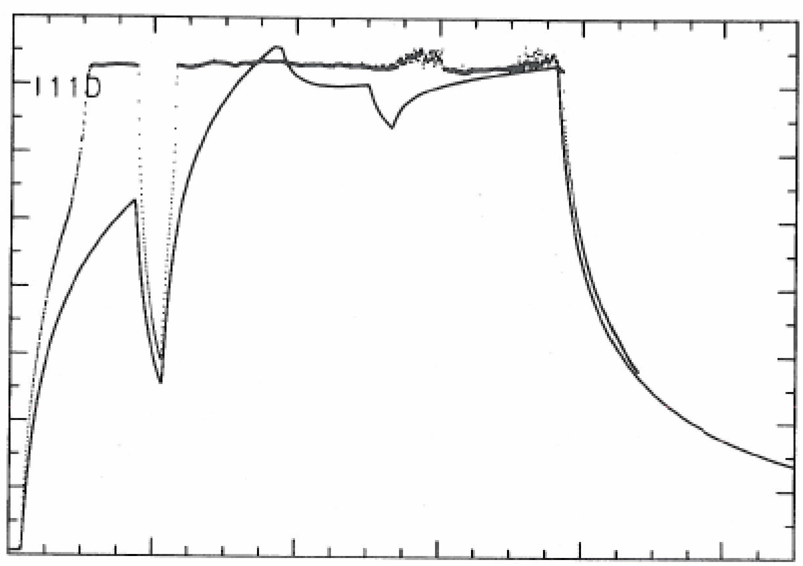
Figures were taken from Montan and Bradkin (1984)] Boreholes I-11 (Figure A-B, C) and J-02 (Figure B, C) had evidence of temperature excursions where temperatures above boiling were rapidly decreased to the boiling temperature. Boreholes J-02, I-10, and I-11 are located about 0.4 m, 0.5 m, and immediately adjacent to the heater borehole. Of interest is that borehole I-11, which is located immediately adjacent to the borehole, did not register temperatures above boiling, instead, temperatures at the heater midplane remained at boiling for essentially the entire test duration when the heater was energized. This indicates that the midplane of I-11 was probably dominated by a heat pipe or, less likely, that liquid water at the boiling temperature was present during this entire time.



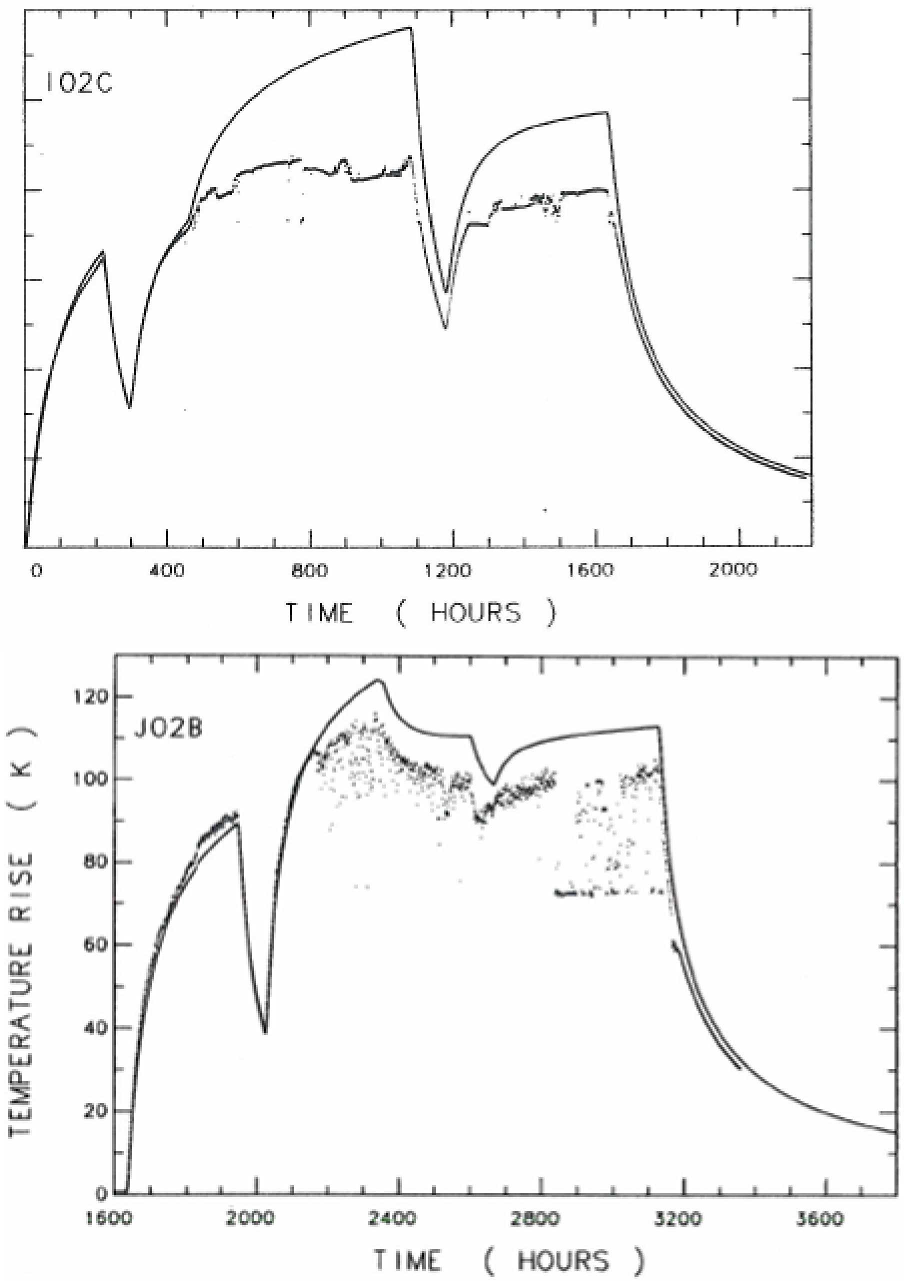
Figures from: Montan, D.N. and W.E. Bradkin. 1984. Heater Test 1, Climax Stock

Granite, Nevada. UCRL-53496. Livermore, CA: Lawrence Livermore National Laboratory. 20p + appendices.





Figures from: Montan, D.N. and W.E. Bradkin. 1984. Heater Test 1, Climax Stock Granite, Nevada. UCRL-53496. Livermore, CA: Lawrence Livermore National Laboratory. 20p + appendices.



Figures from: Montan, D.N. and W.E. Bradkin. 1984. Heater Test 1, Climax Stock Granite, Nevada. UCRL-53496. Livermore, CA: Lawrence Livermore National Laboratory. 20p + appendices.

1.2 Climax Spent Fuel Test

The heating phase of the Spent Fuel Test-Climax was initiated in April-May 1980 and terminated in March-April 1983. The heat source was 11 spent fuel canisters and six electric simulators. The test was conducted at a depth of 420 m below ground surface in the Climax stock granite on the Nevada Test Site. The zone of saturation is at an elevation of about 945 m above mean sea level, which is about 145 m below the horizon of the test (Patrick, 1986). LLNL was responsible for the design, conduct, and analysis of the test. The summary report is by Patrick (1986).

In this test, the boreholes were vertical and located in the drift floor. A carbon steel liner was placed in each borehole. The fuel assemblies and electric heaters were then placed in the lined borehole. Canister temperatures exceeded boiling, liner temperatures approximately attained boiling, but rock temperatures did not achieve boiling (Montan and Patrick, 1986; Patrick, 1986). Consequently, neither heat pipes nor temperature excursions were observed during the tests.

Water Chemistry

Of interest to this evaluation is that water was observed in one of the canister boreholes during the heating phase of the test (Weiss et al., 1985). Fuel assembly number D34 was placed in Climax Emplacement Hole #1 (CEH#1). Although the test horizon was 145 m above the poteniometric surface, CEH#1 apparently intersected a fracture zone with mobile water allowing water to pool in the liner-rock annulus (Weiss et al., 1985). A leak in the liner allowed water to enter the liner cavity. As a result, the bottom portion of the canister was submerged after emplacement for at least the first eight months of the heater test.

The evolution of the presence of water was interpreted by Weiss et al. (1985) using temperature measurements. Weiss et al. (1985) noted that the temperature of D34 (emplacement hole CEH01) at mid-height attained a maximum of between 135 and 140°C for approximately two months. Based on temperatures recorded other boreholes (Patrick, 1986), this two month period was immediately after the onset of heating. Temperatures of the liner and of the canister near the bottom of the canister are illustrated in Figure 1 (taken from Figure 3 in Weiss et al., 1985). Temperatures in the bottom of the borehole were less than those measured at mid-height and did not exceed boiling. As illustrated, the canister temperature increased until 3.1 years out or core, after which the temperature exhibited a slight decline. The liner temperature exhibited anomalous temperature trends. Liner temperature increased monotonically until 3.0 years out of core, at which time a there was an additional increase in temperature for 0.1 years. After 3.1 years out of core, the liner temperature exhibited a steady, modest decline.

Weiss et al. (1985) interpreted that the jump in liner temperature at the 3-yr mark occurred when water in the liner-rock annular space completely departed, either through evaporation or percolation through the rock, resulting in poorer thermal conductance between the rock and liner as heat transport changed from conduction-convection to radiation. Canister temperatures, which gradually increased up to 3.0 years, did not rise at 3.0 years. Weiss et al. (1985) interpret a gradual increase in solute concentration of the water in the liner-canister annular space as the cause for the slight temperature rise leading up to 3.0 years out of core. The decline in canister temperature after 3.1 years is interpreted to be caused by a decline in decay-heat generation.

The liner leak is interpreted to have sealed from precipitation of solute minerals present in the liner-canister, annular-space water. Weiss et al. (1985) asserted that sealing occurred prior to 3.0 years out of core. There was no water present inside the liner when the canister was briefly removed in August 1982. Note that the time of 2.4 years out of core equates to April or May 1980.

Although the source of water that seeped into the liner-rock annulus was interpreted to originate from a fracture that was free flowing prior to the test, the prospect for the water chemistry to have been altered by refluxing is evaluated in this notebook (822E). Fortunately Weiss et al. (1985) analyzed the chemical composition of water sampled from the liner-rock annulus and compared it with the chemical composition of water sampled from two locations in the Climax complex. The major ion concentrations (from Table I, pg 12 of Weiss et al., 1985) are summarized in the following table.

Comparison of water analyses from the Climax facility and well J-13 (mg/L)

Species	NH-01	UG-02	CEH#1	Well J-13
Na	229.	214.	273.	43.9 ± 1.19
Ca	240.	114.	16.0	12.5 ± 0.77
SiO_2	22.5	23.9	1.4	57.7 ± 1.0
K	3.8	4.7	538.	5.11 ± 0.32
SO_4	850.	480.	193.	18.7 ± 0.47
Cl	160.	70.	30.	6.9 ± 0.21
HCO_3	65.	165.	1322*	136. ± 8.1
F	N.D.	N.D.	3.8	2.2 ± 0.32
NO_3	N.D.	N.D.	2.5	9.6 ± 3.63

*calculated from ionic balance
NH-01 and UG-02 were collected from two locations in the Climax Mine complex.
CEH#1 was collected from the liner-rock annulus.

In summary, the water chemistries were as follows. The ambient water (two samples) was relatively high in Na, Ca, SO_4, Cl, and HCO_3. Water from the liner-rock annulus was significantly higher in K and lower in Ca, SO_4, and Cl. Unfortunately HCO_3 was not measured, but ionic balance would dictate a concentration in excess of 1300 mg/l.

Weiss et al. (1985) commented that they did not understand the details of the processes that led to the differences in compositions. They suggested that factors such as variation in equilibria with temperature, concentration by distillation, contact with the zinc-coated steel liner, interaction with the grout, radiolysis, and ion exchange with the rock probably contributed to the differences in measured species concentrations. They also noted that it was possible that contamination by detergent used in drilling the nearby access hole also occurred.

Evidence of Corrosion

The Spent fuel Test - Climax test experienced failure of rod extensiometer transducers, extensiometer connecting rods, and vibrating wire stressmeters. No corrosion was evident on the canisters at the conclusion of the test (Patrick, 1986, pg 280)

The source of the failure of the transducers was complex and not attributed to a single source (Patrick et al., 1981). Hygroscopy of the resistive element was identified as a potential source of failure. The source for water was not identified.

A total of 10 extensiometers failed during and after the Climax Spent Fuel Test (Patrick et al, 1984). Examination indicated that all extensiometers failed due to stress-corrosion cracking. The presence of calcium carbonate at the roots of the corrosion cracks indicated that extensiometer seals had leaked allowing water to enter. Subsequent laboratory analyses (Patrick, 1986) indicated that the extensiometer connecting rods were most susceptible to corrosion when in the presence of chloride ions (pg 281). Post-heater test confirmatory testing in the laboratory confirmed that corrosion of the extensiometer connecting rods would not occur when exposed to Climax water at 50 C. Corrosion failure of the extensiometer rods did occur, however, when $CuCl_2$-$2H_2O$ was added to the Climax water. Subsequent inspection indicated that the extensiometer connecting rods fracture surface indicated the presence of chloride ions (pg 281). It was also noted that the type of corrosion fracturing observed during the test in the presence of the aggressive water was similar to the fracturing observed during the heater test (i.e., a combination of intergranular- and transgranular fracturing). This evidence and analysis indicate that the water that infiltrated past the failed seals on the extensiometers did not have the benign chemistry peculiar to the naturally occurring water in the Climax mine area, but instead had a more aggressive chemistry, possibly with elevated concentrations of chloride. Otherwise, ten extensiometers would not have failed in the way they did. This assessment provides evidence for the possible presence of rock water with solute concentrations elevated by thermal refluxing.

Corrosion of the vibrating wire was experienced in the vibrating wire stressmeters (Patrick et al., 1981). Patrick et al. (1981) noted the source of the water was elusive because gauges were O-ring sealed, coated, and foamed in place in relatively dry holes.

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Section 2. 1980-84 G-Tunnel heater test series by SNL

References

Zimmerman, R.M., M.L. Blanford, J.F. Holland, R.L. Schuch, and W. Barrett. 1986a. *Final Report: G-Tunnel Small-Diameter Heater Experiments.* Sandia National Laboratories-SNL SAND84-2621, DE87-007361 Albuquerque, NM December 1986a

Zimmerman, R.M., R.L. Schuch, D.S. Mason, M.L. Wilson, M.E. Hall, M.P. Board, R.P. Bellman and M.P. Blanford. 1986b. *Final Report: G-Tunnel Heated Block Experiment.* UC-70 Sandia National Laboratories-SNL SAND84-2620, DE86-011768 Albuquerque, NM April 1986b

Johnstone, J.K., G. R. Hadley, and D.R. Waymire. 1985. *In Situ Tuff Water Migration/Heater Experiment: Final Report.* Sandia National Laboratories. SAND81-1918. DE85-010415. Albuquerque, NM. March 1985

Johnstone, J.K. 1980. *In Situ Tuff Water Migration/Heater Experiment: Experimental Plan.* Sandia National Laboratories. SAND79-1276. Albuquerque, NM. August 1980.

2.1 1980 SNL G-Tunnel Water Migration/Heater Test

This heater test was conducted in the G-tunnel complex, located in the welded Grouse Canyon tuff, a member of the Belted Range tuff. The tuff had a porosity of 22 to 28% and liquid saturation > 85% in the vicinity of the experiment. The experiment objectives were (Johnstone et al., 1985):

- Assess water generation/migration behavior in welded tuff
- Support thermal/thermomechanical code development
- Support instrumentation development
- Measure in situ thermal conductivity

Of these, the primary goal of the experiment was to assess the water behavior.

The test entailed one heater borehole, one stress borehole, two thermocouple boreholes, and three water migration boreholes. The seven boreholes were parallel.

A 10.2 cm diameter, 1.22 m long borehole heater was used in the test. It contained two resistive heating elements. Power level was determined based on criteria explained in Johnstone et al. (1985). In summary, the main consideration by Johnstone et al. (1985) was to heat the rock to the highest temperature possible with assurance that the rock would not fracture, disintegrate, or respond in some other manner that would interfere with the observation or confuse the interpretation of the water behavior. Based on these criteria, a maximum Johnstone et al. (1985) specified an operating temperature of 220 C with an accompanying operating power level of 1,000W. The test was energized on

February 5, 1980 and remained energized for about 63 days. Rock temperatures increased at a rate that exceeded pretest thermal analysis predictions. The operating power was eventually decreased from 1,000 W to about 800 W to keep rock temperatures moderated. Actual rock temperatures exceeded 240 C in the heater borehole. This discrepancy between pretest predictions and actual temperatures suggests that: (i) heat transfer mechanisms other than conduction may have been active or (ii) the thermal conductivity or specific heat of the rock was lower than the values assigned in the pretest analyses. Rock wall temperatures in the water collection (i.e., WM) boreholes did not exceed 78 C during the heater test and 88 C in the thermocouple boreholes. Although the temperature of the heater elements was relatively high, there was not a large dryout zone developed around the heater borehole.

Water collection instrumentation was included in three adjoining parallel water migration boreholes (WM-1, WM-2, and WM-3). Water was collected and analyzed from the heater borehole, WM-1, WM-2, and from well #8. No water was collected in WM-3, which was located about 30 cm above and 20 cm to the side of the heater borehole. Well #8 was a local well used to provide water used during drilling of the boreholes. It could reasonably be considered a background well. During the test, a total of 61.7 liter of water was removed (Zimmerman et al., 1986a, pg 8-19). It was noted in Zimmerman et al. (1986a) that there was a high rate of flux during the first three days of heating, after which the flux was reduced.

Following are limited chemistry analysis results of samples collected during the water migration/heater test.

Table x. Anion concentrations at different times in water samples from HH-1, WM-1, WM-2, and well #8 (Johnstone et al., 1985)

Sample No.	Date (J-day)	F (ppm)	C^{l-} (ppm)	PO_3^{4-} (ppm)
HH-1				
HH-3	37.05	1.5	2.1	
HH-12	38.2	1.9	1.2	
HH-19	39.23	0.3	N.D.	
HH-136	80.4	0.1	0.9	N.D.
HH-158	98.36	0.3	0.6	N.D.
WM-1				
WM-129	73.4	2.7	1.4	4.1
WM-160	99.36	0.8	5.6	
WM-2				
WM-28	38.4	9.2	10	15
WM-124	70.4	2.1	8.4	4.6
WM-161	99.38	1.8	5.0	
Well #8	1.5	8.3	2.5	

Date is in terms of Julian date from start of year.

The decrease in ion concentrations is interpreted to indicate the collection of condensate in the water sampling locations. Assessment of the impact of refluxing water in this heater test was obscured because water was both injected into boreholes prior to energizing and periodically removed from boreholes during heating. There was no evidence in the temperature measurements that would indicate thermal refluxing occurred during the experiment, however, this lack of evidence may have been obscured by the water removal.

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2.2 1982-84 SNL G-Tunnel Heater Test – Three boreholes

SNL conducted a series of heater tests in the G-Tunnel complex in 1982-1984 to test the thermal and hydrothermal response of welded and non-welded tuff to heating. The tests consisted of one heated block experiment (Zimmerman, 1986b)(Section 2.3) and three borehole heater tests (Zimmerman, 1986a). There were two alcoves, Alcove 1 in a welded tuff, the Grouse Canyon member, and the Alcove 2 in a nonwelded tuff, referred to as Tunnel Bed 5. The Grouse Canyon member has a porosity of 12 to 25% and the Tunnel Bed 5 has a porosity of approximately 45%. There was significant water present in the units. Two borehole experiments (i.e., IW and IIW) were run in Alcove 1 and one borehole experiment was run in Alcove 2 (i.e., IN). IW and IN were vertical and IIW was horizontal. The heated borehole tests are designated here as follows:

Table x. G-Tunnel Small Diameter Heater Tests

Test	Date	Sponsor	Duration	Max Heater Temp	Max Rock Temp
G-Tunnel single borehole series - IWa	1982	SNL	21.7 days	460 C	240 C
G-Tunnel single borehole series - IWb	1982	SNL	7.1 days	460 C	240 C
G-Tunnel single borehole series – IN	1982	SNL	35.0 days	360 C	175 C
G-Tunnel single borehole series – IIWc	1984	SNL	7.8 days	325 C	100 C
G-Tunnel single borehole series – IIWd	1984	SNL	8.1 days	460 C	195 C
G-Tunnel single borehole series – IIWe	1984	SNL	7.9 days	500 C	240 C
G-Tunnel single borehole series - IIWf	1984	SNL	11.2 days	530 C	310 C

The letter subscripts are added to be able to differentiate among the tests.

Each heater unit consisted of a 114.9 cm long heater unit and a 76.2 cm cool extension. The heater units were hermetically sealed from the alcoves. The alcoves are stated to be 600 m above the regional water table. The ambient temperature of boiling is stated to be 94 C. [**These last two items may be in error. The depth to water may be closer to 200 m and the temperature of boiling may be closer to 97 C. This information will be checked**.] [**The elevation of G-Tunnel is approximately 1,900 m. The water level at Yucca Mt is 700-800 m. Therefore, because Rainer Mesa is north of Yucca Mt (i.e., upgradient), it is reasonable that the water table is 1,300 m at Rainier Mesa.]**

The heater units were equipped with one of two types of thermocouples to measure the temperature of the rock wall of the emplacement holes (i.e., tipout thermocouples and thermocouples bonded directly into the rockwall) to directly measure the rockwall temperature. The Phase II experiment only used thermocouples bonded directly into the rockwall. Level 1-3 thermocouples were in the heater section of the boreholes, levels 4 and 5 were immediately above the heated section and levels 6 and 7 were above the terminal section. Experiment IIW had a satellite hole with six thermocouples. These thermocouples were placed near potential hydraulic-conducting fractures. There is no mention that the satellite hole was grouted. Phase II of IW (e.g., IIW) was conducted in a second borehole from Phase I to allow for detection of pooled water. Water sensing sensors were placed at 2.5 cm increments from the bottom to a height of 38 cm to detect liquid water. Results were reported in J-days (e.g., days after start of calendar year). Phase I experiments were in 1982 and the Phase II experiment was in 1984. Data were collected at 5-minute to 30-minute intervals.

Zimmerman et al. (1986a) evaluated scaling relationships that would relate the tests to actual emplacement dimensions, however no attempt was made to conduct a scaled experiment. This analysis was conducted to ensure that test power levels were relevant to repository applications. For an experimental borehole radius of 6.4 cm and an emplacement borehole radius of 17.8 cm, they calculated a scaling factor of 6.4/17.8 = 0.36. For pure conduction, time scale varies as the square of the geometric ratio, which means a 0.36 geometric ratio equates to 0.13 time ratio, however, heater lengths do not have the same scaling relationship. If only the radius geometry is considered, a 1 week experiment equates to 7.7 weeks for an emplacement borehole. Likewise, for the radius scale relationship, a test heater power of 1,000 W would equate to an operating canister operating at 2,170 W.

2.2.1 Test IW

Test IW operated at a constant power level of 800 W for a period of 21.67 days (Test IWa). Heater element temperatures exceeded 450 C. Emplacement hole temperatures approached 240 C. The level 1 thermocouple in test IW was the only thermocouple to record an event that indicated thermal refluxing. The level 1 thermocouple was located at the bottom of a vertically oriented borehole. Two rapid temperature excursions were observed within one day (Figure 6.1.5) (Zimmerman et al., 1986a). Temperature decreased from about 175 C to about 90 C during the first excursion and from about 160 C to 105 C during the second excursion. Water collected in the heater emplacement hole during early heating. There was no mention of water chemistry analysis, but it is likely the water was mostly condensate because it occurred soon after the onset of heating. The temperature excursions are likely indicators of thermal refluxing of low TDS condensate water.

15 days after Test IWa was concluded, the heater was re-energized for an additional 7.1 days (Test IWb). During the 15 day heating hiatus, the emplacement hole was flooded with water for 15 hr to re-saturate the host rock. No water was detected during this experiment.

2.2.2 Test IN

The heater handling pipe at the top of the heater was full of water when the emplacement hole was opened at the end of the test. The volume of water was estimated to be 0.5 liter (Zimmerman et al., 1986). The bottom of the heater pressure unit had a few drops of water at its base when opened. There is no mention of water chemistry analysis. There is no mention of corrosion. No temperature excursions were observed during IN.

2.2.3 Test IIW

The phase two welded test, IIW, was conducted at 4 power levels that were ramped up during the 35 day long test: 400W (7.8 days)(IIWc), 800W (8.1 days)(IIWd), 1,000W (7.9 days)(IIWe), and 1200W (11.2 days)(IIWf). Maximum heater internal temperatures were 325 C, 460 C, 500 C, and 530 C. Maximum rock temperatures for the same test phases were 100 C, 195 C, 240 C, and 310 C. Temperature excursions, as evidenced by rapid decreases in temperature down to approximately boiling (i.e., 94 C), were observed during those phases (i.e., IIWd,e,f) in which rock temperatures were in excess of boiling. As indicated in Figure 6.3.7 of Zimmerman et al. (1986a), the temperature excursions occurred immediately after power was ramped up. No water was detected by pressure transducers located in the bottom of the borehole indicating that water amounts were not large or that the downward flowing water was diverted prior to arriving at the bottom of the borehole. It is assumed that the reluxing water was mostly condensate with low TDS.

No other refluxing event was observed although a heat pipe was observed at the 180-185 m mark in the satellite borehole during the IIW tests. Similar to the 1980 SNL G-Tunnel heater test, assessment of the impact of refluxing water was obscured because water was both periodically removed from boreholes during heating. There was no evidence in the temperature measurements that would indicate thermal refluxing occurred during the experiment, however, this lack of evidence may have been obscured by the periodic water removal that occurred during testing.

February 19, 2007 Ronald Green

2.3 1981-84 SNL G-Tunnel Heater Test – heated block

The heated block test was conducted in the Grouse Canyon member of the Belted Range tuff in the G-Tunnel Underground Facility at Rainier Mesa. The specific site was located in a well-fractured volume of tuff. The block was 2 m x 2 m at the surface an extended to a depth of 3 m, although the tested portion was the upper 2 m so that the volume of tested tuff was 8 m^3. The elevation of the drift was approximately 6,215 ft (1,894 m) msl. The tuff is welded at this location.

There were three thermal cycles in the test: October 5, 1983 to November 22, 1983; November 22, 1983 to January 17, 1984; and April 5, 1984 to August 16, 1984. Each had a heating cycle and a cooling cycle. The heaters were placed outside the block in the intact rock. Temperatures were measured in the block, in the cut slots (i.e., in the flat jacks), and in the contiguous intact rock. There was minimal remarkable data. Of limited interest was that development of a heat pipe was indicated by temperatures maintained at the boiling temperature for extended durations. The basic test design (i.e., no rock above the heated block) and insufficient measurement resolution resulted in minimal meaningful thermal reflux information.

Section 3. 1988-89 G-Tunnel heater test by LLNL

Ramirez, A.L. and D.G. Wilder. 1991. *Prototype Engineered Barrier System Field Tests (PEBSFT): Progress Report Through November 1, 1988*. UCID-21640. Lawrence Livermore National Laboratory. Livermore, CA.

Ramirez, A.L. 1991. *Prototype Engineered Barrier System Field Tests (PEBSFT): Final Report.* UCID-106159. Lawrence Livermore National Laboratory. Livermore, CA.

Lin, W., A. Ramirez, and D. Watwood. 1991. *Temperature Measurements from a Horizontal Heater Test in G-Tunnel.* UCID-106693. Lawrence Livermore National Laboratory. Livermore, CA.

The LLNL heater test was conducted in 1988-89 in the G-Tunnel Underground Facility. The test environment was the Grouse Canyon tuff, which is a welded tuff with properties similar to the welded units of the Topopah Springs tuff. The test was located in the small diameter heater alcove in the rock Mechanics Drift of the facility. The heater borehole was inclined slightly upward and crossed a significant vertically oriented fracture. The heating unit was 3-m long and was energized at 3.3 kW on November 7, 1988. The heating phase lasted for 128 days after which power was ramped down in 20 steps over 67 days.

There were seven horizontal neutron probe boreholes, three combined psychometric/thermocouple boreholes, and one thermocouple-only borehole. In addition, thermocouples were also installed in the neutron probe boreholes. Microwave coaxial resonators were installed in the pressure boreholes as part of a system that was developed and installed to measure water vapor partial pressure in the boreholes at temperatures up to 250 C. A capacitance sensor (Humicap) was installed in the heater borehole in front of the packer. The resonator was behind a packer and could not be removed during testing.

The microwave resonators were not tested prior to installation and operated erratically soon after installation. The source for the erratic behavior was hypothesized as follows. As explained in the 1988 progress report (Ramirez and Wilder, 1991), the resonator was thought to be cooler than the surrounding environment causing water to condense inside the resonator. This water did not dry out and eventually caused corrosion inside each resonator rendering the system inoperative. A similar response was replicated in the laboratory. This replicated test was cited as verification of their explanation of why the resonator failed. The system apparently never worked. There was no discussion of the microwave system in the final report (Ramirez, 1991).

It is possible that there is an alternative explanation for the resonator equipment failure, although the LLNL explanation is plausible. The presence of corrosion on the resonator electronic components observed at the conclusion of the test and the similar response of a laboratory-based test to evaluate the effect of water on the resonator performance support the premise that the presence of liquid water on the components led to the equipment failure. One factor in the LLNL explanation that is questionable is that the resonator was sufficiently cooler than the borehole environment to cause water to condense on the resonator and to indefinitely remain on the resonator after thermal equilibrium. Once shut in, the sensor environment would have quickly equilibrated to the ambient temperature and the close to 100% relative humidity.

It is possible that a mechanism other than condensation due to a cold trap could have led to water accumulation on the resonator. In particular, thermal refluxing could have contributed to liquid water accumulation in the borehole cavity. Supporting this hypothesis is the presence of a vertically oriented fracture in the borehole which could have provided an opportunity for refluxing back to the resonator.

One additional observation from Ramirez and Wilder (1991) was that the resonator began to malfunction immediately after the borehole was grouted. This observation suggests that the mechanism that led to water accumulation on the resonator occurred soon after the instrument was shut in by grouting. It is unlikely that thermal refluxing would have occurred immediately after grouting. However, in the absence of detailed examination of corrosion products, condensate water, CO_2 partial pressure, fracture location and orientation relative to the resonator, and the specific timing of events, it is difficult to conclusively identify which mechanism led to the corrosion and which mechanisms can be categorically dismissed.

Section 4. Fran Ridge Large Block Test

References for the LBT Section:

Lin, W.; Blair, S.C.; Wilder, D.; Carlson, S.; Wagoner, J.; DeLoach, L.; Danko, G.; Ramirez, A.L.; and Lee, K. 2001. Large Block Test Final Report. UCRL-ID-132246, Rev. 2. Livermore, California: Lawrence Livermore National Laboratory. TIC: 252918.

Wilder, D.G., W. Lin, S. C. Blair, T. Buscheck, R. C. Carlson (Woodward Clyde), K. Lee, A. Meike, A. L. Ramirez, J. L. Wagoner, and J. Wang (LBL). 1997. Large Block Test Status Report. Lawrence Livermore National Laboratory Livermore, California 94551. UCRL-ID-128776

OCRWM. 2002. Thermal Testing Measurements Analysis and Modeling Report. ANL-NBS-HS-000041

The following text and graphs are from the 1997 Status Report Wilder et al. (1997):

5.2 Temperature

"Temperatures in the large block are measured using resistance temperature devices (RTDs) both in boreholes and on the surfaces of the block. Borehole temperature measurements are being conducted in fourteen boreholes: two vertical holes (TT1 and TT2), seven horizontal holes (NT1, NT2, NT3, NT4, WT1, WT2, and WT3), and the five heater holes (EH1 to EH5)."

The location of these holes was described in Section 4 of this report [1997 Status Report]. The two vertical RTD holes and the seven horizontal RTD holes were sealed with cement grout; the five heater holes are not sealed. The temperatures measured from the surface mounted RTDs on the four vertical sides of the large block are to monitor the heat flux away from the block. The temperatures measured from the RTDs on the top of the block are used to monitor the temperature on top of the block, which is controlled by a heat exchanger to be at 60°C.

In this report, the temperature measured from the two vertical RTD holes and the seven horizontal RTD holes will be presented in figures. The RTDs in those holes were separated by a spacing of 20 cm. The RTD numbering was always starting from the bottom of a hole. For example, TT1-1 is the RTD at the bottom of the vertical RTD hole TT1, and NT1-14 is the RTD near the collar of the horizontal RTD hole NT1, which was drilled from the north face of the block and ended at a distance about 30 cm from the south face of the block. All of the other temperature data are available in spread sheets in the LLNL data base.

The five heaters of the LBT were energized at about 10 am on February 28, 1997 to a power level of about 450 W each. Background ambient temperature in the block was collected about 18 hours before the heaters were turned on. The data collection frequency was once per hour. The data acquisition frequency was increased to once per 10 minutes on June 30, 1997 to have a more accurate monitoring of the temperature variations, which started on June 12, 1997. This will be discussed in greater detail later in this section.

From the Thermal Test Measurement AMR, pg 6.1-2

"The LBT is a controlled test to provide data for a better understanding of the coupled thermal-hydrologic-mechanical-chemical processes in a heated unsaturated rock mass. The LBT was conducted at the outcrop of the middle nonlithophysal unit of the Topopah Spring tuff (Tptpmn) at Fran Ridge, Nevada. A 3 × 3 × 4.5 m high column of the rock mass was isolated from the outcrop at the eastern slope of Fran Ridge (See Figure 6.1-1). The base of the column is still connected to the ground. [The total height of the block appears to be 4.375 m, not 4.5 m.] The block was heated from February 28, 1997, to March 10, 1998. [Approximately 375 days.] A natural cooling phase started on March 10, 1998, until the termination of the data acquisition on September 30, 1998."

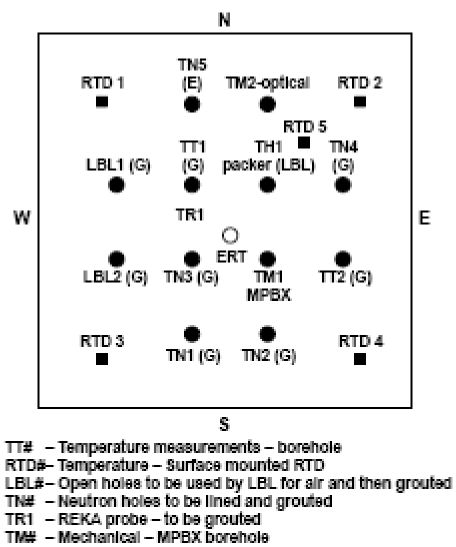


Figure 4-1. Location of instruments on the top surface of the large block.

Figure from: Wilder, D.G., W. Lin, S. C. Blair, T. Buscheck, R. C. Carlson (Woodward Clyde), K. Lee, A. Meike, A. L. Ramirez, J. L. Wagoner, and J. Wang (LBL). 1997. Large Block Test Status Report. Lawrence Livermore National Laboratory Livermore, California 94551. UCRL-ID-128776.

Two boreholes, TT1 and TT2 are 1.5-inch- [3.81-cm-] diameter vertical boreholes drilled into the top of the block. The locations of TT1 and TT2 on the top of the block are illustrated in Figure 4.1, taken from the 1997 LBT Status Report by Wilder et al (UCRL-ID-128776). Each TT borehole hosted a bundle of 30 RTDs. Each bundle of RTDs was grouted with cement in the two temperature boreholes. Some of the RTDs were placed in thin-walled stainless-steel tubes so that they could be calibrated or replaced during the test. **[Which of the RTDs were grouted and which were placed in thin-walled stainless-steel tubes? This is important to the interpretation of thermal refluxing. Grouted RTDs should not exhibit rapid temperature fluctuations.]**

Appendix B from the LBT Final Report notes that TT1 has a total depth of 3.90 m and that TT2 has a total depth of 4.04 m.

The RTDs in those holes were separated by a spacing of 20 cm. The RTD numbering was always starting from the bottom of a hole. For example, **TT1-1 is the RTD at the bottom of the vertical RTD hole TT1**. Since there were 30 RTDs in TT1 & TT2, the RTD number and depth from top are:

TT1-30	20cm	
TT1-29	40cm	
TT1-28	60cm	
TT1-27	80cm	
TT1-26	100cm	
TT1-25	120cm	
TT1-24	140cm	
TT1-23	160cm	
TT1-22	180cm	
TT1-21	200cm	
TT1-20	220cm	
TT1-19	240cm	
TT1-18	260cm	heater horizon is at 275 cm from top
TT1-17	280cm	
TT1-16	300cm	
TT1-15	320cm	
TT1-14	340cm	
TT1-13	360cm	
TT1-12	380cm	
TT1-11	400cm	
TT1-10	420cm	
TT1-9	440cm	
TT1-8	460cm	
TT1-7	480cm	
TT1-6	500cm	
TT1-5	520cm	
TT1-4	540cm	
TT1-3	560cm	
TT1-2	580cm	
TT1-1	600cm	

These RTD locations are not consistent with location descriptions in the Final

Report. The Status Report must be incorrect with regard to the 20 cm separation between the RTDs in TT1 and TT2.

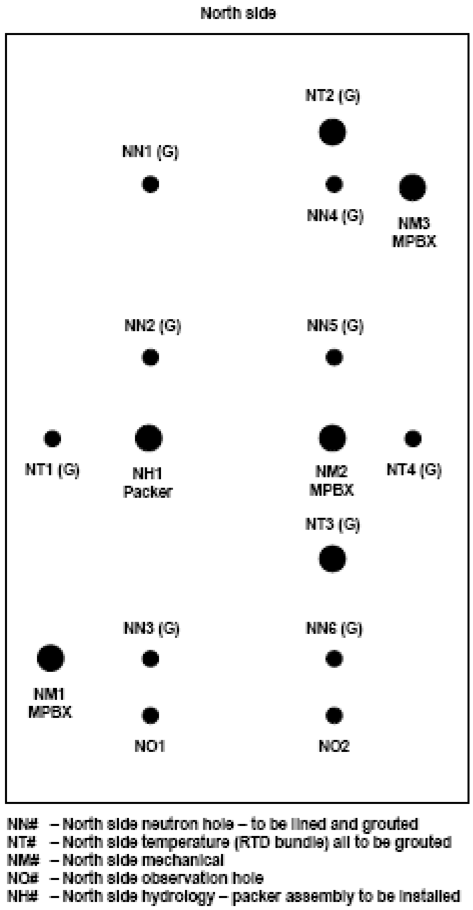


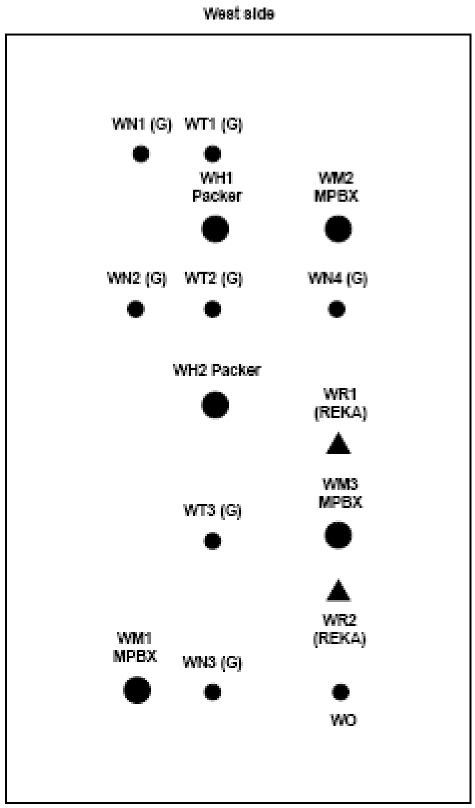
Figure 4-2. Location of instruments on the north face of the large block.

Figure from: Wilder, D.G., W. Lin, S. C. Blair, T. Buscheck, R. C. Carlson (Woodward Clyde), K. Lee, A. Meike, A. L. Ramirez, J. L. Wagoner, and J. Wang (LBL). 1997. Large Block Test Status Report. Lawrence Livermore National Laboratory Livermore, California 94551. UCRL-ID-128776.

There were four NT# boreholes drilled into the north side of the block to measure temperature. Borehole locations are illustrated in Figure 4.2, taken from the 1997 LBT Status Report by Wilder et al (UCRL-ID-128776). Two NT# boreholes were 3 inches in diameter (NT2 and NT3) and two were 1.5 inches in diameter (NT1 and NT4), each with 14 RTDs grouted in place.

The RTDs in those holes were separated by a spacing of 20 cm. The RTD numbering was always starting from the bottom of a hole. For example, NT1-14 is the RTD near the collar of the horizontal RTD hole NT1, which was drilled from the north face of the block and ended at a distance about 30 cm from the south face of the block.

For the NT series, the RTD number 1 is near the south side of the block; RTD number 14 is near the north side of the block.



WN# – West side neutron hole – to be lined and grouted
WT# – West side thermal (RTD bundle) to be grouted
WH# – West side horizontal – packer assembly to be installed
WM# – West side mechanical (MPBX) hole – to be grouted
WO# – West side observation hole

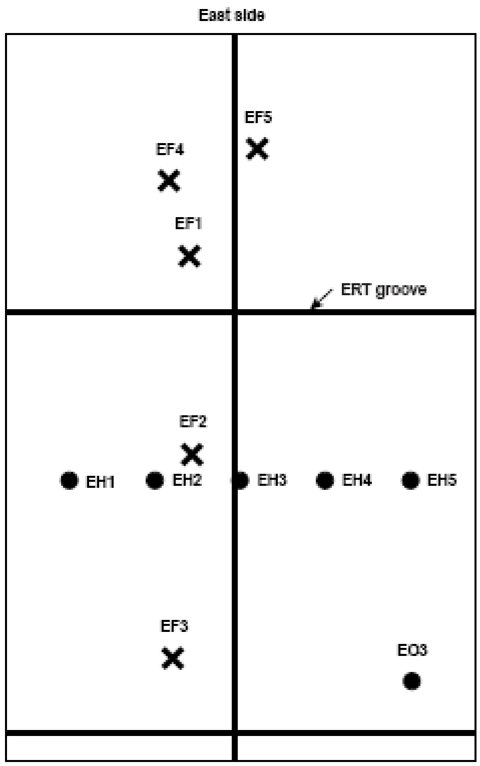
Figure 4-5. Location of instruments on the west face of the large block.

Figure from: Wilder, D.G., W. Lin, S. C. Blair, T. Buscheck, R. C. Carlson (Woodward Clyde), K. Lee, A. Meike, A. L. Ramirez, J. L. Wagoner, and J. Wang (LBL). 1997. Large Block Test Status Report. Lawrence Livermore National Laboratory Livermore, California 94551. UCRL-ID-128776.

There were three WT# boreholes drilled into the west side of the block to measure temperature. Borehole locations are illustrated in Figure 4.5, taken from the 1997 LBT Status Report by Wilder et al (UCRL-ID-128776). All three WT# boreholes were 1.5 inches (3.81 cm) in diameter, each with 14 RTDs grouted in place.

The RTDs in those holes were separated by a spacing of 20 cm. The RTD numbering was always starting from the bottom of a hole.

For the WT series, the RTD number 1 is near the east side of the block, and the RTD number 14 is near the west side of the block.



EH# – East heater hole (heater assembly w/ERT)
EO – East observation
EF# – Fracture monitors

Figure 4-3. Location of instruments on the east face of the large block.

Figure from: Wilder, D.G., W. Lin, S. C. Blair, T. Buscheck, R. C. Carlson (Woodward Clyde), K. Lee, A. Meike, A. L. Ramirez, J. L. Wagoner, and J. Wang (LBL). 1997. Large Block Test Status Report. Lawrence Livermore National Laboratory Livermore, California 94551. UCRL-ID-128776.

There were five EH# boreholes drilled into the east side of the block to provide a source of heat. Heaters were installed in each of the five boreholes. Temperature was measured in the EH# boreholes. Borehole locations are illustrated in Figure 4.3, taken from the 1997 LBT Status Report by Wilder et al (UCRL-ID-128776). All five EH# boreholes were 1.5 inches in diameter. The heaters boreholes are centered 2.75 m from the top of the block. One 2.44-m-long, 300-W heating element with three RTDs attached to the heater was installed in each of the five heater holes.

March 12, 2007 Ronald Green

The following section is taken from the 1997 Status Report. It includes preliminary discussion and interpretation of the two TH events.

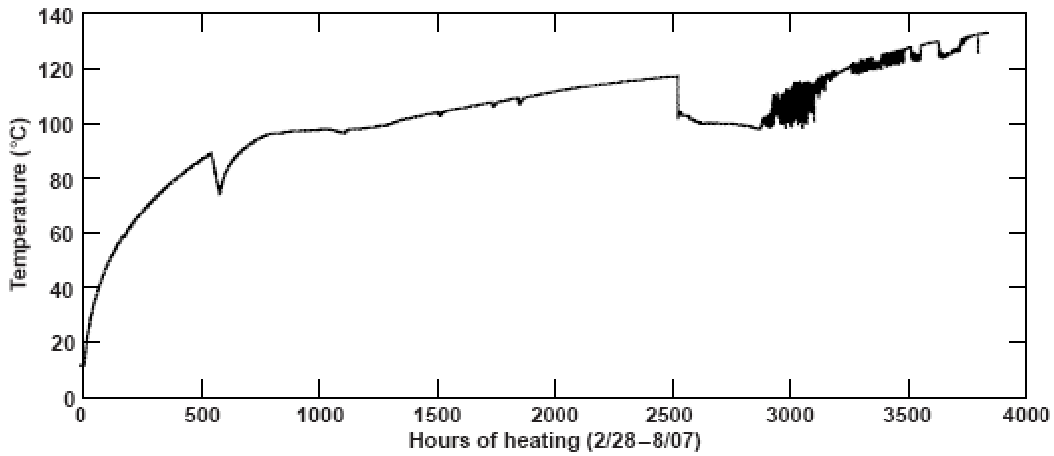


Figure 5-2. Temperature at TT1-14 as a function of time.

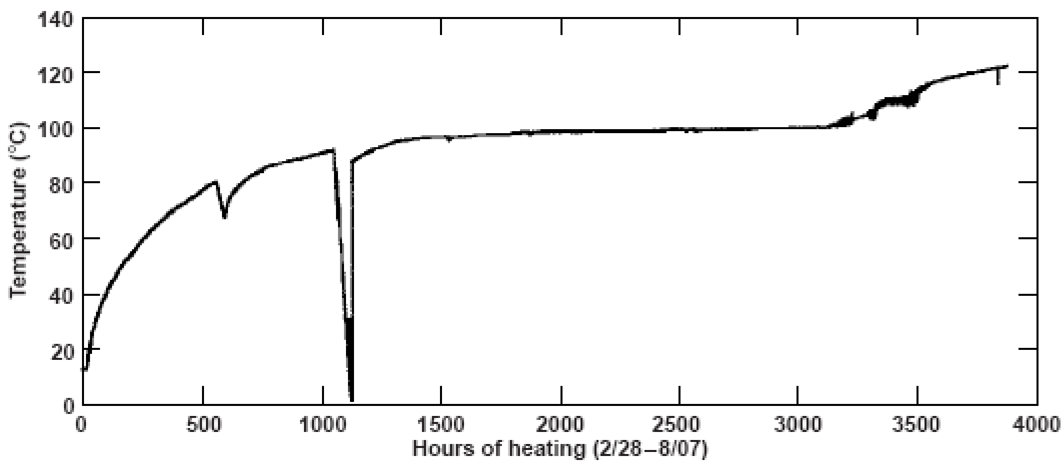


Figure 5-3. Temperature at TT2-14 as a function of time.

Figures from: Wilder, D.G., W. Lin, S. C. Blair, T. Buscheck, R. C. Carlson (Woodward Clyde), K. Lee, A. Meike, A. L. Ramirez, J. L. Wagoner, and J. Wang (LBL). 1997. Large Block Test Status Report. Lawrence Livermore National Laboratory Livermore, California 94551. UCRL-ID-128776.

"All of the sharp decreases in temperature, which occurred before 2500 hour, are related to power outages. The straight-line segment at about 3200 hour was caused by a temporary malfunction of the data acquisition system. Temperature variations after 2500 hour, as shown in Figs. 5-2 and 5-3, will be discussed later. Figures 5-4 and 5-5 show weekly snapshots of the temperatures measured at every RTD along TT1 and TT2, respectively. **Again, the RTD numbers 1 through 30 in both TT1 and TT2 are from the bottom to the top of the block**. The flat temperature profile involving several RTDs in both TT1 and TT2, when the temperature was about the boiling point of water, may be related to boiling of water in the rock. This topic will be discussed further later."

“Figures 5-6 to 5-12 show weekly snapshots of the temperature profiles along the seven horizontal RTD holes; NT1, NT2, NT3, NT4, WT1, WT2, and WT3, respectively. Again, for the NT series, the RTD number 1 is near the south side of the block; RTD number 14 is near the north side of the block. For the WT series, the RTD number 1 is near the east side of the block, and the RTD number 14 is near the west side of the block. Generally speaking, the horizontal temperature profiles are fairly flat. All of the temperature data are input to EarthVision to construct a 3D contour of the temperature field within the block at certain instances.”

“Figure 5-13 shows one example of the 3D contour of the temperatures in the block at about 10 am on August 7, 1997. This figure shows the temperature contour in a vertical cross section along TT1. With the 3D temperature field contour, temperatures within any cross section in the block can be illustrated. As shown in Figure 5-2, the temperature in the block began to show abnormal behavior shortly after 2500 hour, which was on June 12, 1997. The following figures show the duration and spatial distribution of the temperature variations. Excel, which is the software used to plot the temperature data, has a limit of 4000 data points in each series. Therefore, the temperature time plots are divided into several figures.”

The next section in the 1997 Status Report is a discussion of the first TH event (day 105.2).

“Figure 5-14 shows the temperatures at **TT1-8 to TT1-13** as a function of time from June 12 to July 23, 1997. Figure 5-15 shows the temperatures at **TT1- 14 to TT1-19** as a function of time from June 12 to July 23, 1997. As shown in these two figures the event at 2525 hour, in which the temperatures seemed to converge toward the boiling point of water, affected all of the RTDs included in those figures. But the amplitude of the temperature variation was most significant for **TT1-13 to TT1-19**.”

“The cause of this event is still under investigation. One of the possible explanations is that some mechanisms, such as fracturing, released the pressure in the superheated pore water and allowed hot water to flow quickly along the borehole toward the RTDs below. The temperatures at **TT1-13 and TT1-14** began to rise and fluctuate at about 2880 hour. At 2930 hour, the data acquisition rate was increased to once every 10 minutes to have a better sampling of the high-frequency fluctuation in the temperature.”

“The temperature fluctuation did not occur at RTDs **below TT1-13**, nor at RTDs **above TT1-22**. It did not occur at RTDs **TT1-17 and 18** either. Figures 5-16 and 5-17 show the temperatures at some of the RTDs in hole TT2 during the same period as that in Figures 5-14 and 5-15. The event at 2525 hour seemed also to affect those RTDs in TT2, with a much smaller amplitude than that in TT1. Then the high-frequency fluctuation in the temperature occurred at **TT2-13 and -14** at a later time than that at **TT1-13 and -14**. **TT2-13 and TT2-14** were the only two RTDs in this hole showing the temperature fluctuation before July 23, 1997. So far, as shown in Figures 5-18 to 5-21, up to August 7, 1997 most of the RTDs registered stable temperatures except **TT1-17 and TT1-19** in hole TT1, and TT2-19 in hole TT2.”

“The causes of the high-frequency temperature fluctuations at some of the RTDs are still under investigation. We had switched wires of one of the RTDs with that of one of the standard resistors at the junction box of the signal cables to verify that the fluctuation in temperature was not caused by the data acquisition system. **One of the possible causes of the fluctuation in temperature is the refluxing of the condensed pore water either in the block or within the vertical boreholes.** We will replace one of the removable RTDs with a thermocouple to see if the same behaviors in the temperature will be recorded by the thermocouple. In the final analyses of the measured data, the temperatures from all of the RTDs will be compared to search for correlation among the temperatures measured at various locations within the block. In addition, the correlation between the temperature measurements and other parameters, such as the displacements, will be evaluated.”

The following is from pg 6.1-5 of the Thermal Testing Measurements AMR (2002)

“As shown in Figure 6.1.1.2-1, the temperature at TT1-14 increased rapidly with time at the early stages of the heating. The temperature increased mainly from heat conduction. Rate of increase for the temperature decreased with time, mainly because of the decrease in thermal gradient at the RTD location as the thermal front expanded with time. When the temperature reached the boiling point of water, which is about 96°C at the elevation of Fran Ridge, the rate of temperature increase was significantly decreased. This decrease was caused by consumption of energy in the vaporization of the pore water in the rock. During the 20-day period between Day 30 and Day 50, the temperature at TT1-14 increased from about 96°C to about 98°C. After Day 50, the temperature at TT1-14 increased faster with time, indicating that most of the pore water had vaporized. **Then at Day 105 (June 13, 1997) the temperature dropped to near the boiling point of water. This is the onset of the first of the two thermal-hydrological (TH) events. The second TH event occurred at Day 186 (September 2, 1997). The temperature fluctuations in those TH events indicated condensate refluxing.** On Day 220 (October 6, 1997), the heater power started to ramp down to keep the TT1-14 temperature at approximately 137°C. The heaters were turned off on March 10, 1998, to start a natural cooling phase. The data acquisition was terminated on September 30, 1998.”

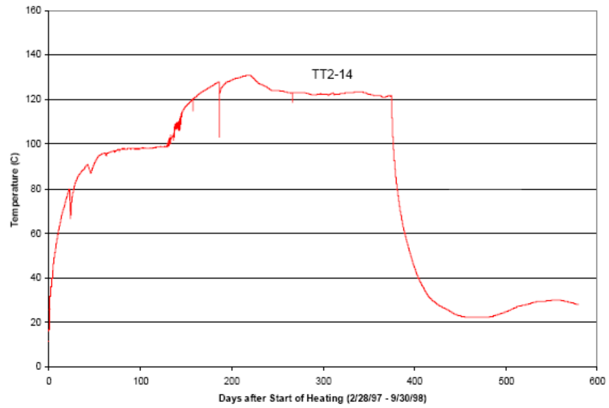


Figure 6.1.1.2-2. Temperature History at LBT TT2-14

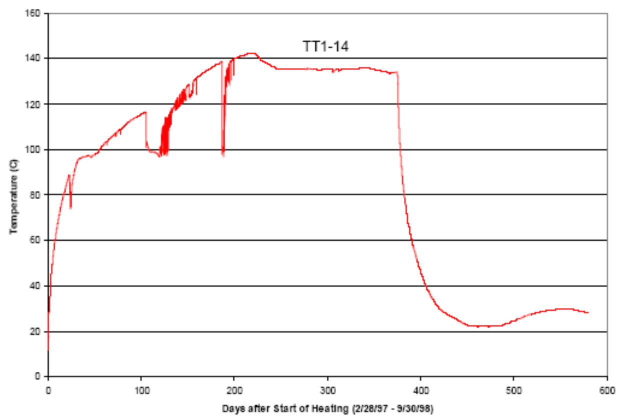


Figure 6.1.1.2-1. Temperature History at LBT TT1-14

Figures from: Lin, W.; Blair, S.C.; Wilder, D.; Carlson, S.; Wagoner, J.; DeLoach, L.; Danko, G.; Ramirez, A.L.; and Lee, K. 2001. Large Block Test Final Report. UCRL-ID-132246, Rev. 2. Livermore, California: Lawrence Livermore National Laboratory. TIC: 252918.

March 13, 2007 Ronald Green

The following is provided in Section 5 of the Large Block Test Final Report (Lin et al. 2001 [159069]).

"Figures 5-2 and 5-3 show the history of the heating at TT1-14 and TT2-14. These two RTDs are 5 cm above and below the heater horizon, respectively."

This statement is confusing. TT1-14 and TT2-14 are both below the heater horizon.

These figures are from the 1997 status report and only include the first 160 days of the test. The locations are corrected in the Final Report and the Thermal Testing Measurements AMR.

The LBT Final Report reports on page 5-2:

"TT1-14 and TT2-14 are at 5 and 10 cm below the heater plane, respectively."

And also:

"The temperatures at TT1-14 are about 10°C greater than those at TT2-14. This is mainly because TT1-14 is about 5 cm closer to the heater plane than TT2-14."

The location reported in the Final Report is believed to be representative of the final built. If so, then the comment in the 1997 Status Report that the RTDs in TT1 and TT2 are separated by 20 cm is incorrect. Based on the Final Report and the Thermal Testing Measurements AMR, the heater is at a depth of 2.75 m below the top of the block, TT1-14 is at a depth of 2.80 m, and TT2-14 is at a depth of 2.85 m.

The following discussion on the two TH events is from pages 5-3,4 of the Final Report:

"As shown in Figures 5-6 and 5-7, the temperature in the LBT illustrated two TH events on June 13, 1997, (Day 105.2) and September 2, 1997 (Day 186.5). There was no evidence that the June 13, 1997, event was associated with rain. It is known for certain that the September 2, 1997, event was associated with heavy rain, which had started the night before the event. The heat exchanger, which controlled the temperature on top of the block at about 60°C, was out of function for a few days starting on June 12, 1997 (Day 104.2). During the week from June 12, 1997 (Day 104.2) to June 19, 1997 (Day 111.4), the temperature of the block top varied from 59°C to about 42°C, then back to about 59°C. During the September 2, 1997, event the heat exchanger functioned normally. The common features of these two events included: the temperature at some RTDs decreased sharply; the temperature at some RTDs increased sharply; the temperature at those RTDs near the heater plane tended to converge to the boiling point of water; the temperatures stayed at the boiling point of water for a while then increased with time sequentially, apparently when the rock began to dry out; and during the drying process the temperatures fluctuated with time with high frequency. However, there are differences between these two events, as discussed in the following paragraphs."

March 14, 2007 Ronald Green

Discussion of the anomalous thermal responses observed during the LBT

There were two events during the 191-day long LBT that resulted in anomalous thermohydrogeological responses. The events were on days 105.2 and 186.5. The DOE interpretation is that causes for each event are different.

Temperatures of the anomalous events were recorded in several boreholes that had been instrumented with resistance temperature devices (RTDs. There were three sets of boreholes instrumented with RTDs: TT#, NT#, and WT#. In addition, the five heater boreholes, EH#, were monitored for temperature. The instrument locations were taken from the LBT 1997 status report.

In summary,

Event 1. Day 104.2. June 13, 1997. The heat exchanger, which controlled the temperature on top of the block at about 60°C, was out of function for a few days starting on June 12, 1997 (Day 104.2). During the week from June 12, 1997 (Day 104.2) to June 19, 1997 (Day 111.4), the temperature of the block top varied from 59°C to about 42°C, then back to about 59°C.

Event 2. Day 186.5. September 2, 1997. The September 2, 1997, event was associated with heavy rain, which had started the night before the event.

March 15, 2007 Ronald Green

Event 1 Description

Temperatures recorded at TT1-14 and TT2-14 are inspected in terms of Event 1. The responses of temperature at the two RTDs are different. The temperature at TT1-14 was approximately 116°C prior to Event 1. The temperature quickly dropped on Day 105 by about 20°C to the approximate boiling point of water. After about 10-15 days, the temperature at TT1-14 began to increase above the boiling temperature. The increase was not uniform and showed rapid fluctuations between the temperature of boiling and 110 to 115°C, although the average trend in temperature was increasing. This temperature response is illustrated in Figure 5-15 of the Thermal Testing Measurements AMR.

There was no obvious response in temperature at TT2-14 during Event 1. The temperature at TT2-14 had been at or slightly below boiling for a several week period leading up to Event 1 presumably as rock water was boiled off. The temporal plateau in temperature was a possible indicator that heat pipe conditions were present.

The temperature at both TT1-14 and TT2-14 began to increase about 15-20 days after Event 1. The temperature increase at both RTDs was precipitous.

The first TH event occurred at the 2525 hr time. Leading up to TH event 1, the temperature at TT1-14, which is located 5 cm below the heater horizon, was 116°C and at TT1-15, which is located immediately above the heater horizon, was 110°C. The temperature at TT1-16 was at boiling and the temperatures of the all RTDs above TT1-16 in borehole TT1 were all below boiling. After the onset of Event 1, the temperatures of the RTDs at TT1-14 and TT1-15 declined to 101-102°C. The temperature at TT1-16, which was at boiling, declined slightly, but remained close to boiling. In contrast to declines in temperature observed at TT1-14 and TT1-15, the temperatures at TT1-17 through TT1-19 exhibited fluctuating increases in temperature for about 300 hours. After 2880 hours, the temperature fluctuations halted and RTDs TT1-14 through TT1-19 stabilized essentially at the boiling temperature.

At about 2875 hours, the temperature at TT1-14 increased above boiling and soon began to exhibit large fluctuations in temperature. By the 3000 hour, the temperature fluctuations approached 15°C in amplitude, during which time they alternated between 114-115°C and boiling. At about the 2300 hour, the temperature at TT1-15 started to fluctuate, with minor fluctuations (i.e., 1-2°C) continuing until the 3130 hour. After this time, the temperature at TT1-15 steadily increased with fluctuations. The amplitude of these fluctuations did not exceed 10°C. At some point during the period 3200-3270, the temperature at TT1-16 increased above boiling and exhibited fluctuations generally in the range of 5°C.

March 15, 2007 Ronald Green

GED Interpretation

These temperature data are used to interpret TH Event 1. Failure of the heat exchanger at day 105.2 appears to be the only identified factor that could have altered the TH regime in the block from near the heater horizon to the block top. Failure of the heat exchanger resulted in the temperature of the block top decreasing by 17°C from 59°C to 42°C for a period of no more than a week, however the impact on the temperature and TH regime in the block appeared to have lasted significantly longer.

The impact of Event 1 was unambiguously seen in temperatures observed at TT1. The response of Event 1 at TT2 was subtle, but clearly captured by several RTDs. In particular, there was a slight (i.e., less 2°C) increase in temperature observed at several RTDs located below the heater horizon (i.e., TT2-10, TT2-11, TT2-12, and TT2-13). There was a subtle (i.e., less 0.5°C) decrease in temperature at TT2-14 and no discerned change in temperature at TT2-15 and TT2-16 (located above the heater horizon). The only significant thermal response observed in borehole TT2 during TH Event 1 was at RTD TT2-17 in which temperature was depressed by about 3-4°C. The temperature at TT2-17 appeared to remain depressed for about 15-20 days.

One question is whether TT1 and TT2 are open to water movement or are the RTDs completely grouted into the boreholes. The 1997 Status Report noted the following. "A bundle of RTDs was grouted with cement in temperature holes. Some of the RTDs were placed in thin-walled stainless-steel tubes so that they could be calibrated or replaced during the test." Temperature measurements in TT1 suggest that there is ample opportunity for refluxing to occur at RTDs TT1-13 through TT1-19. In the absence of additional information on installation of individual RTDs, it is difficult to discern if these TT1 RTDs were grouted or placed in open tubes. For the purposes of this interpretation, RTDs which exhibit rapid fluctuations are interpreted to be positioned such that there is sufficient open space available next to the RTD to allow for refluxing (i.e., dripping or episodic flow). Based on this conceptualization, it is assumed that TT1 is open, either via open tubes or by virtue of a fracture, to provide an avenue for refluxing water. Only some of the RTDs in TT2 appear to be open to refluxing water. In particular, only RTDs TT2-13, TT2-14, and possibly TT2-17 exhibited rapid temperature fluctuations during TH Event 1. RTD TT2-17 exhibited a relatively large response (i.e., a decrease of ~3-4°C) to TH Event 1, but the temperature decrease and subsequent increase did not exhibit rapid fluctuations observed by other RTDs.

This water was sufficient to cool TT1-14 and TT1-15 to the temperature of boiling. The source of this cooling water is not clear. It was reported that there was no significant precipitation at this time. Therefore, rainfall is precluded as a source of cooling water during Event 1. The source must be condensation that formed due to cooler temperatures

The interpretation is that the temperature at TDRs TT1-17, TT1-18, and TT1-19, which are located above the heater, increased (to about boiling) at the same time the temperature at TT1-14 and TT1-15 decreased. One possible explanation is all these TDRs were consumed by a heat pipe that stabilized the environment at a temperature close to boiling. This interpretation is supported by the observation that the temperature fluctuations at TT1-17, TT1-18, and TT1-19 prior to 2880 are not as rapid as those observed at boiling. A downward advancement of the heat pipe explains why there was a precipitous decrease in temperature at TT1-14 and TT1-15.

In support of this interpretation is the progression in which the heat pipe decreased with time as the pre-existing TH regime was re-established after the heat exchanger was continued. TT1-13, located 10-20 cm?? cm below the heater horizon, and TT1-14 were the first two to respond, at about 2880 hours. The next RTDs above the heater horizon to increase above boiling were, in order increased heating, TT1-15, TT1-16, and TT1-17.

The temperature at TT1-19 after hour 2930 is perplexing. The temperature abruptly rises by over 10°C to boiling at hour 2800. This suggests that heat pipe consumed TT1-19 soon after hour 2800. Since this phenomenon appears to have occurred slightly earlier at the RTDs lower than TT1-19, it could be argued that the heat pipe was rising during this time. The temperature at TT1-20 is not readily available, but there is no reason to think the heat pipe went much higher.

Temperatures exceeded boiling first at TT1-14, before other RTDs that are located above TT1-14. This suggests that sufficient water vapor to sustain a heat pipe may have been present above TT1-14 to maintain these RTDs at the boiling temperature. The temperature at TT1-19 behaves differently than other RTDs below it. Soon after TT1-14 supposedly dries out at hour 2880, the temperature at TT1-19 starts to fluctuate rapidly, but with boiling being the highest temperature and the lowest temperature at about 86°C. There are two possibilities: One is that the heat pipe receded to a lower depth and that cooler water vapor or air was entering from above. The rock temperature must be close to boiling to anchor the top temperature at boiling.

This last section describes an explanation of the response. But what caused these TH responses to Event 1? Points:

1) Borehole TT1 is apparently open to fluid movement. TT2 is not open, although several RTDs (i.e., TT2-13, TT2-14, and TT2-17) may be sufficiently close to a fracture to allow for refluxing and flashing.
2) The heat exchanger at the top failed at hour 2520 allowing the temperature at the top to drop from 59°C to 42°C. Although the temperature drop at the top would have been rapid, the temperature in the block would have been more gradual. Air temperature in fractures, however, could have been quicker.
3) The cooler temperature at the top must have allowed for water to condense at the top providing a source of water for the water that refluxed down borehole TT1.
4) This water was sufficient to cool the two RTDs that were above boiling (TT1-14 and TT1-15).
5) The refluxing water was heated by passing through the boiling zone and was sufficient in terms of mass and temperature to raise the temperature of the RTDs in TT1 that were below the heater horizon.

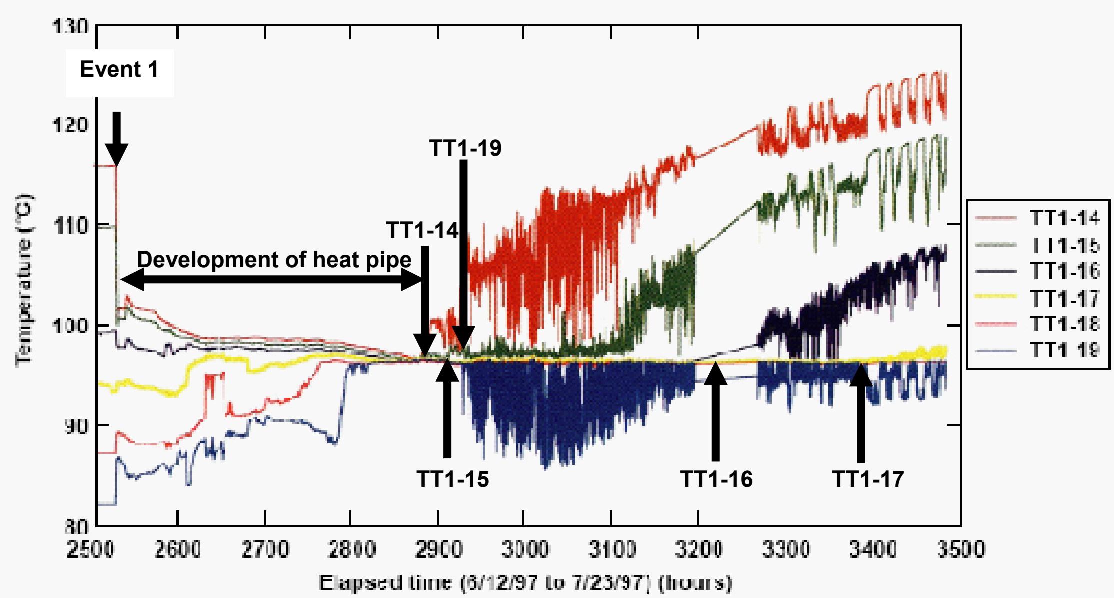


Figure 5-15. Temperatures at TT1-14 to -19 as a function of heating time.

The arrows denote the times at which the individual RTDs are no longer contained in a heat pipe. After that time, the RTDs are subject refluxing and episodic exposure to dripping water. This figure is from the August 26, 1997 LBT Status Report (Wilder et al., 1997).

Figure from: Wilder, D.G., W. Lin, S. C. Blair, T. Buscheck, R. C. Carlson (Woodward Clyde), K. Lee, A. Meike, A. L. Ramirez, J. L. Wagoner, and J. Wang (LBL). 1997. Large Block Test Status Report. Lawrence Livermore National Laboratory Livermore, California 94551. UCRL-ID-128776.

The following two graphs are for TT1 temperatures recorded during Event 1. The figures are from the 1997 Status Report. Event 1 occurred at 2525 hrs.

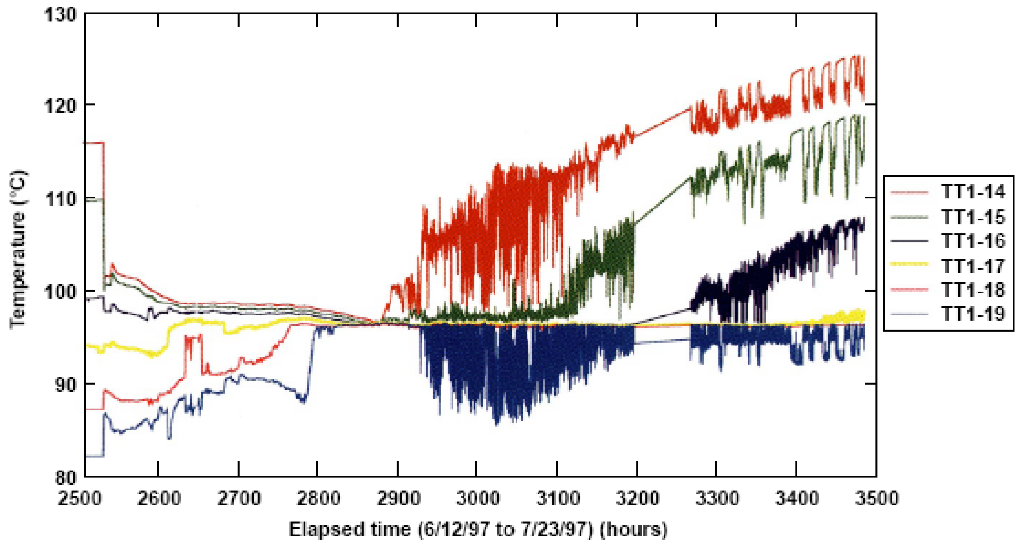


Figure 5-15. Temperatures at TT1-14 to -19 as a function of heating time.

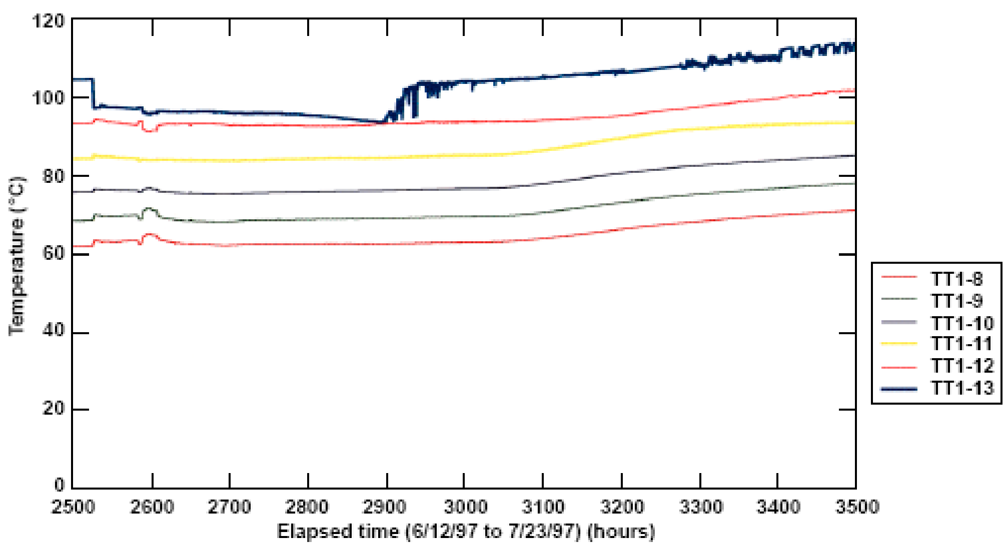


Figure 5-14. Temperatures at TT1-8 to -13 as a function of heating time.

Figures from: Wilder, D.G., W. Lin, S. C. Blair, T. Buscheck, R. C. Carlson (Woodward Clyde), K. Lee, A. Meike, A. L. Ramirez, J. L. Wagoner, and J. Wang (LBL). 1997. Large Block Test Status Report. Lawrence Livermore National Laboratory Livermore, California 94551. UCRL-ID-128776.

The following is taken from the Large Block Test Final Report, 2001, Lin et al.

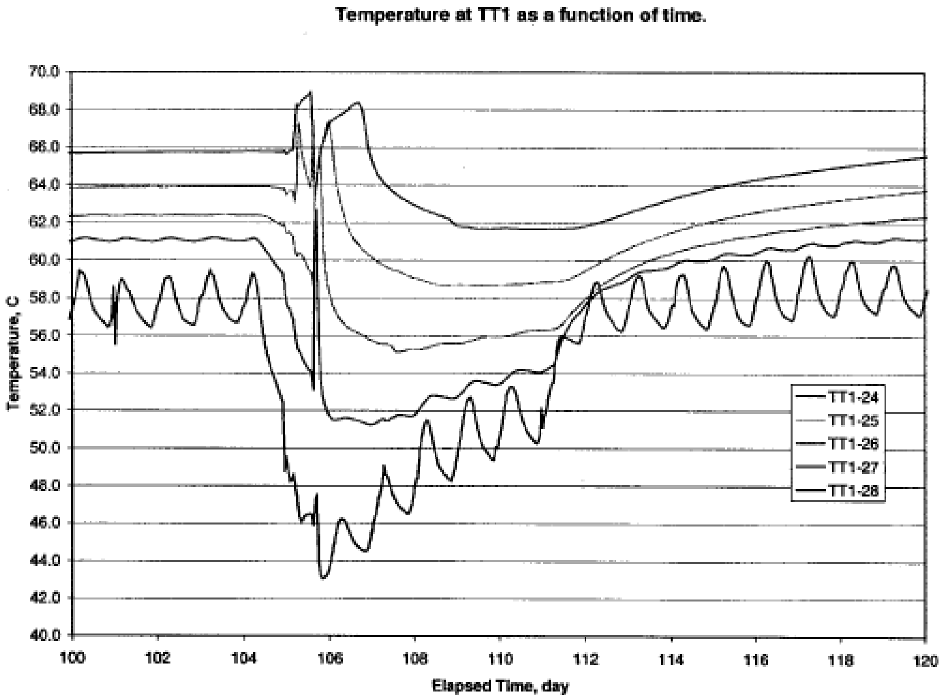


Figure 5-21. Temperature at TT1-24 to TT1-28, Showing the Effect of the TH Event on June 13, 1997 (105.2 Day)

Figure from: Lin, W.; Blair, S.C.; Wilder, D.; Carlson, S.; Wagoner, J.; DeLoach, L.; Danko, G.; Ramirez, A.L.; and Lee, K. 2001. Large Block Test Final Report. UCRL-ID-132246, Rev. 2. Livermore, California: Lawrence Livermore National Laboratory. TIC: 252918.

The bottom line (TT1-28) in the graph is the RTD closest to the top. It must be at the surface, or very close to it, because it reflects diurnal variations in temperature. From this graph, it appears the heat exchanger started working again at less than full power on day 106, and resumed full power on day 111. There is a temperature spike about one day after the heat exchanger failure. The spike is most prominent at TT1-27 and less prominent with depth as demonstrated by TT1-26, TT1-25, and TT1-24. Flashing of water is one possible source for the temperature spike. Movement up a fracture, rather than TT1, could explain why the spike is greatest at TT1-27 (closest to the fracture) than at other RTDs.

The following two graphs are for TT2 temperatures recorded during Event 1. The figures are from the 1997 Status Report. Event 1 occurred at 2525 hrs.

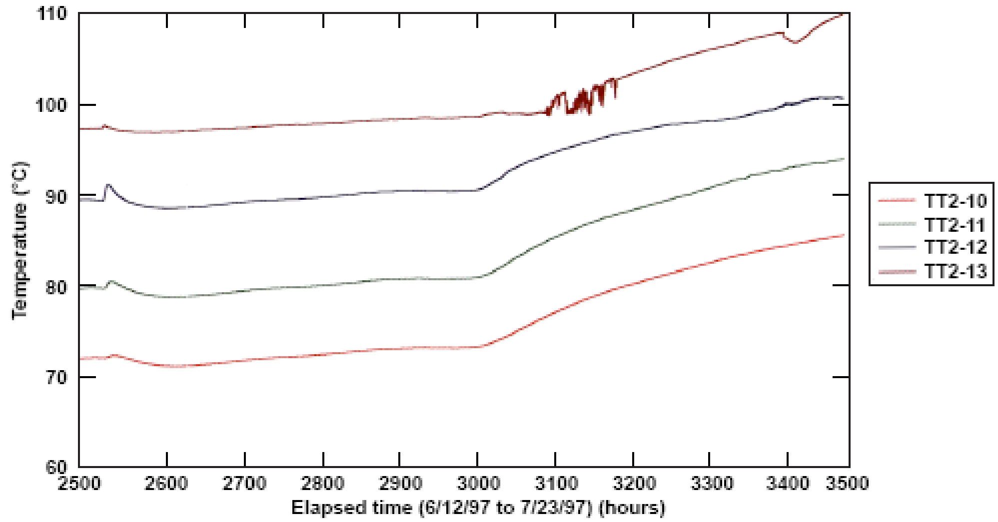


Figure 5-16. Temperatures at TT2-10 to -13 as a function of heating time.

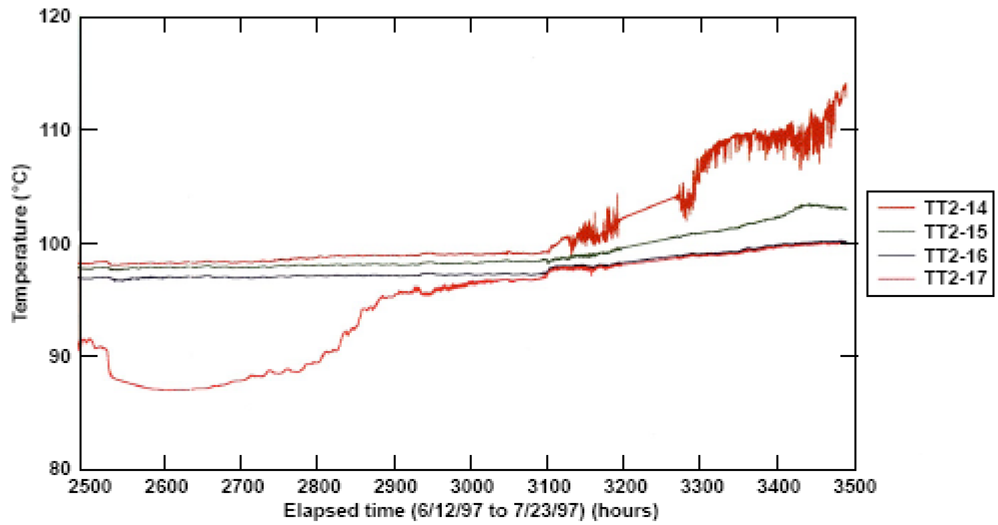


Figure 5-17. Temperatures at TT2-15 to -17 as a function of heating time.

Figures from: Wilder, D.G., W. Lin, S. C. Blair, T. Buscheck, R. C. Carlson (Woodward Clyde), K. Lee, A. Meike, A. L. Ramirez, J. L. Wagoner, and J. Wang (LBL). 1997. Large Block Test Status Report. Lawrence Livermore National Laboratory Livermore, California 94551. UCRL-ID-128776.

Although very subtle, the same general trends were observed in TT2 that were observed in TT1, that it: temperatures at RTDs below the heater horizon increased during Event 1 and temperatures at RTDs above the heater horizon decreased during Event 1. On exception is TT2-14 which is located 5 cm below the heater horizon.

The following two graphs are for TT1 temperatures recorded during a period between Event 1 and Event 2 when temperatures were mostly stable. From 1997 Status Report.

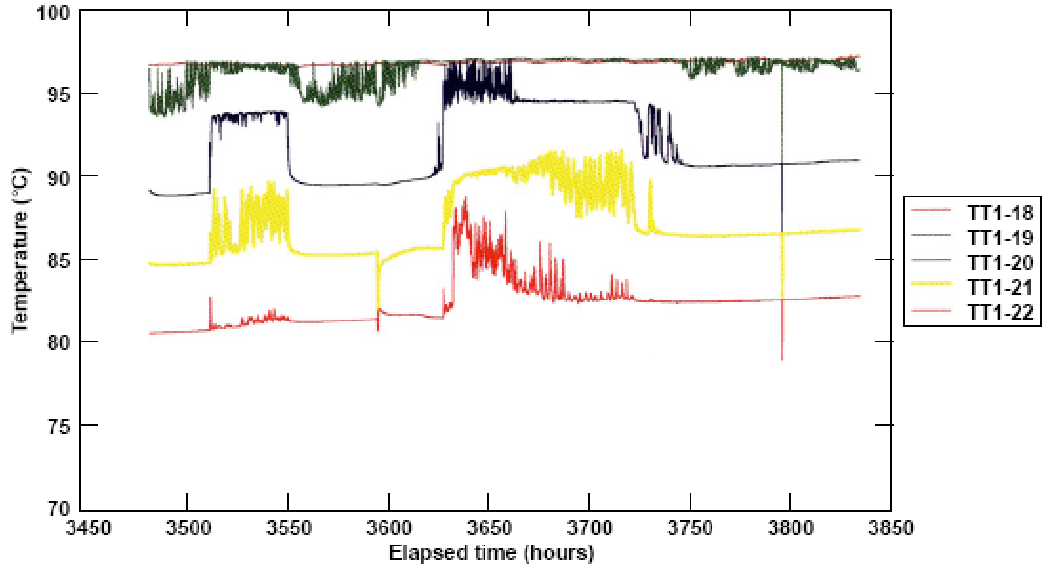


Figure 5-19. Temperatures at TT1-18 to -22 as a function of heating time.

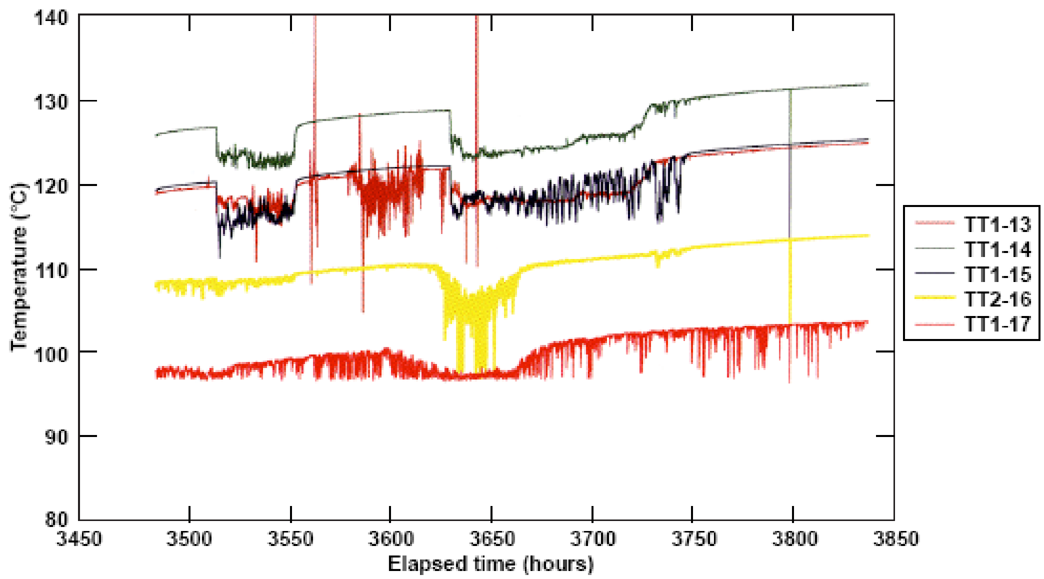


Figure 5-18. Temperatures at TT1-13 to -17 as a function of heating time.

Figures from: Wilder, D.G., W. Lin, S. C. Blair, T. Buscheck, R. C. Carlson (Woodward Clyde), K. Lee, A. Meike, A. L. Ramirez, J. L. Wagoner, and J. Wang (LBL). 1997. Large Block Test Status Report. Lawrence Livermore National Laboratory Livermore, California 94551. UCRL-ID-128776.

Although temperatures are relatively stable, evidence of TH observed during this quiescence period. A general comment is that RTDs above boiling are depressed to boiling by refluxing water and RTDs below boiling are increased by flashing water vapor. A minor event that occurred at about hour 3515 and lasted until 3550 clearly illustrates this coupled behavior.

March 22, 2007 Ronald Green

The following two graphs are for TT2 temperatures recorded during a period between Event 1 and Event 2 when temperatures were mostly stable. From 1997 Status Report.

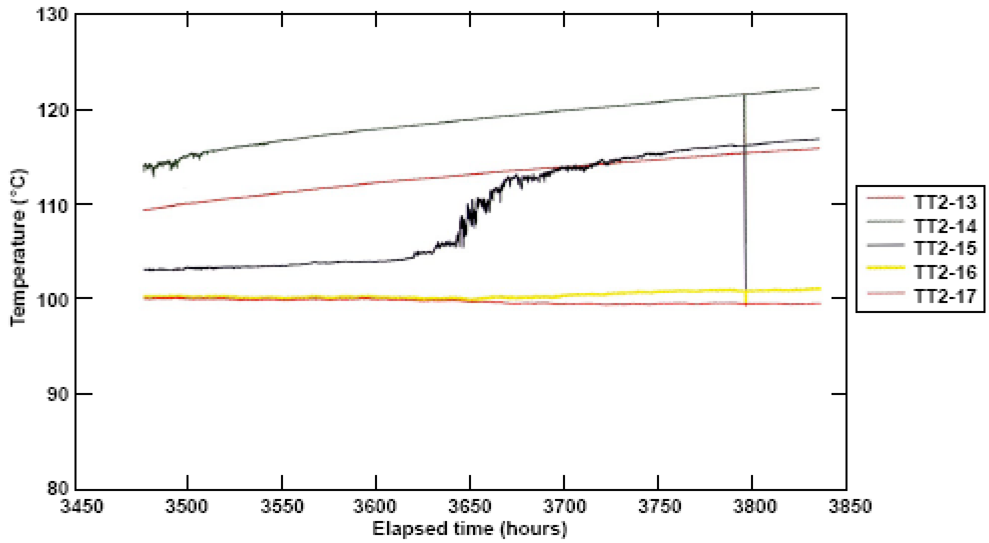


Figure 5-20. Temperatures at TT2-13 to -17 as a function of heating time.

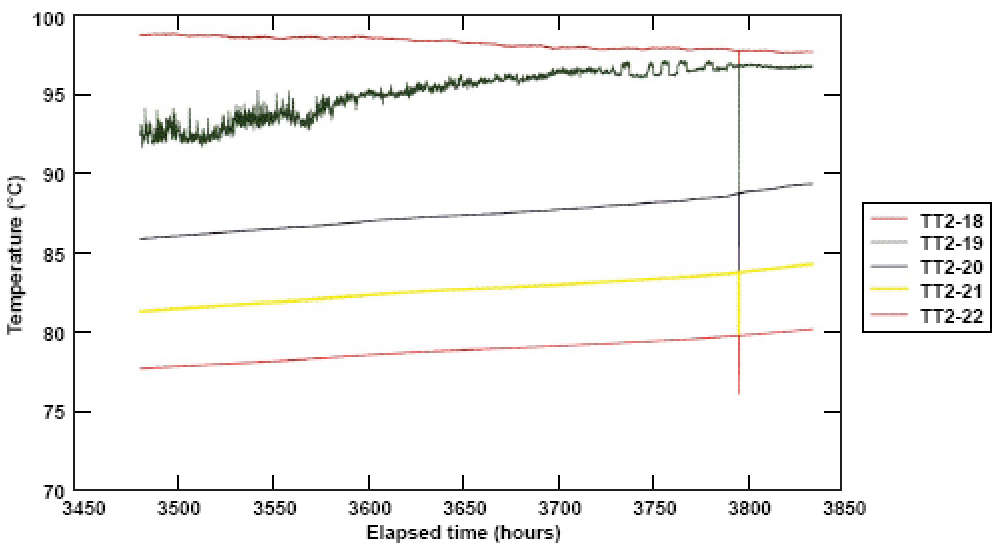


Figure 5-21. Temperatures at TT2-18 to -22 as a function of heating time.

Figures from: Wilder, D.G., W. Lin, S. C. Blair, T. Buscheck, R. C. Carlson (Woodward Clyde), K. Lee, A. Meike, A. L. Ramirez, J. L. Wagoner, and J. Wang (LBL). 1997.

Large Block Test Status Report. Lawrence Livermore National Laboratory Livermore, California 94551. UCRL-ID-128776.

There is minimal evidence of TH mechanisms active during this time.

The following is taken from the Large Block Test Final Report, 2001, Lin et al.

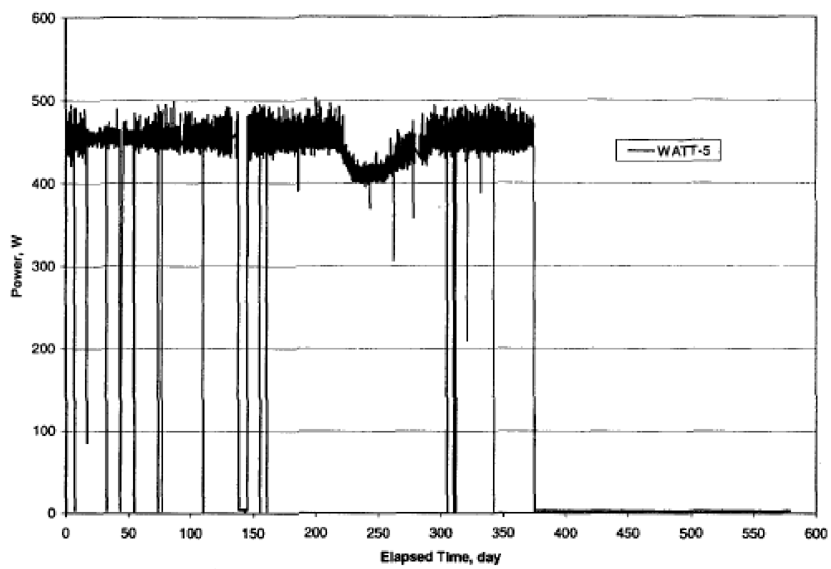


Figure 5-5. The Power Output of the Heater in EH5 as a Function of Time

Figure from: Lin, W.; Blair, S.C.; Wilder, D.; Carlson, S.; Wagoner, J.; DeLoach, L.; Danko, G.; Ramirez, A.L.; and Lee, K. 2001. Large Block Test Final Report. UCRL-ID-132246, Rev. 2. Livermore, California: Lawrence Livermore National Laboratory. TIC: 252918.

Although this is only one of five separate heaters, power cutoffs were the same for all five heaters.

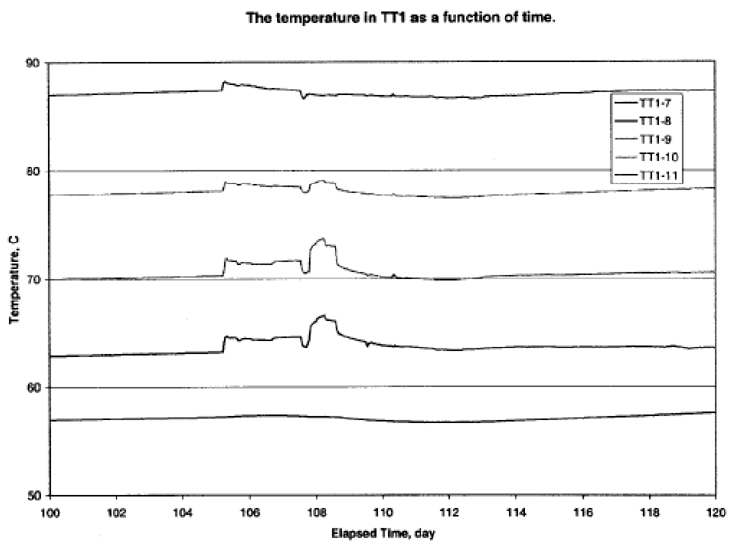


Figure 5-18. The Temperature at TT1-7 to TT1-11, Showing the Effect of the TH event on June 13, 1997 (105.2 Day)

Figure from: Lin, W.; Blair, S.C.; Wilder, D.; Carlson, S.; Wagoner, J.; DeLoach, L.; Danko, G.; Ramirez, A.L.; and Lee, K. 2001. Large Block Test Final Report. UCRL-ID-132246, Rev. 2. Livermore, California: Lawrence Livermore National Laboratory. TIC: 252918.

March 23, 2007 Ronald Green

Following are figures from the Final Report showing effect of 2nd TH event (heavy rainfall), Event 2, recorded at RTDs 7 to 28 in TT1.

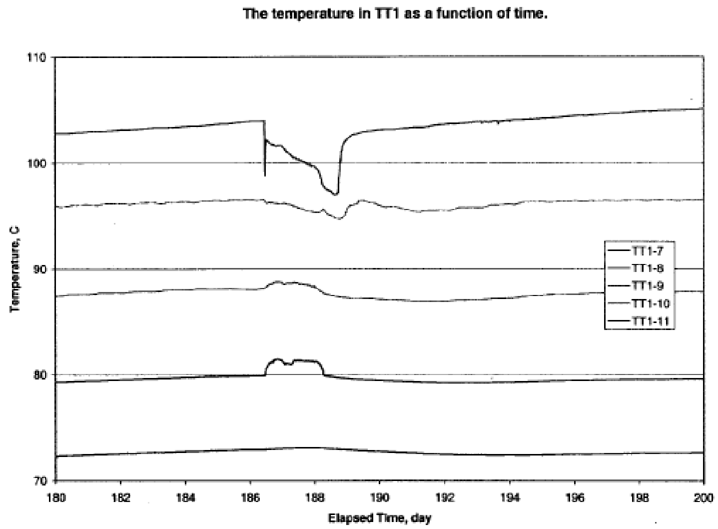


Figure 5-22. The Temperature at TT1-7 to TT1-11 as a Function of Time, Showing the Effect of the TH Event on September 2, 1997 (186.5 Day)

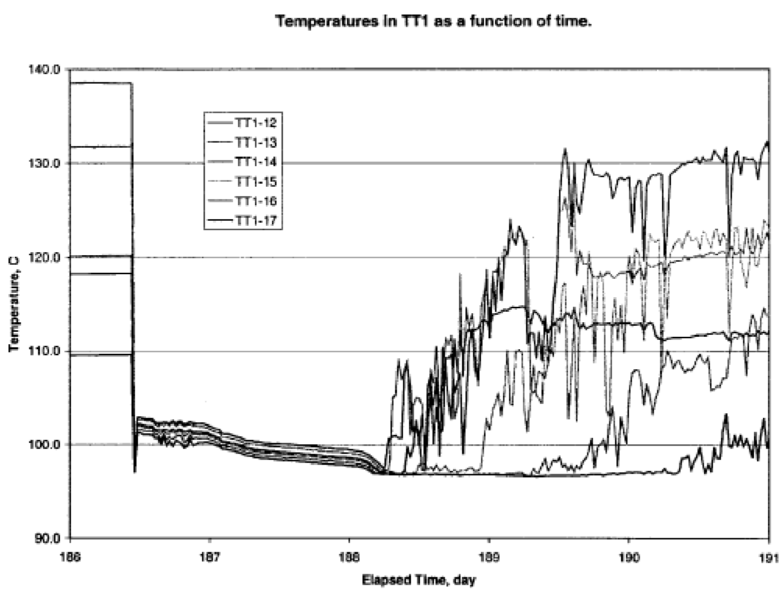


Figure 5-23. The Temperature at TT1-12 to TT1-17 as a Function of Time, Showing the TH Event on September 2, 1997 (186.5 Day)

Figure from: Lin, W.; Blair, S.C.; Wilder, D.; Carlson, S.; Wagoner, J.; DeLoach, L.; Danko, G.; Ramirez, A.L.; and Lee, K. 2001. Large Block Test Final Report. UCRL-ID-

132246, Rev. 2. Livermore, California: Lawrence Livermore National Laboratory. TIC: 252918.

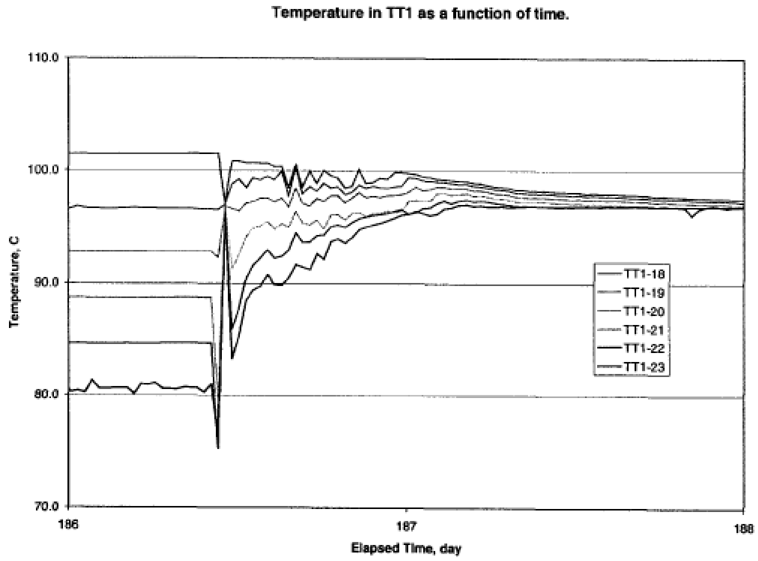


Figure 5-24. The Temperature at TT1-18 to TT1-23, Showing the Effect of the TH Event on September 2, 1997 (186.5 Day)

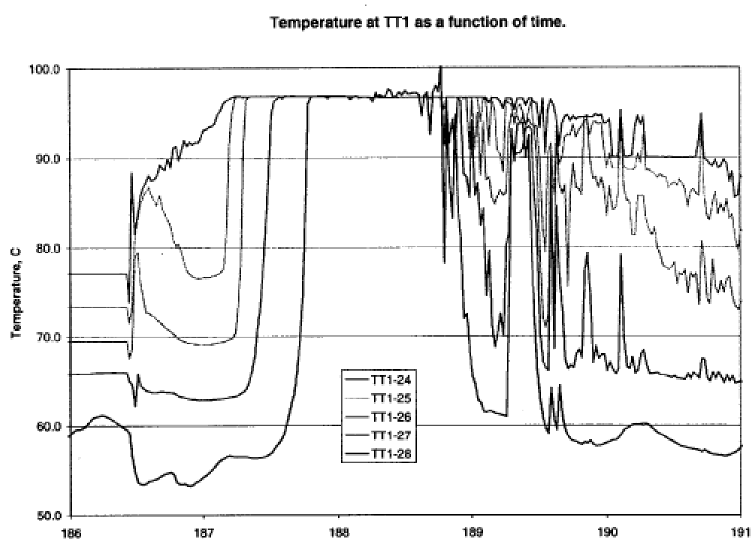


Figure 5-25. The Temperature at TT1-24 to TT1-28, Showing the Effect of the TH event on September 2, 1997 (186.5 Day)

Figures from: Lin, W.; Blair, S.C.; Wilder, D.; Carlson, S.; Wagoner, J.; DeLoach, L.; Danko, G.; Ramirez, A.L.; and Lee, K. 2001. Large Block Test Final Report. UCRL-ID-132246, Rev. 2. Livermore, California: Lawrence Livermore National Laboratory. TIC: 252918.

March 26, 2007 Ronald Green

Event 2. The large rain event occurred at day 186.5. It immediately depressed the temperature at every RTD from the top down to TT1-11, with the time to depression taking slightly longer with greater depth. All temperatures that were depressed, were depressed to boiling or lower. However, as soon as the water or vapor as part of a heat pipe apparently reached the heater horizon, where temperatures were as high as 138°C, water flashed and temperatures at all RTDs from TT1-11 and above began to increase. With the exception of TT1-28 at the top, the temperature increase was abrupt. This supports the "flashing" hypothesis. After the flashing event, temperatures at TT1-20 through TT1-27 were again lowered. It appears there was a second pulse of water that entered the TT1 borehole. The total time for these events was about an hour. Afterwards, the temperatures at TT1-12 through TT1-18 converged on the boiling temperature. It is interpreted that the second rain event was sufficient to immerse the RTDs in water or water vapor thereby establishing a heat pipe and stabilizing their temperatures at boiling until day 188.2. After which time, the RTDs began to dry out or the heat pipe collapsed and temperatures increased above boiling.

There was sequential immersion and drying through this process. The heat pipe started at the RTDs near the heater horizon and expanded to the top. RTDs above the heater horizon were subsequently included in the heat pipe as borehole TT1 eventually consumed enough water to sustain a heat pipe at the boiling temperature. At day 188.2, the heat pipe started to fail, first at the heater horizon shrinking toward the top, eventually disappearing by day 189.5.

Temperature responses at approximate day 189.2 indicate that a second recharge event was experienced. This recharge was best illustrated by the abrupt decrease in temperature at RTD TT1-14 and the corresponding abrupt increase in temperature in all RTDs below the heater horizon, that were previously a below boiling temperatures.

One perplexing issue remains. The temperatures at TT1-11 through TT1-18 do not immediately stabilize at the boiling temperature, as would be expected if they were part of a heat pipe. Instead, these temperatures first centered around 101-103°C, then steadily declined and eventually arrived at the boiling temperature (about 96°C) over the course of 1-1/2 days. RTDs above TT1-18 appeared to arrive at the boiling temperature quicker.

March 28, 2007 Ronald Green

Consensus GED Interpretation of LBT.

There were two TH events during the 375-day duration of the heating phase of the LBT. The first event occurred at day 105.2 and is attributed to a failed heat exchanger at the top of the block. The second event occurred at say 186.5 and is attributed to a large precipitation event that was allowed to introduce water into the top of the block. Although the events are different, there effects from each are similar, both events resulted in water getting introduced into the top of the block. The response to the two events had common characteristics. The original pulse of water depressed temperatures in areas where temperatures exceeded boiling. The water vaporized and moved upward raising temperatures in the top part of the block. The water vapor established a heat pipe that moderated temperatures at boiling over a relatively large region. Once the water vapor was driven off, the heat pipe collapsed allowing temperatures at and above the heater horizon to increase above boiling and temperatures below the heater horizon to decrease below boiling.

In general, decreases in temperature above the heater horizon correlated with increases in temperature below the heater horizon. This relationship is believed to have been driven by TH mechanisms where the decrease in temperature was caused by the downward flow of liquid water and the resulting generation of water vapor increased the temperature below the heater horizon. This mechanism is effective where the temperatures below the heater horizon are below boiling and the temperatures above the heater horizon are above boiling. Water vapor at the temperature of boiling thereby increases temperatures that are below boiling and decrease temperatures that are above boiling.

There is another TH phenomenon of potentially greater significance than the two recharge events. The RTDs captured temperature excursions during periods other than during the two TH events. Temperatures measured at TT1-16 and TT1-17 offer clear examples. Although the baseline temperature at TT1-17 exceeded boiling by 1-5°C during the 16 days of data presented in Figure 5-18 from the 1997 Status Report, there were frequent occurrences of rapid declines in temperature in which the temperature was decreased to the boiling temperature. Similarly, the there was an approximately 1-day period during these 16 days where the temperature was decreased at TT1-16 from its baseline temperature of about 110°C to the boiling temperature. There is additional evidence of rapid fluctuations, however, these two specific examples of temperature excursions provide an indication of liquid water refluxing into a place that was previously above boiling.

Prior to Event 1, the block appeared to be absent of sufficient water (potentially as either vapor or liquid) to affect temperatures, as evidenced by the quiescent temperatures (i.e., no fluctuations) prior to day 105. Temperatures returned to a mostly quiescent state leading up to Event 2 at day 186, after which temperature fluctuations were again encountered. The fluctuations are interpreted to occur only when liquid water was present.

March 29, 2007 Ronald Green

Section 5: 1985 Superior Road Tunnel heater test by the U of AZ

No information was available on this field test.

Section 6. Single Heater Test

References

CRWMS M&O. 1999. Single Heater Test Final Report. BAB000000-01717-5700-00005 REV 00 ICN 1. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000103.0634. 129261

Thermal Testing Measurements Report. 2002. ANL-NBS-HS-00041 REV 00.

From pg 6.2-1

The SHT was the first of several planned and conducted *in situ* thermal tests to investigate coupled processes in the local rock mass surrounding the potential repository. These coupled processes are thermally driven by heat released from an electrical heater that simulates heat from emplaced nuclear waste. The SHT is located in the same rock unit (Tptpmn) as the LBT, but the LBT block is from an outcrop while the SHT (and DST) are in situ or underground. More specifically, the SHT is located in Alcove 5 in the ESF as shown in Figure 6.2-1. The heating phase of the SHT started in August 1996 and continued for nine months until May 1997. The cooling phase continued for seven months until January 1998, at which time post-cooling characterization of the test block commenced. A detailed description of the SHT is in the Single Heater Test Final Report (CRWMS M&O 1999 [129261]).

A plan and cross section of the SHT are shown in Figure 6.2-2. The SHT block is approximately 12.9 m wide, 9.5 m deep and 5.5 m high. Forty-one boreholes with total length of 230 m are drilled into the block. Borehole 1 (shown in red in Figure 6.2-2) houses the single 5 m long heater capable of generating nominal 4 kW of heat. The other boreholes are installed with various equipment systems and sensors to monitor the thermal, mechanical, hydrological, and chemical responses of the rock as it was heated and cooled. Detailed description of the SHT as-built borehole locations is provided in Table 6.2-2. Coordinates of the various SHT sensors are provided in Appendix G of the Single Heater Test Final Report (CRWMS 1999 [129261]) and the respective Output-DTNs identified in Table 6.2-1. The origin of the SHT XYZ coordinate system is the center of the collar for the heater borehole. The X-axis is horizontal and positive to the right when facing the heater borehole, the Y-axis is also horizontal and follows the longitudinal direction of the heater borehole, and the Z-axis is vertical and positive in the upward direction. The borehole numbers in Figure 6.2-2 correspond to those in Table 6.2-2. Table 6.2-2 gives the sensor type or type of measurement for which any particular borehole is used. A total of 530 sensors were housed in the boreholes. Several boreholes were drilled for post-cooling characterization. The layout of the additional boreholes in the SHT block is shown in Table 6.2-3.

Table 6.2.4.1-1. Chemistry Analysis of SHT Borehole 16-4 Waters with Reported *In-Situ* Waters from the General Area

BH 16-4	SPC00521206 Suite 1	SPC00521245 Suite 2	SPC00521252 Suite 3	SPC00522238 Suite 4	Perched Water UZ-14 PT-4 [e]	SZ Ground-water J-13 [f]	Pore Water UZ-5-TP-4 [g]	Rainier Mesa Fracture Water [g]	SZ Ground-water G-4 [f]
Collection Date	11/25/96 *	02/04/97	02/27/97	05/22/97					
DCS Temp (°C)	NA	46.9	47.60	51.20					
	LLNL	LLNL	LLNL	LLNL					
Na (mg/L)	16	13.9	12.20	11.00	34.0	45.8	33	35	57
Si (mg/L)	16.8	17.4	14.50	15.20	32.1	28.5	99	25	21
Ca (mg/L)	13	9.76	8.65	7.70	27.0	13	58	8.4	13
K (mg/L)	2.5 2.69[a]	2.5	3.30	2.30	1.8	5	9	4.7	2.1
Mg (mg/L)	1.63	1.16	1.01	0.92	2.1	2.01	12	1.5	0.20
pH	6.2[h]	6.9	6.80	6.55		7.4		7.5	
HCO_3 (mg/L) [d]	188				141.5	129		98	139
F^- (mg/L)	0.44	0.12	<0.5	<0.50		2.18		0.25	2.5
Cl^- (mg/L)	2.54 2.1[b]	1.45	1.00	2.20	6.7	7.1	34	8.5	5.9
S (mg/L)	0.71		0.20	0.21					
SO_4^{2-} (mg/L)	1.83 1.5[b]	0.42	<2	<2	14.1	18.4	39	15	19
PO_4^{3-} (mg/L)	<0.03	<0.4	<2	<2		<10			
NO_2^- (mg/L)	<0.01	0.15	<2	<2					
NO_3^- (mg/L)	1.1	<0.4	<2	<2	14.5	8.8			
Li (mg/L)	<0.03	<0.03	<0.01	<0.01		0.048			
B (mg/L)	0.37	0.74	0.66	0.93		0.134			
Al (mg/L)	<0.06	<0.06	<0.06	<0.06	0.0	0.02			
Fe (mg/L)	0.74	0.13	0.30	0.03			74		
Sr (mg/L)	0.2 0.1850[a] 0.22[c]	0.14	0.12	0.11		0.04	559		
Rb (mg/L)	0.0066[a]								
Br^- (mg/L)	<0.02 0.008[b]	<0.4	<2	<2	0.1				
δ D	–101.7 –95.00[a] –93.1[c]	–99.6 –94.0[a]	–98.2	–100.6	–97.3	–98			–103
δ ^{18}O	–12.9 –11.80[a] –13.1[c]	–12.9 –13.1[a]	–12.8	–13.57	–13.4	–13			–13.8
Tritium	0.44 ± 0.19 TU <0.3 TU[b]				0.0				
$^{87}Sr/^{86}Sr$	0.71243[a] 0.71240[c]								
U (mg/L)	1.013×10^{-1} [c]								
$^{234}U/^{238}U$	8.03200[c]								

NOTE:
* This column contains non-Q data as discussed in text.
[a] LBNL data
[b] Los Alamos National Laboratory (LANL) data
[c] USGS data
[d] derived from charge balance
[e] Yang et al. 1996 [100194], p. 36, Table 6
[f] Harrar et al. 1990 [100814], p. 5.5, Table 5.1
[g] Harrar et al. 1990 [100814], p. 6.5, Table 6.1
[h] See text for description of pH measurement.

Findings of the SHT include:

"Electrical resistivity tomography and ground penetrating radar measurements in the Single Heater Test tend to suggest, as does dual permeability modeling, that rock moisture mobilized by heating drains (on condensation) by gravity via fractures to below the heated region rather than stay perched above it. This is an important finding with respect to a hot repository, and various observations in the Drift Scale Test so far are bearing this out. (from Executive Summary, CRWMS M&O. 1999)."

Also from the Executive Summary (CRWMS M&O. 1999):

"A number of the findings of the Single Heater Test listed above are also borne by the other thermal tests, namely, the Large Block Test and the early results of the Drift Scale Test. The following recommendations are, therefore, appropriate for taking into account in future total system performance assessments and the various analyses supporting them:

- The dual permeability model should be the preferred conceptual model over the equivalent continuum model for simulating the thermal-hydrological responses of the near-field rock mass in the drift scale. The dual permeability model should also be the preferred model for simulating the thermal-hydrological-mechanical responses.

- All three thermal tests indicate that the rock porewater mobilized by the heat tends to drain by gravity, via the fractures, to below the heated region rather than stay perched above it. **This means that condensate refluxing or episodic seepage into the emplacement drifts are unlikely to occur during the postclosure period."** Emphasis added here.

Noteworthy is the following description of monitoring (pg 3-7, CRWMS M&O. 1999):

"The temperature sensors were scanned and the temperature recorded by the DCS on an **hourly** basis starting from before the start of heating and during the entire heating and cooling phases. A detailed description of the thermal measurements can be found in Subsections 5.1.1 and 5.1.2 of the *Single Heater Test Status Report* (CRWMS M&O 1997b)."

Infrequent temperature measurement lessens the opportunity to capture temperature excursions.

The final report of the SHT provided the following hypothesis for minerals encountered during post-test analysis (CRWMS M&O, 1999, pg 6-46&7)

"6.4.9.2 Origin of Silica Tubules

The silica tubules in opal-A deposits are distinctive structures that have not been observed in natural opal-A at Yucca Mountain. Tubular structures of macroscopic dimensions in mineral deposits are widely recognized even in popular literature on caves, springs, and deep-ocean hydrothermal sites. The submicrometer-scale tubules from the

SHT are unlikely to have formed from dripping water or fluids streaming through an orifice. The potential roles of water vapor or condensed steam are difficult to assess. Maximum bottom-hole temperatures in NEU-2 were slightly below 80°C, although the bottom was only about half a meter away from the boiling front at the end of the heating phase (CRWMS M&O 1997b, pp. 3-3 and I-1). Vapor or steam could have entered the borehole carrying entrained fine mineral particulates to be deposited eventually on the borehole surface. There is no textural evidence, however, that vapor or steam were discharging into the borehole through minute pores at the locations where opal tubules were formed. It is therefore difficult to envision that vapor or steam played a direct role in the formation of the tubules.

A mechanism to form the tubules from liquid water may have involved capillary imbibition. The tubules may have formed by capillary suction of silica-bearing water into microscopic pores within the masses of amorphous silica deposited on the borehole surface. Some pores, without appended tubules, are visible in the opal mass of Figure 6-24. Evaporation at the pore openings may have led to the gradual deposition of new silica outward from the original opening, with more water being drawn into the developing tubule. As described above, evaporative mineral deposition may have occurred mostly during the cool-down phase of the experiment."

Also noted in CRWMS M&O (1999, pg 6-47) was:

"If a database on the three-dimensional distribution of secondary minerals were constructed, it would be possible to test whether attributes of mineralogy or mineral textures correlate with the geometries of the dryout and condensation zones. Evidence of reflux might also be detectable with a more complete investigation of mineral deposition in fractures."

This is interpreted to mean that insufficient fracture coating evidence was collected to form an opinion whether refluxing occurred and if it occurred, whether it was the source for the anomalous mineral assemblages.

Temperature measurements for the SHT are as follows:

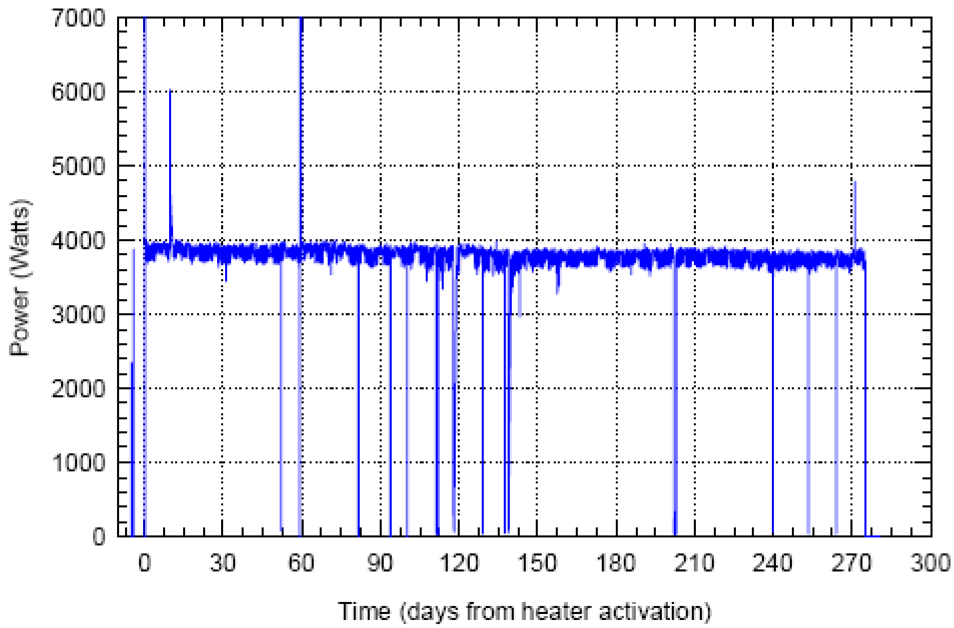
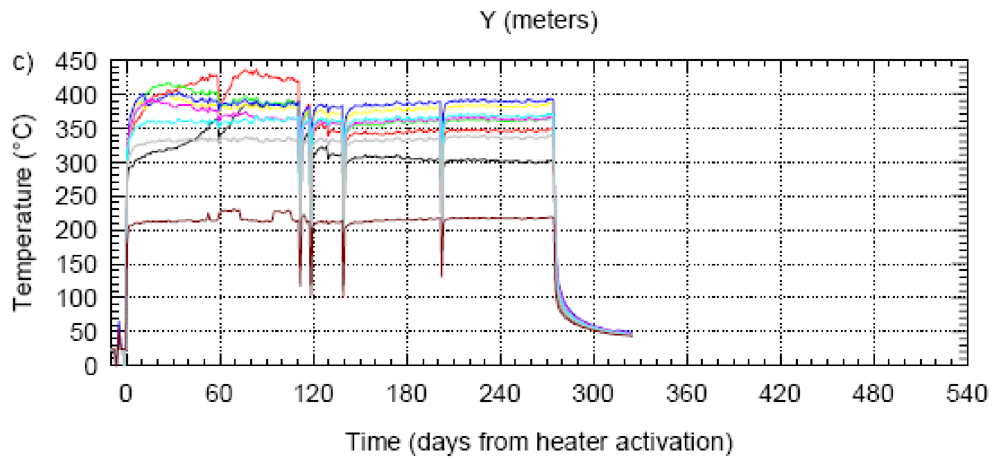


Figure 7-1a. Heater Power Summary through May 28, 1997



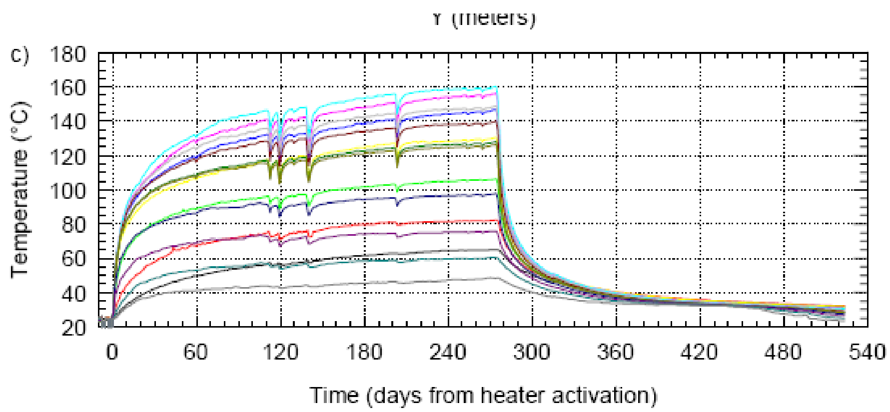
NOTE: Temperatures reflect measurements taken by thermocouples evenly spaced along the heater.
Temperature shown: (a) as a function of Y every 14 days during the heating phase of the SHT
(b) as a function of Y every 14 days during the cooling phase of the SHT
(c) as a function of time.

Figure 7-3. Median Daily Temperature of the Gages in Probe TMA-H-1-TCT (x=-0.005 m, z=0.04 m)

Figures from: CRWMS M&O. 1999. Single Heater Test Final Report. BAB000000-01717-5700-00005 REV 00 ICN 1. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000103.0634. 129261

As illustrated in Figure 7-3 from the SHT Final Report (CRWMS M&O (1999), there were 4 temperature excursions recorded by thermocouples placed on the surface of the heaters. The times of the excursions (i.e., 111, 119, 138, and 201) are well correlated with heater power shut downs (Figure 7-1a).

As seen in Figure 7-6, these temperature excursions were also observed at a depth of 0.42 m from the borehole wall into the rock.

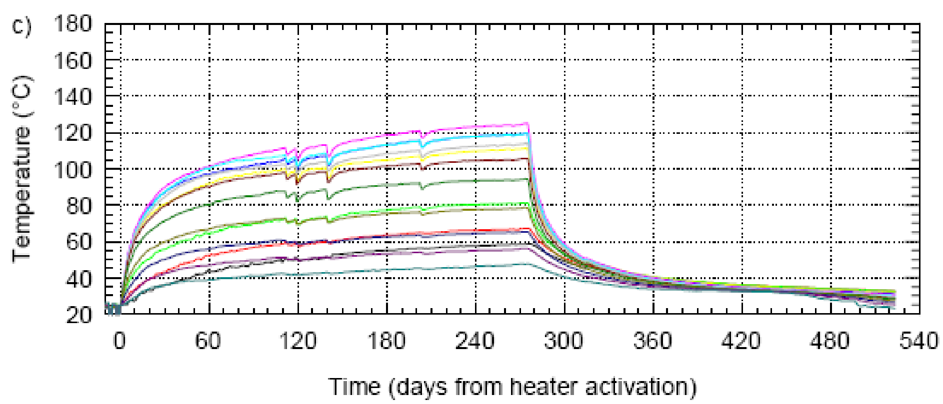


NOTE: Temperatures reflect measurements taken by thermocouples evenly spaced in a borehole parallel to and 0.42 m away from the heater.
Temperature shown: (a) as a function of Y every 14 days during the heating phase of the SHT
(b) as a function of Y every 14 days during the cooling phase of the SHT
(c) as a function of time.

Figure 7-6. Median Daily Temperature of the Gages in Probe TMA-TC-1 (x=-0.237 m, z=0.342 m)

Figure from: CRWMS M&O. 1999. Single Heater Test Final Report. BAB000000-01717-5700-00005 REV 00 ICN 1. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000103.0634. 129261

As seen in Figure 7-8, these temperature excursions were also observed at a depth of 0.66 m from the borehole wall into the rock, but were slightly more subdued.

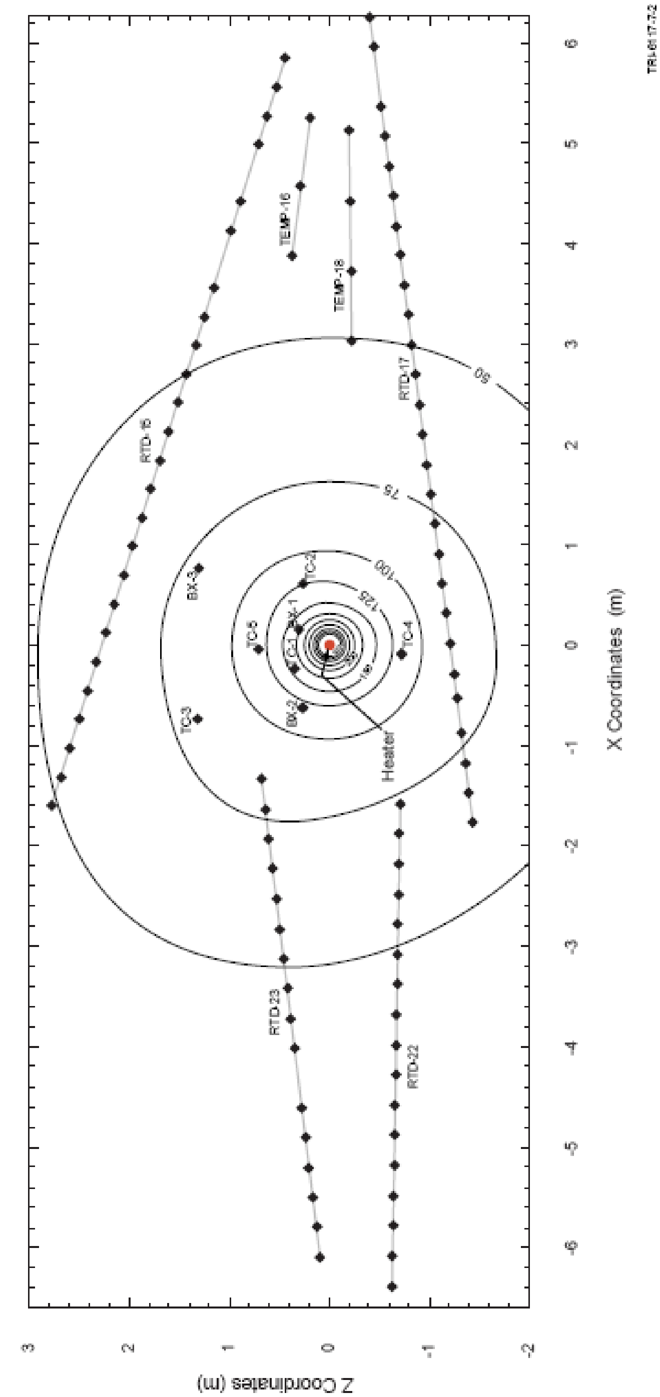


NOTE: Temperatures reflect measurements taken by thermocouples evenly spaced in a borehole parallel to and 0.66 m away from the heater.
Temperature shown: (a) as a function of Y every 14 days during the heating phase of the SHT
(b) as a function of Y every 14 days during the cooling phase of the SHT
(c) as a function of time.

Figure 7-8. Median Daily Temperature of the Gages in Probe TMA-TC-2 (x=0.613 m, z=0.263 m)

Figures from: CRWMS M&O. 1999. Single Heater Test Final Report. BAB000000-01717-5700-00005 REV 00 ICN 1. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000103.0634. 129261

There is no evidence of temperature excursions recorded by thermocouples at locations in the rock mass. This is not surprising. As can be seen in the following image (Figure 7-36, CRWMS M&O, 1999), the boiling isotherm did not penetrate sufficiently deep into the rock mass to be detected by thermocouples set in the rock mass.



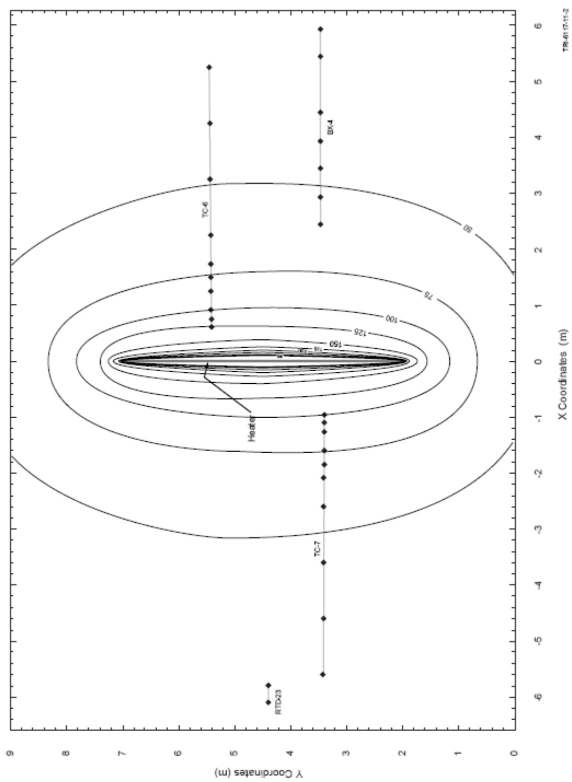
NOTE: Gages in close proximity to the plane of the slice are shown for reference. Contour interval = 25°C.

Figure 7-36. Temperature Contours, after 275 Days of Heating, on a Plane Perpendicular to the Heater Axis at Y=4.5 m

Figure from: CRWMS M&O. 1999. Single Heater Test Final Report. BAB000000-01717-5700-00005 REV 00 ICN 1. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000103.0634. 129261

The end thermocouples in boreholes TC-7 and BX-4 barely extend to the boiling isotherm. I was not able to find temperature measurements for these two boreholes.

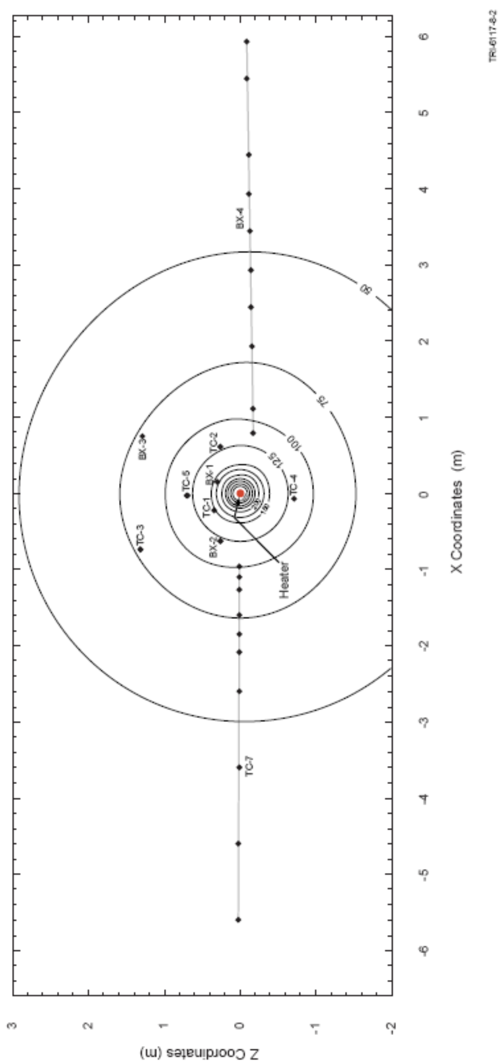
As can be seen by the following, TC-6 also extends into the boiling isotherm.



NOTE: Gages in close proximity to the plane of the slice are shown for reference. Contour interval = 25°C.

Figure 7-40. Temperature Contours on a Horizontal Plane Parallel to the Heater Axis at Z=0 m after 275 Days of Heating

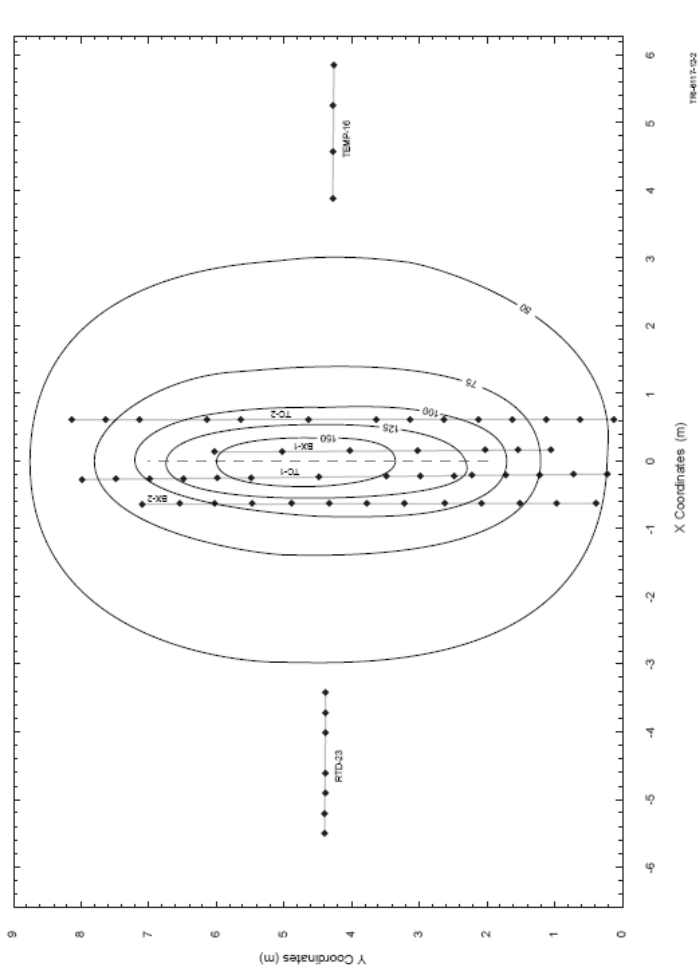
Figure from: CRWMS M&O. 1999. Single Heater Test Final Report. BAB000000-01717-5700-00005 REV 00 ICN 1. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000103.0634. 129261



NOTE: Gages in close proximity to the plane of the slice are shown for reference. Contour interval = 25°C.

Figure 7-37. Temperature Contours, after 275 Days of Heating, on a Plane Perpendicular to the Heater Axis at Y=3.5 m

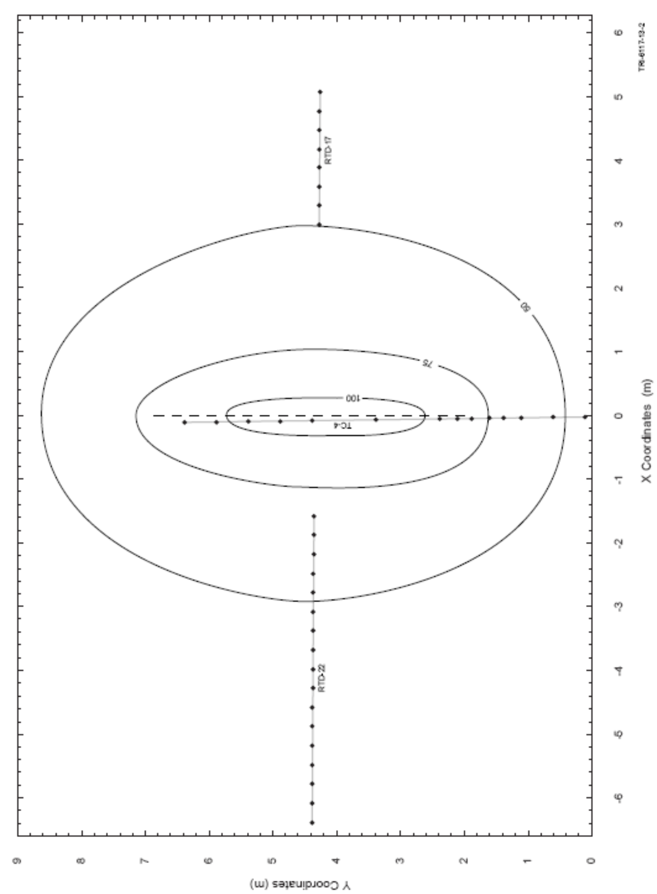
Figure from: CRWMS M&O. 1999. Single Heater Test Final Report. BAB000000-01717-5700-00005 REV 00 ICN 1. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000103.0634. 129261



NOTE: Gages in close proximity to the plane of the slice are shown for reference. Contour interval = 25°C.

Figure 7-41. Temperature Contours on a Horizontal Plane Parallel to the Heater Axis at Z=0.3 m after 275 Days of Heating

Figure from: CRWMS M&O. 1999. Single Heater Test Final Report. BAB000000-01717-5700-00005 REV 00 ICN 1. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000103.0634. 129261



NOTE: Gages in close proximity to the plane of the slice are shown for reference. Contour interval = 25°C.
Figure 7-42. Temperature Contours on a Horizontal Plane Parallel to the Heater Axis at Z=0.7 m after 275 Days of Heating

Figure from: CRWMS M&O. 1999. Single Heater Test Final Report. BAB000000-01717-5700-00005 REV 00 ICN 1. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000103.0634. 129261

It is noted in CRWMS M&O (1999, 8-56) that:

"In borehole 9, for example, the temperature increases to nominal boiling within about 50 days, but then continues to increase without the evidence of a significant temperature plateau. The other sensors registering temperatures above 100°C show similar behavior; it seems that the rock properties in the SHT do not allow for appreciable liquid reflux from the condensation zone back to the heater."

Temperature data are not provided in CRWMS M&O (1999) for the thermocouples located inside the boiling isotherm. Therefore, it is not known if there were temperature excursions.

April 2, 2007 Ronald Green

Corrosion

From pages 10-28 & 29 (CRWMS M&O (1999), the following discussion on corrosion is provided.

10.7 EFFECT ON WASTE PACKAGE MATERIAL COUPONS

As mentioned in Section 3.3.4, coupons or test specimens of carbon steel were placed in sections of boreholes 16 and 18 to observe the effect of heating and cooling on them. The temperature, relative humidity, and air pressure were monitored during the test. Temperatures in these sections of the boreholes rose during heating and the highest measured temperatures ranged between 36°C and 52°C. The relative humidity in these sections of boreholes 16 and 18 ranged between 85 percent and 100 percent. Also, zone 4 in borehole 16 was filled with water at different times during the heating phase of the test. Some of the metal coupons in 16-4 were thus submerged in water from time to time.

After the end of the cooling period and after the completion of post-cooling pneumatic measurements in these two boreholes, the packer systems in them along with the metal coupons were withdrawn and sent to the laboratory for analyses. All the metal coupons retrieved from boreholes 16 and 18 had undergone various degrees of corrosion. The corrosion products were identified by x-ray diffraction and Raman spectroscopy.

Goethite (α-$Fe_{+3}O(OH)$) and magnetite (Fe_3O_4) were identified on all the specimens that were analyzed. In addition, the chloride containing mineral akaganeite (β-$Fe_{+3}O(OH,Cl)$) was identified on a specimen that had been exposed to liquid water. The corrosion product on most specimens did not cover the entire surface and was somewhat adherent. The corrosion products on the specimens that were exposed to liquid water covered the entire surface, were voluminous, and were not adherent.

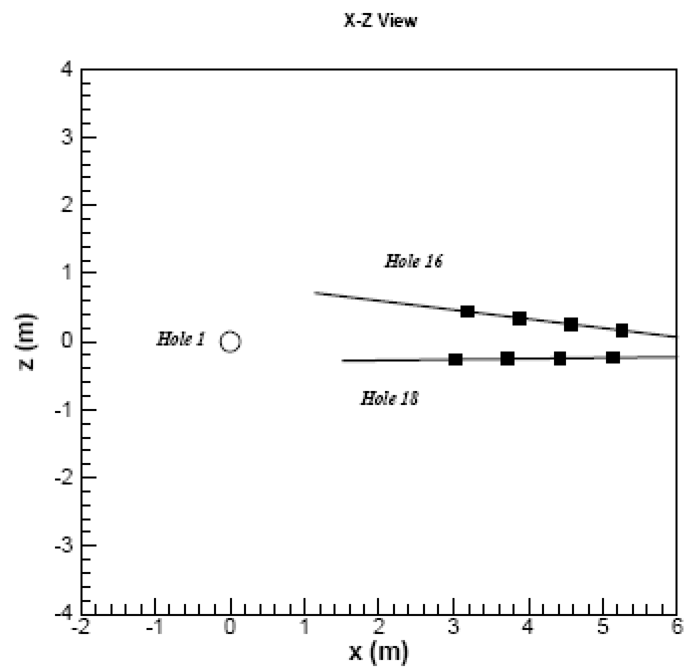


Figure 8-7. Multi-Zone Configuration of Borehole 1, and Boreholes 16 and 18 for Post-Cooling Air Injection Tests

Figure from: CRWMS M&O. 1999. Single Heater Test Final Report. BAB000000-01717-5700-00005 REV 00 ICN 1. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000103.0634. 129261

Figure 7-36 (above) shows that boreholes 16 and 18 are not near the boiling isotherm. They are apparently in the water shedding region. Nonetheless, there was some corrosion.

April 5, 2007 Ronald Green

Section 7: 1997-2005 ESF Drift-Scale Heater Test (DST) by LBNL

References

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Lin, W., J. Cho, J. Wagoner, and D. Wilder. 2001. Deformation of the Rock Mass in the Drift Scale Test. UCRL-JC-141167. 9th International High-Level Radioactive Waste Management Conference, Las Vegas, NV, April 29 – May 3, 2001

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Yucca Mountain Site Characterization Project. 2002. Effects of Introduced Materials in the Drift Scale Test. North Las Vegas, Nevada: Yucca Mountain Site Characterization Office. ACC: MOL.20020304.0044. 158176.

Bechtel SAIC Company. 2002a. Thermal Testing Measurements Report. ANL-NBS-HS-000041 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20021004.0314.

Bechtel SAIC Company. 2003. Technical Basis Document No. 5: In-Drift Chemical Environment. Revision 1. DE-AC28-01RW12101. Las Vegas, Nevada.

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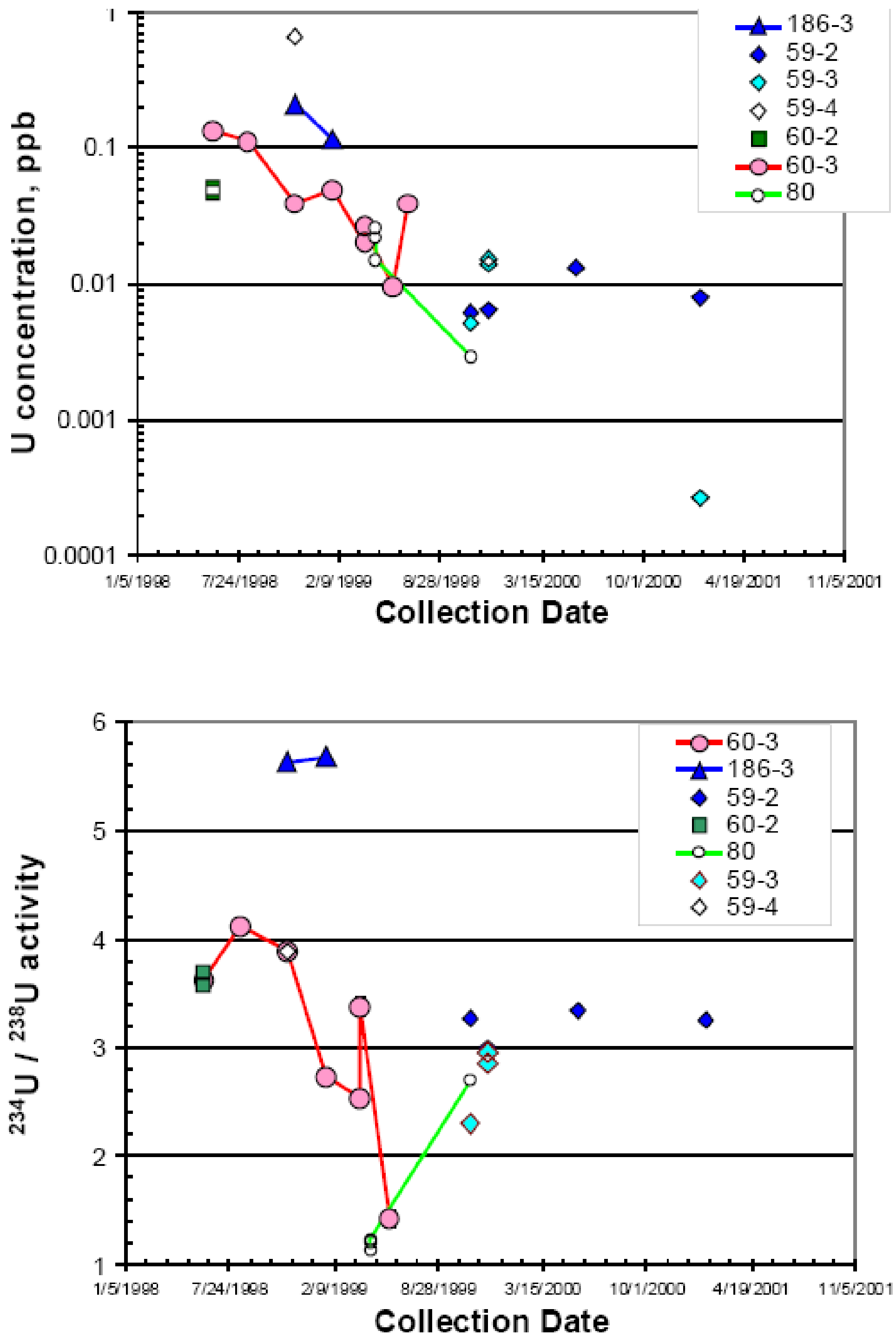
DE-AC28-01RW12101
QA: NA
November 2003

DST Water Chemistry

A small number of samples yielded distinctive, concentrated waters. Borehole 59-4 samples (November 1998 and January 1999) in particular appeared to be evaporatively concentrated, and boreholes 59-2 (August 1999) and 76-3 (October 1999) yielded waters with somewhat elevated concentrations of the principal analytes (BSC 2002a, Section 6.3.4.1). Strontium and Uranium in DST Water Samples–This section discusses strontium and uranium isotopic data obtained from a subset of water samples collected from the

DST during the heating phase (BSC 2002a, Section 6.3.4.1). Measurements of strontium and uranium concentrations and isotopic compositions in water samples may provide information on mineral reactions and water flow paths occurring as the block is heated during the test. In addition, isotopic analyses can provide evidence for interaction of test-produced water with the engineered materials introduced into the test block during construction. Uranium and strontium concentrations were determined by isotope dilution mass spectrometry, and the isotopic ratios were determined by thermal-ionization mass spectrometry (DTNs: GS011108312322.008; GS011108312322.009). Waters from DST locations sampled at successive times during the heating phase show a systematic decrease in uranium concentration with time (Figure 6.3.4.4-2). Temporal changes in U/238U are not as systematic. The general trends of decreasing uranium concentration with time are consistent with increasing proportions of condensate mixed in with pore water that was mobilized during the DST heating phase. The wide range in uranium concentrations observed in Topopah Spring pore waters makes it difficult to quantify the mixing fraction of condensate; however, all but two samples with uranium concentrations greater than 0.15 µg/L appear to contain at least some condensate. Samples with uranium concentrations less than 0.01 µg/L November 2003 3-9 No. 5: In-Drift Chemical Environment probably consist of more than 90 percent condensate. Even though these samples are particularly susceptible to contamination, most still have 234U/238U activity ratio within the range f observed pore water.

Bechtel SAIC Company. 2002a. Thermal Testing Measurements Report. ANL-NBS-HS-000041 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20021004.0314.



ıre 6.3.4.4-2 U Concentration (upper) and $^{234}U/^{238}U$ Activity Ratios (lower) in DST Samples Plotted versus Collection Date

Figures from: Bechtel SAIC Company. 2002a. Thermal Testing Measurements Report. ANL-NBS-HS-000041 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20021004.0314.

Source: BSC 2002a, Figure 6.3.4.4-2. Uranium Concentration and 234U/238U Activity Ratios in Drift Scale Test Samples Plotted November 2003 3-10 versus Collection Date

Table 4.3.4.1-1 is from the Thermal Testing Measurements Report 2002a. It lists all occurrences where liquid water was sampled from DST boreholes.

Table 6.3.4.1-1. Summary of DST Water Samples, the Field Data, and Important Observations through January 14, 2002

Date	Approx. Start Time	Approx. Finish Time	Est. Volume (mL)	Collection Hole/Zone	pH	Electrical Conductivity (mS/cm)	Total Dissolved Solids (ppm)	Sample Number	Solution Temp. (°C)	Comments
06/04/98	9:30		500	60/2	7.5			SPC00527968		anion
06/04/98	9:30		500	60/2	7.5			SPC00527969		metals
06/04/98	9:30		500	60/2	7.5			SPC00527970		O, H, & C
06/04/98	9:30		500	60/2	7.5			SPC00527971		Tritium
06/04/98	9:30		500	60/2	7.5			SPC00527972		U, Sr
06/04/98	9:30		500	60/2	7.5			SPC00527973		U, Sr
06/04/98	9:30		500	60/2	7.5			SPC00527974		^{36}Cl
06/04/98	9:30		2200	60/2	7.5			SPC00527975		Surplus H_2O
06/04/98	10:45		250	60/3	7.7			SPC00527977		
08/12/98	8:23	8:50	125	60/2	6.9			SPC00527915		
08/12/98	8:51	9:10	900	60/3	6.8			SPC00527916		
08/12/98	9:49	10:07	200	77/3	5.5			SPC00527917		
11/12/98	9:53	10:04	100	59/4	6.6			SPC00541803	25	Color noted as yellow by lab report
11/12/98	10:22	11:42	4000	60/3	6.9			SPC00541804	26.5 - 49.6	
11/12/98	13:37	14:04	3000	186/3	6.8			SPC00541805	34.3 - 35.1	
01/26/99	10:20	10:29	25	59/4				SPC00504397		Not Filtered
01/26/99	9:11	9:14	2000	60/3	7.36-7.44		140-141	SPC00504396	52	est. 3.5 L pumped, not filtered
01/26/99	11:33	11:50	800	186/3	7.24-7.17		320	SPC00527961		Not Filtered
03/30/99	9:50	10:10	700	60/3	8.0			SPC00529637		
03/30/99	12:40		200	77/3	7.0			SPC00529634	31	
04/20/99	9:00	9:32	175	60/3	4.19-4.50		30	SPC00551100	32-41	
04/20/99	12:00	13:45	500	60/3	4.8		10	SPC00551103	40	
04/20/99	9:15	10:07	375	BH80	6.39-6.72		30-50	SPC00551102	64	
05/10/99	10:20		40*	60/3	4.78-4.80	12.4	7.98	SPC00551104	21.1-24.0*	
05/10/99	10:24		40*	60/3	4.68	11.37	7.09	SPC00551105	34.8-36.3*	
05/10/99	10:10	10:29	175*	60/3	4.68-4.80*			SPC00551106	21.1-36.3*	100 mL used for alkalinity
05/10/99	11:04		40*	60/3	4.84	9.67-8.72	6.01-5.38	SPC00551107	35.3-41.3*	Conductivity & TDS represent pre - post filtration
05/25/99	9:40		40*	60/3	4.75	11.74	7.43	SPC00551111	26.4-27.3*	
05/25/99	9:23		40*	60/3	4.68	16.07	10.18	SPC00551110	24.1-25.6*	
05/25/99	9:10	9:50	150*	60/3	4.68-4.75*			SPC00551151	24.1-27.3*	100 mL used for alkalinity
05/25/99	10:04		40*	60/3	4.75	9.37	5.92	SPC00551112	24.8*	
06/24/99	9:17		40*	60/3	5.02	8.84		SPC00551154	27.5*	
06/24/99	9:25	9:55	170*	60/3	5.08*			SPC00551157	28.9*	100 mL used for alkalinity
06/24/99	9:25	9:27	40*	60/3	5.08			SPC00551156	28.9*	
10/27/99	12:54		150*	59/2	5.93	113.4		SPC00557028*	43.4*	
10/27/99	13:03		50*	59/2	6.08	110.2		SPC00557029*	52*	
10/27/99	13:27		250*	59/3	6.64	203.1		SPC00557035*	60.2*	
10/27/99	13:45		40*	59/3	6.81	192.3	118.1	SPC00557036*	62.3*	
10/27/99	14:27		50*	76/3	6.14-6.46			SPC00557039*	28.7*	
11/30/99	10:21		50*	59/2	7.53	80.8	52.84	SPC00557062*	39.5*	
11/30/99	10:24		150*	59/2	7.24	69.14	43.9	SPC00557080*	46.6*	
11/30/99	10:30			59/2	6.8	67.04	42.3			
11/30/99	10:38		40*	59/2		70.3	44.36	SPC00557063*	55.9*	
11/30/99	10:47		50*	59/3	7.06	105.2	65.86	SPC00557042*	47.3*	
11/30/99	10:50		150*	59/3	7.27	106.8	65.4	SPC00552575*	60*	
11/30/99	10:55		40*	59/3	7.47	112	63.8	SPC00557043*	68.4*	

Table 6.3.4.1-1. Summary of DST Water Samples, the Field Data, and Important Observations through January 14, 2002 (continued)

Date	Approx. Start Time	Approx. Finish Time	Est. Volume (mL)	Collection Hole/Zone	pH	Electrical Conductivity (mS/cm)	Total Dissolved Solids (ppm)	Sample Number	Solution Temp. (°C)	Comments
11/30/99	11:59		50"	76/3	7.04	307.2	196.6	SPC00552577"	37.7"	
11/30/99	12:03		150"	76/3	6.91	312.3	201.3	SPC00557065"	48.9"	
11/30/99	12:10		125"	76/3	6.86	317.7	199.4	SPC00552576"	57.9"	
11/30/99	12:20		40"	76/3	6.94	326.2	207.3	SPC00552579"	53.2"	
11/30/99	13:10		50"	77/3	4.68	156.4	9.99	SPC00557084"	45.2"	Reported conductivity and TDS values are suspect.
01/25/00	9:30		150"	59/2	7.43	104.7	67.1	SPC00550668"	27.1"	
01/25/00	9:33		150"	59/2	7.07	62.03	39.35	SPC00550669"	38.5"	
01/25/00	9:36		150"	59/2	6.85	63.01	39.31	SPC00550671"	51.5"	
01/25/00	9:45			59/2	6.68	61.21	37.89		57.5"	
01/25/00	11:35		50"	77/2	4.63	61.24	40.24	SPC00550672"	37"	
01/25/00	12:00		50"	77/3	3.47	224.9	145.5	SPC00550674"	36.8"	
05/23/00	11:58		150"	59/2	6.96	96.13	61.27	SPC00550680"	30.5"	
05/23/00	12:00		150"	59/2	6.95	96.55	61.91	SPC00550682"	42.6"	
05/23/00	12:15			59/2	6.96	99.73	61.76		60.4"	
05/23/00	12:26		120"	59/3	5.19	5.2	3.14	SPC00550687"	46.4"	
05/23/00	9:11		160"	76/3	6.92-6.96	134.8	86.86	SPC00550697"	21-40.8"	
06/29/00	11:20			59/2	6.81-6.92	100.3	62.73		47.2"	
06/29/00	11:24			59/2	7	111.7	68.4		58.4"	
06/29/00	11:27			59/2	6.99-7.06	79.9	49.12		50.9"	
06/29/00	11:45			59/3	5.39	4.39	2.74		40.4"	
06/29/00	11:50			59/3	5.6	4.7	2.91		45.9"	
06/29/00	12:00			59/4	4.6	13.72	8.48		50.2"	
06/29/00	12:03			59/4	4.74	14.83	9.21		49.2"	
06/29/00	9:35			76/3	5.75	13.81	8.64		35.8"	
06/29/00	9:46			76/4	4.74-4.77	12.85	7.99		34.4"	
06/29/00	10:10			78/2	4.12	35.64	20.44		32.8"	
06/29/00	10:18			78/3	4.22	28.54	17.78		42.1"	
08/21/00	10:46	10:52	20"	76/3	6.27-5.04					
08/21/00	10:52	11:02	15"	76/4	5.01-4.99					
08/21/00	11:03	11:10	10"	78/3	5.05-5.21					
01/23/01	12:00	12:03	100"	59/2				SPC00530399"		Ultrameter problem, no pH, TDS
01/23/01	12:00	12:03	100"	59/2				SPC00529636"		Ultrameter problem, no pH, TDS
01/23/01	12:00	12:03	100"	59/2				SPC00529635"		Ultrameter problem, no pH, TDS
01/23/01	12:00	12:03	90"	59/2				SPC00530398"		Ultrameter problem, no pH, TDS
01/23/01	12:13	12:15	60"	59/3				SPC00530316"		Ultrameter problem, no pH, TDS
01/23/01	12:13	12:15	60"	59/3				SPC00530314"		Ultrameter problem, no pH, TDS
01/23/01	12:13	12:15	60"	59/3				SPC00530313"		Ultrameter problem, no pH, TDS
01/23/01	12:13	12:15	60"	59/3				SPC00530397"		Ultrameter problem, no pH, TDS
01/23/01	12:30	12:35	30"	60/4				SPC00530318"		Ultrameter problem, no pH, TDS
04/17/01	10:10	10:25	120	59/2	4.9	6.6	10.4	SPC00559467	32	Preserved with HNO_3
04/17/01	10:10	10:25	100	59/2	5.3	6.7	4.2	SPC00559468	35	Preserved with HNO_3
04/17/01	10:40	10:50	200	59/3	6.0	54.2	34.7	SPC00559463	30	Preserved with HNO_3
04/17/01	10:40	10:50	100	59/3	5.8	30.6	19.0	SPC00559465	38	Preserved with HNO_3
04/17/01	11:15	11:30	200	59/4	5.2	9.8	6.1	SPC00559466	33	Preserved with HNO_3

Table 6.3.4.1-1. Summary of DST Water Samples, the Field Data, and Important Observations through January 14, 2002 (continued)

Date	Approx. Start Time	Approx. Finish Time	Est. Volume (mL)	Collection Hole/Zone	pH	Electrical Conductivity (mS/cm)	Total Dissolved Solids (ppm)	Sample Number	Solution Temp. (°C)	Comments
04/17/01	12:40	12:45	200	76/2	5.7	40.1	25.8	SPC00559460	29	
04/17/01	12:45	12:50	500	76/2	7.7	41.5	25.8	SPC00559464	43	Preserved with HNO_3
04/17/01	12:50	12:55	500	76/2	7.9	40.2	24.8	SPC00559461	48	
04/17/01	12:55	13:00	500	76/2	8.1	38.9	24.7	SPC00559462	33	
04/17/01	13:00	13:09	500	76/2	8.2	38.4	24.4	SPC00559459	29	
04/17/01	13:09	13:20	250	76/2	8.2	37.8	24.1	SPC00559458	30	
04/17/01	13:20	13:25	120	76/2	8.3	33.5	22.5	SPC00559456	33	
04/17/01	13:25	13:33	120	76/2	8.3	37.3	24.0	SPC00559457	31	
06/26/01			10	76/3	5.3		3.7		32	
06/26/01	11:40	11:55	80	76/4	5.5	11.2	6.7	SPC00559493	42	
06/26/01	12:10	12:20	25	78/2	5.3	5.2	3.2	SPC00559494	44	
06/26/01	12:25	12:35	25	78/3	5.0	5.2	3.4	SPC00559495	47	
06/26/01	12:40	12:50	25	78/4	5.0	6.7	4.0	SPC00559496	44	
06/27/01	10:40	10:50	240	59/2	5.2	6.1	3.6	SPC00559497	57	Preserved with HNO_3
06/27/01	10:50	11:25	500	59/2	5.1	4.5	2.6	SPC00559498	58	
06/27/01	11:25	12:10	500	59/2	5.2	4.2	2.5	SPC00559499	56	
06/27/01	12:10	12:40	100	59/2	5.6	6.4	3.8	SPC00559471	49	
06/27/01	12:40	13:15	500	59/2	5.1	4.6	2.7	SPC00559472	54	
06/27/01	13:15	13:35	25	59/2	5.5	4.5	3.1	SPC00559473	48	
06/27/01	13:35	14:20	500	59/2	5.2	4	2.4	SPC00559474	42	
06/28/01	12:30	12:50	100	59/3	4.9	8.3	5.1	SPC00559476	44	
06/28/01	9:20	12:00	400	BH-72	4.8	14.6	8.9	SPC00559475	55	Using flex-tubing and rods
06/28/01	13:30	13:50	40	60/3	3.3	189	115.0	SPC00559477	35	
06/28/01	13:55	14:05	10	60/4	5.1	10.5	8.8		39	
08/07/01			5	76/3	5.2	4.1	2.5		48	
08/07/01	11:55	12:05	60	76/4	5.4	7.8	4.7	SPC00559454	61	
08/07/01	11:55	12:05	15	76/4	5.4	7.8	4.7	SPC00575214	61	
08/07/01	12:15	12:25	100	77/2	3.3	284	173.0	SPC00559455	61	
08/07/01	12:15	12:25	15	77/2	3.3	284	173.0	SPC00575218	61	
08/07/01	12:35	12:45	60	77/3	3.3	231	138.0	SPC00559484	60	
08/07/01	12:35	12:45	15	77/3	3.3	231	138.0	SPC00575213	60	
08/07/01	12:55	13:05	30	78/2	4.5	8.8	5.2	SPC00559485	47	
08/07/01			5	78/3	5.2	9.1	5.6		40	
08/07/01			10	78/4	5.5	14.3	8.8		38	
08/08/01	10:30	10:50	500	59/2	5.4	2.2	1.3	SPC00559486	38	
08/08/01	10:30	10:50	15	59/2	5.4	2.2	1.3	SPC00575215	38	
08/08/01	11:00	11:40	200	59/3	4.9	6	3.6	SPC00559487	58	
08/08/01	11:00	11:40	15	59/3	4.9	6	3.6	SPC00575212	58	
08/08/01	11:50	12:05	200	59/4	5.1	2.8	1.6	SPC00559488	51	
08/08/01	11:50	12:05	15	59/4	5.1	2.8	1.6	SPC00575217	51	
08/08/01			5	60/1	4.8	25	15.0		35	
08/08/01	12:20	12:35	100	60/2	3.1	309	194.0	SPC00559490	52	
08/08/01	12:20	12:35	15	60/2	3.1	309	194.0	SPC00575216	52	
08/08/01	13:30	13:50	15	60/3	3.4	186	114.0	SPC00559491	56	
08/08/01	13:55	14:05	10	60/4	4.4	14.5	8.8		41	
10/22/01	10:30	10:40	50	76/3	5.2	8.4	5.1	SPC00575220	42	
10/22/01	10:45	10:55	30	76/4	5.1	5.2	3.0	SPC00575222	62	
10/22/01	11:05	11:15	100	77/2	3.1	403	245.0	SPC00575226	53	
10/22/01	11:20	11:30	30	77/3	3.2	344	206.0	SPC00575223	58	
10/22/01			5	78/1	4.2	11.6	6.9		57	

Table 6.3.4.1-1. Summary of DST Water Samples, the Field Data, and Important Observations through January 14, 2002 (continued)

Date	Approx. Start Time	Approx. Finish Time	Est. Volume (mL)	Collection Hole/Zone	pH	Electrical Conductivity (mS/cm)	Total Dissolved Solids (ppm)	Sample Number	Solution Temp. (°C)	Comments
10/22/01			5	78/2	4.8	5.6	3.3		52	
10/22/01			10	78/3	5.0	7.7	4.5		59	
10/22/01			10	78/4	5.4	10	6.0		53	
10/22/01	10:30	10:50	100	59/2	4.9	8.5	5.2	SPC00575227	52	
10/22/01			10	59/3	5.0	5.2	3.0		57	
10/22/01			10	59/4	4.9	6	3.5		61	
10/22/01	12:50	13:00	80	60/2	3.2	406	252.0	SPC00575225	56	
10/22/01	13:10	13:20	30	60/3	3.5	151	90.0	SPC00575221	56	
10/22/01	13:25	13:35	40	60/4	3.8	63	38.0	SPC00575224	49	
10/22/01			5	61/1	4.4	14.6	8.7		51	
10/22/01			10	61/3	4.9	7.9	4.8		45	
10/22/01			10	61/4	5.0	7.1	4.3		52	
11/08/01	14:45	15:10	50	BH 72	5.1	20.0	12.5	SPC00575228	28	HF Experiment
11/08/01				BH 72	5.5	17.5	10.8		27	HF Experiment
11/15/01	11:00	12:15	20	BH 55	7.5	279.0	176.0	SPC00575231	23	HF Experiment
11/21/01			100					SPC00559482		HF Exp., rinse of flex tubing
11/21/01			4	BH 55				SPC00559483		HF Experiment-not filtered
11/26/01	9:50	10:30	100	BH 72	5.3	13.8	8.6	SPC00575219	25	HF Experiment
11/26/01	13:10	15:10	20	BH 55	5.0	20.5	12.8	SPC00575229	24	HF Experiment
11/29/01	10:30	11:00	100	BH 72	3.8	39.7	24.3	SPC00559478	39	HF Experiment
11/29/01	10:30	11:00		BH 72	3.8	41.4	25.3		40	HF Experiment
11/29/01	11:30	14:30	13	BH 55	5.2			SPC00559479		HF Experiment
12/05/01	12:00	13:00	200	BH 72	3.5	111.5	70.6	SPC01016065	21	HF Experiment
12/05/01	12:00	13:00		BH 72	3.4	167.3	106.0		32	HF Experiment
12/05/01	12:00	13:00	500	BH 72	3.4	135.0	85.4	SPC01016066	20	HF Experiment
12/05/01	11:00	15:10	10	BH 55				SPC01016067		HF Experiment
01/07/02			2	BH 55				SPC01016084		HF Experiment
01/07/02	11:30	11:40	500	76/2	7.8	30.2	18.0	SPC01016082	52	
01/07/02	11:30	11:40	15	76/2	7.8	30.2	18.0	SPC01014151	52	
01/07/02	11:40	11:50	50	76/3	4.9	7.3	4.3	SPC01016076	56	
01/07/02	11:40	11:50	15	76/3	4.9	7.3	4.3	SPC01014154	56	
01/07/02	11:50	12:00	30	76/4	4.8	5.5	3.2	SPC01016074	55	
01/07/02	11:50	12:00	15	76/4	4.8	5.5	3.2	SPC01016071	55	
01/07/02	12:15	12:25	30	78/2	5.1	4.9	2.9	SPC01016075	44	
01/07/02	12:15	12:25	15	78/2	5.1	4.9	2.9	SPC01016070	44	
01/07/02	12:25	12:35	30	78/3	4.9	5.1	3.1	SPC01016078	43	
01/07/02	12:25	12:35	15	78/3	4.9	5.1	3.1	SPC01014147	43	
01/07/02	12:40	12:50	40	78/4	4.9	5.4	3.2	SPC01016072	40	
01/07/02	12:40	12:50	15	78/4	4.9	5.4	3.2	SPC01014149	40	
01/07/02	13:05	13:20	400	59/2	5.2	3.3	2.0	SPC01016083	30	
01/07/02	13:05	13:20	15	59/2	5.2	3.3	2.0	SPC01014150	30	
01/07/02	13:20	13:35	250	59/3	5.3	2	1.2	SPC01016079	34	
01/07/02	13:20	13:35	15	59/3	5.3	2	1.2	SPC01014153	34	
01/07/02	13:40	13:50	40	59/4	4.8	5.7	3.5	SPC01016073	35	
01/07/02	13:40	13:50	15	59/4	4.8	5.7	3.5	SPC01014152	35	
01/07/02	14:00	14:10	50	61/2	5.5	6.5	4.0	SPC01016081	32	
01/07/02	14:00	14:10	15	61/2	5.5	6.5	4.0	SPC01014148	32	
01/07/02	14:15	14:25	40	61/3	5.2	4.8	2.9	SPC01016080	28	
01/07/02	14:15	14:25	15	61/3	5.2	4.8	2.9	SPC01016068	28	

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Table 6.3.4.1-1. Summary of DST Water Samples, the Field Data, and Important Observations through January 14, 2002 (continued)

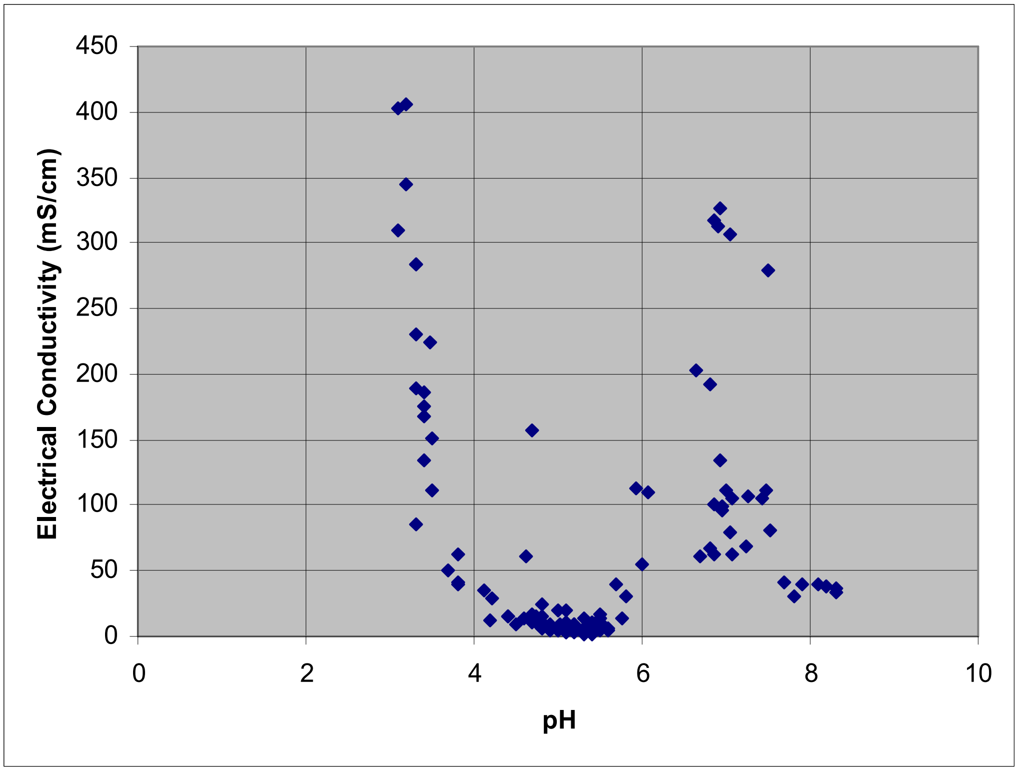
Date	Approx. Start Time	Approx. Finish Time	Est. Volume (mL)	Collection Hole/Zone	pH	Electrical Conductivity (mS/cm)	Total Dissolved Solids (ppm)	Sample Number	Solution Temp. (°C)	Comments
01/07/02	14:30	14:40	50	61/4	5.1	7.7	4.5	SPC01016077	33	
01/07/02	14:30	14:40	15	61/4	5.1	7.7	4.5	SPC01016069	33	
01/09/02	9:30	9:50	120	77/2	3.7	49.8	30.6	SPC01014156	41	
01/09/02	9:30	9:50	15	77/2	3.7	49.8	30.6	SPC01014159	41	
01/09/02	10:00	10:20	100	77/3	3.4	176	106.0	SPC01014155	54	
01/09/02	10:00	10:20	15	77/3	3.4	176	106.0	SPC01014158	54	
01/09/02	10:20	10:50	150	BH 72	3.3	85.8	54.9	SPC01014157	16	HF Exp. F.A. done on 1/16/02
01/09/02	10:20	10:50	15	BH 72	3.3	85.8	54.9	SPC01014160	16	HF Exp. F.A. done on 1/16/02

NOTES: 1) A single set of field measurements, in conjunction with multiple samples from a single borehole/zone, indicates that samples were split.
2) Volumes and temperatures listed are included for information only.
3) Small fluid volumes (<10mL) were depleted after conducting field measurements and not saved as samples.
4) Blank cell indicates no measurement recorded.
5) Asterisk indicates information source from Cho 2001 [159473].

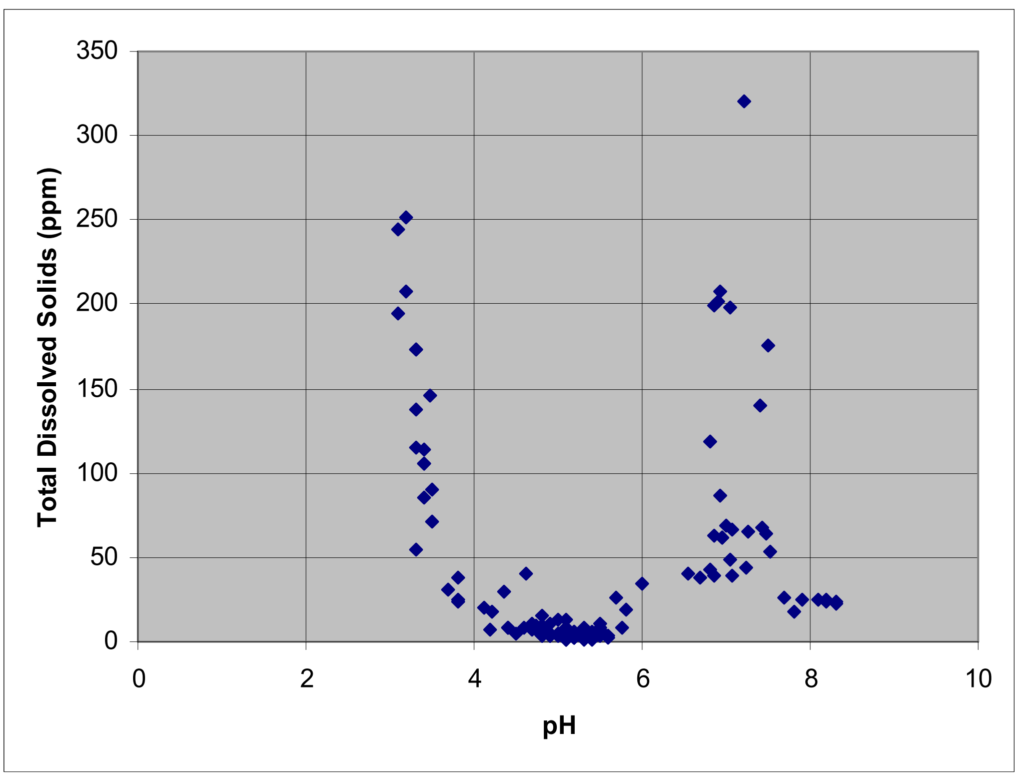
April 10, 2007 Ronald Green

Following are plots of water chemistry taken from Table 6.4.3.1-1 of the Thermal Testing Measurements AMR. Initially, it was thought that the high electrical conductivity and TDS associated with low pH water might be indicators of high concentration solute due to refluxing. Additional examination of the water chemistries indicates that chemical concentrations are too low to indicate refluxing water that has experienced increased concentrations due to evaporation. Instead, the measured chemistries are indicative of condensate water.

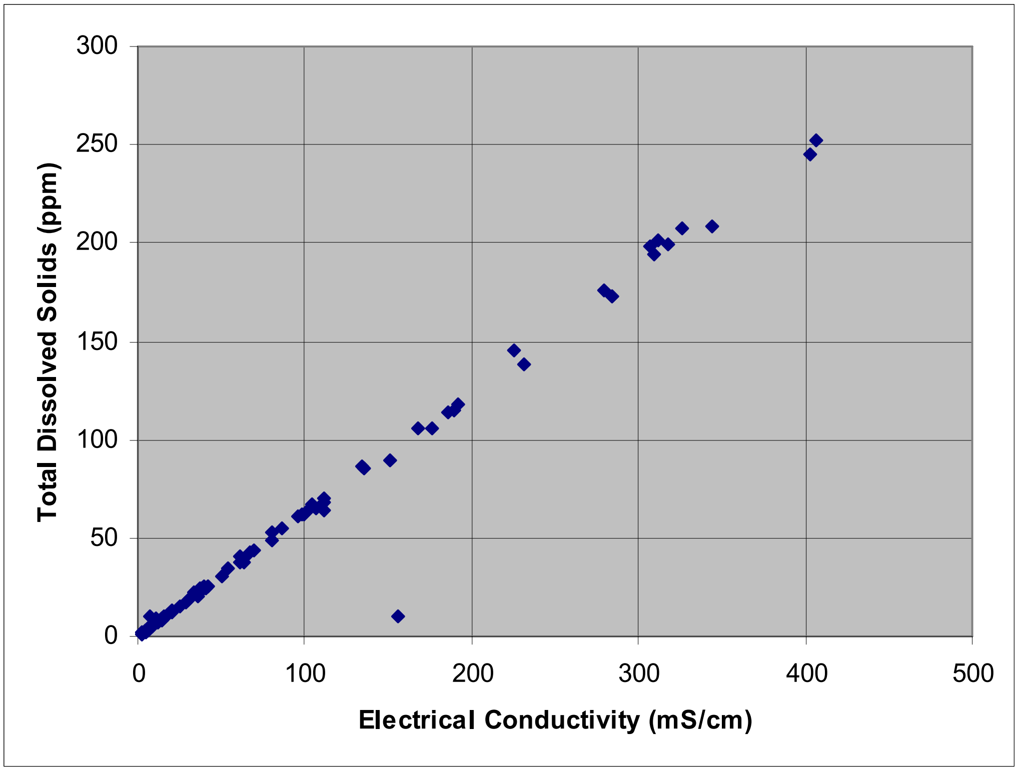
These observations are consistent with the explanation given in the Thermal Testing Measurements AMR on why some water quality indicators are what they are.



Electrical Conductivity (mS/cm)
450
400
350
300
250
200
150
100
50
0
0
2
4
6
8
10
pH



Total Dissolved Solids (ppm)
350
300
250
200
150
100
50
0
0
2
4
6
8
10
pH



The following is from the Thermal Testing Measurements Report AMR ANL-NBS-HS-000041 Rev 00, ICN 00. This is the DOE explanation of why elevated fluoride was detected in sampled waters. Review of their discussion and examination of the data suggest that their reasoning is plausible. Supporting their argument is that samples with elevated fluoride do not have elevated concentrations of other constituents that would otherwise indicate the water was from a reflux mechanism.

6.3.4.5 Investigation of Waters with High Fluoride Concentrations

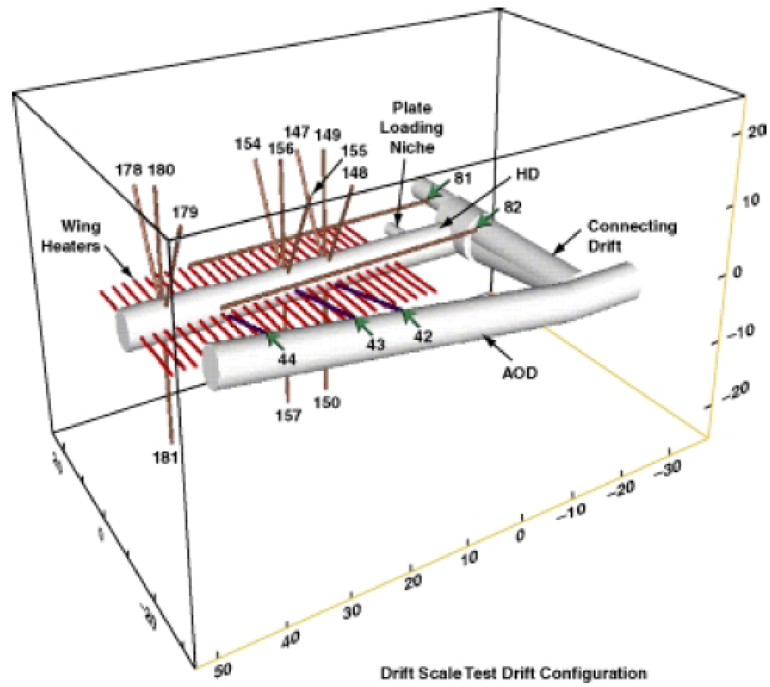
Certain water samples acquired from superheated (>140°C) zones within DST hydrological boreholes (see Table 6.3.4.1-2) show relatively high fluoride concentrations (9–74 ppm) and low pH (3.1–3.5) values relative to background values (sub-ppm fluoride and pH greater than 4.5). In these high-temperature regions of the rock, water is present as superheated vapor only—liquid water is formed during the sampling process by cooling. The compositions of these condensed steam samples show near-stoichiometric balance of hydrogen and fluoride ions, suggesting dissolution of hydrogen fluoride (HF) gas into the aqueous phase. Since HF can be corrosive, it could have deleterious effects on the performance of the waste package if it originated from the rock. If the source of the HF is from introduced materials, the source can be eliminated through use of alternative materials. Field and multiple laboratory tests were initiated to identify the source of the HF gas in the DST.

Several water samples were collected in the DST to determine whether the HF results from the degradation of materials originally introduced to facilitate measurements, or whether the HF could have been derived from fluoride-bearing minerals in the host rock. The materials introduced in this test include fluoroelastomer (abbreviated “FKM”) synthetic rubber manufactured by Seaquest Rubber company (similar in composition to Vitonä manufactured by DuPont) and Teflonä. The fluoroelastomer was used in making pneumatic packers to isolate test zones, while the Teflonä tubing was used to draw water and steam from the test zones.

Analyses of water samples taken both before and after the introduction of materials to a previously clean borehole in the DST demonstrate clearly that the source of the fluoride is the introduced materials. Data from the field tests were submitted to the TDMS with the following Input-DTNs: SN0203F3903102.001 [159133] and LL020405123142.019 [159307]. More detailed discussion of this investigation has been documented in a white paper (YMP 2002 [158176]).

June 17, 2007 Ronald Green

DST Temperature Evidence



Source: Borehole locations are from *Drift-Scale Test As-Built Report* (CRWMS M&O 1998).

Figure 1. Layout of the Drift-Scale Test. Numbered boreholes are those containing MPBX instrumentation.

Figure from: CRWMS M&O. 1998. Drift Scale Test As-Built Report. BAB00000-01717-5700-00003 REV 01.

This figure (Figure 1) is from Blair et al. (2001). Location of borehole 156, which contains MPBX-9, is vertical. Borehole 156 is on the middle fan of displacement sensors. The MPBXs (multiple point borehole extensometer) were installed at various locations. Each of the anchors was connected to a Delrin MPBX head at the collar with an Invar rod (Lin et al., 2001). There are 6 anchors in each of holes #42-44 and#81 -82; there are 4 anchors in each of the rest of the MPBX holes, including Borehole 156. A linear variable displacement transducer (LVDT) measured displacement of each anchor with respect to the MPBX head at the collar. Temperatures in the MPBX holes were measured by thermocouples installed adjacent to the Invar rods. The thermocouples are described as Type J (chromel-alumel) mineral insulated/metallic sheathed ungrounded thermocouples (CRWMS M&O. 1998). A schematic figure of an extensometer (Figure 5-3 from the As-Built Report, CRWMS M&O. 1998) is shown below. It is inferred from this diagram and the aforementioned discussion that there is sufficient open space in each anchor for direct transport of liquid water and water vapor.

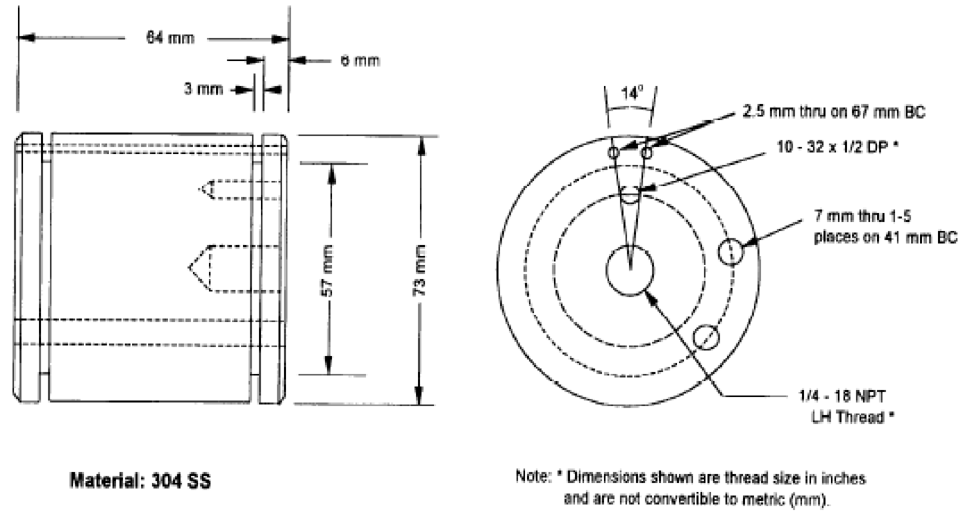


Figure 5-3. Front and Side Views of Multiple-Point Borehole Extensometer

Figure from: Bechtel SAIC Company. 2002a. Thermal Testing Measurements Report. ANL-NBS-HS-000041 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20021004.0314.

June 14, 2007 Ronald Green

Thermocouple junction locations were identified relative to borehole collar coordinates. The locations of the thermocouple sensors in borehole 156 are given in Appendix A of the As-Built report (CRWMS M&O, 1998). The reference location (0,0,0) is located on the heater drift axis on the hot side of the bulkhead. Thus, if the radius of the drift is 2.5 m, then the 8 thermocouples are 0.004, 1.104, 2.104, 3.004, 4.104, 6.004, 9.504, and 14.854 m vertically above the crown of the drift.

				X	Y	Z
156	ESF-HD-156-MPBX9-TC-1	I	Thermal - TC	-0.013	21.001	2.504
156	ESF-HD-156-MPBX9-TC-2	I	Thermal - TC	-0.010	20.997	3.604
156	ESF-HD-156-MPBX9-TC-3	I	Thermal - TC	-0.007	20.993	4.604
156	ESF-HD-156-MPBX9-TC-4	I	Thermal - TC	-0.005	20.990	5.504
156	ESF-HD-156-MPBX9-TC-5	I	Thermal - TC	-0.002	20.985	6.604
156	ESF-HD-156-MPBX9-TC-6	I	Thermal - TC	0.003	20.978	8.504
156	ESF-HD-156-MPBX9-TC-7	I	Thermal - TC	0.013	20.965	12.004
156	ESF-HD-156-MPBX9-TC-8	I	Thermal - TC	0.028	20.944	17.354
156	ESF-HD-156-MPBX9-ANC-1	I	Mechanical - MPBX	-0.010	20.997	3.604
156	ESF-HD-156-MPBX9-ANC-2	I	Mechanical - MPBX	-0.007	20.993	4.604
156	ESF-HD-156-MPBX9-ANC-3	I	Mechanical - MPBX	-0.002	20.985	6.604
156	ESF-HD-156-MPBX9-ANC-4	I	Mechanical - MPBX	0.028	20.944	17.354

Of interest are the thermocouples whose temperatures exceeded boiling: TC-1, TC-2, TC-

3, TC-4, and TC-5. The temperature at all 5 of these thermocouples exceeded boiling during the heating portion of the test. The time after the start of heating when temperatures exceed boiling were 80 days (TC-1), 300 days (TC-2), 500 days (TC-3), unknown (TC-4), and 1000 days (TC-5). There was no indication of heat pipe development at the time the temperature exceeded past boiling. Refluxing (as indicated by temperature excursions) was observed at TC-1 starting at day 600 at which time the local ambient temperature was about 170 C. Temperature was depressed by about 25 to 40 C for the period lasting up to day 660. Refluxing was observed again, intermittently starting at day 720. The depression in temperature approached 60 C by day 830 and 100 C by day 940. These approximately 100 C depressions in temperature lowered the temperature to boiling and continued until day 1300.

The color versions of these figure is from the Thermal Testing Measurements AMR.

Figure 5.2-2. Temperature Data for DST Borehole 156 (MPBX9)

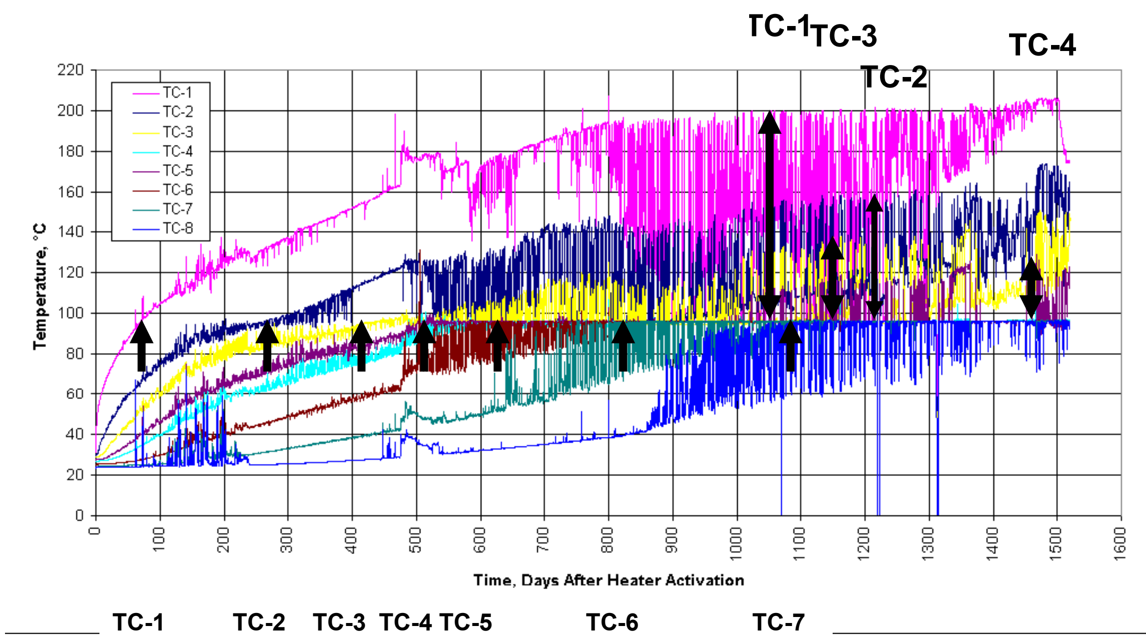


Figure from: Bechtel SAIC Company. 2002a. Thermal Testing Measurements Report. ANL-NBS-HS-000041 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20021004.0314.

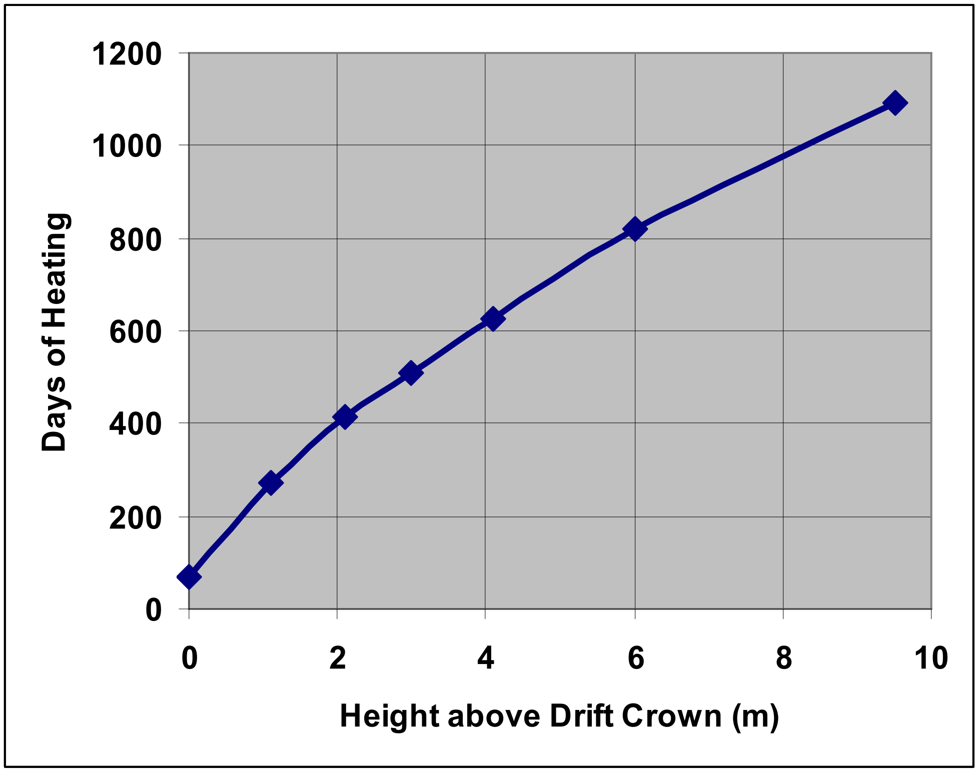
Temperatures at TC-2, TC-3, and TC-4 followed a trend similar to TC-1. The maximum temperatures at TC-2, TC-3, and TC-4 were about 160 C, 140 C, and 125 C, respectively, with excursions in temperature sufficiently large to depress the temperature to boiling.

The times at which it appears the temperature of the rock mass neat each thermocouple reached boiling was:

TC-1	TC-2	TC-3	TC-4	TC-5	TC-6	TC-7	TC-8

0.004	1.104	2.104	3.004	4.104	6.004	9.504	14.854
70	270	415	510	625	820	1090	-

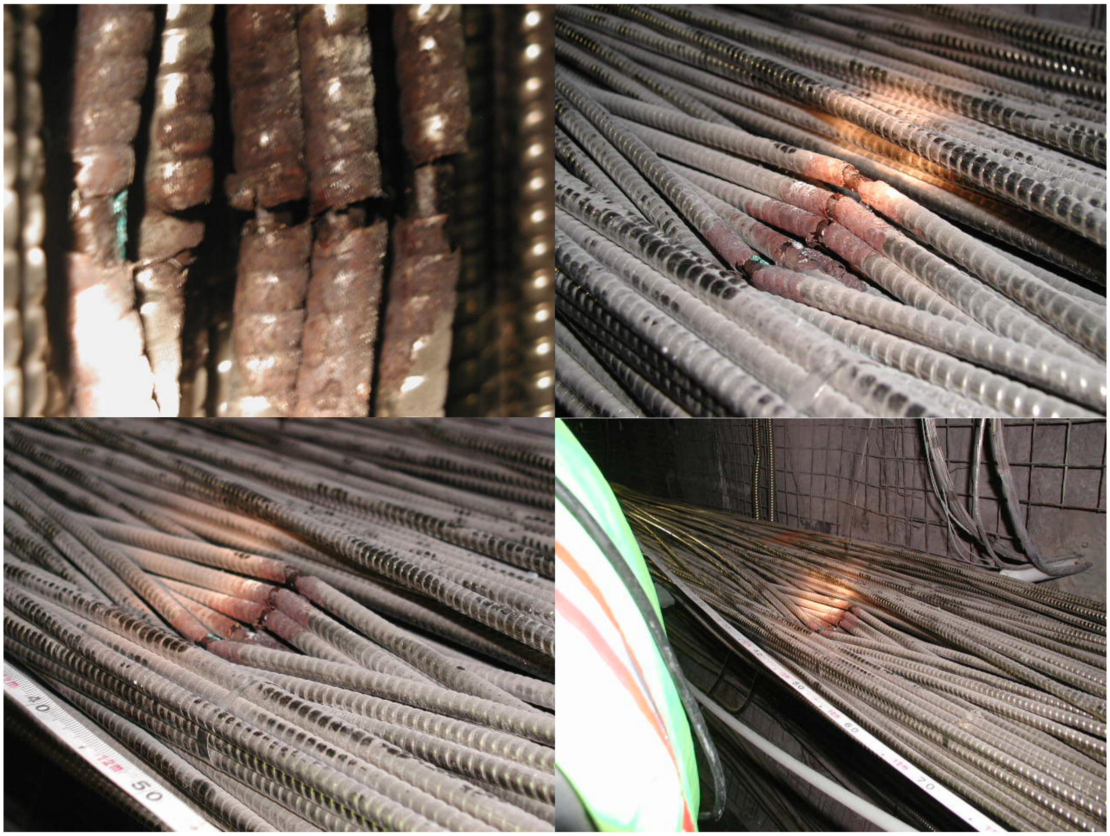
When time at which the temperature at a thermocouple exceeded boiling (i.e., ~96 C) was plotted against the height above the drift crown. It appears that the rate of heating is following the diffusion curve (this could be shown for reasonable values of thermal conductivity) indicating that the global temperature regime around MPBX9 is consistent with the setting.



The boiling isotherm arrived at TC-6 (located 6 m into the rock) by day 840 and TC-7 (located 9.5 m into the rock) by day 1,100. Temperature excursions at the drift crown (i.e., TC-1) were sufficiently large to depress the temperature there to boiling until day 1300. Therefore, the boiling isotherm was penetrated as much as 9.5 m and as much as 100 C for a 200-day duration from day 1,100 until day 1,300.

July 2, 2007 Ronald Green

DST Corrosion and Dripping Evidence

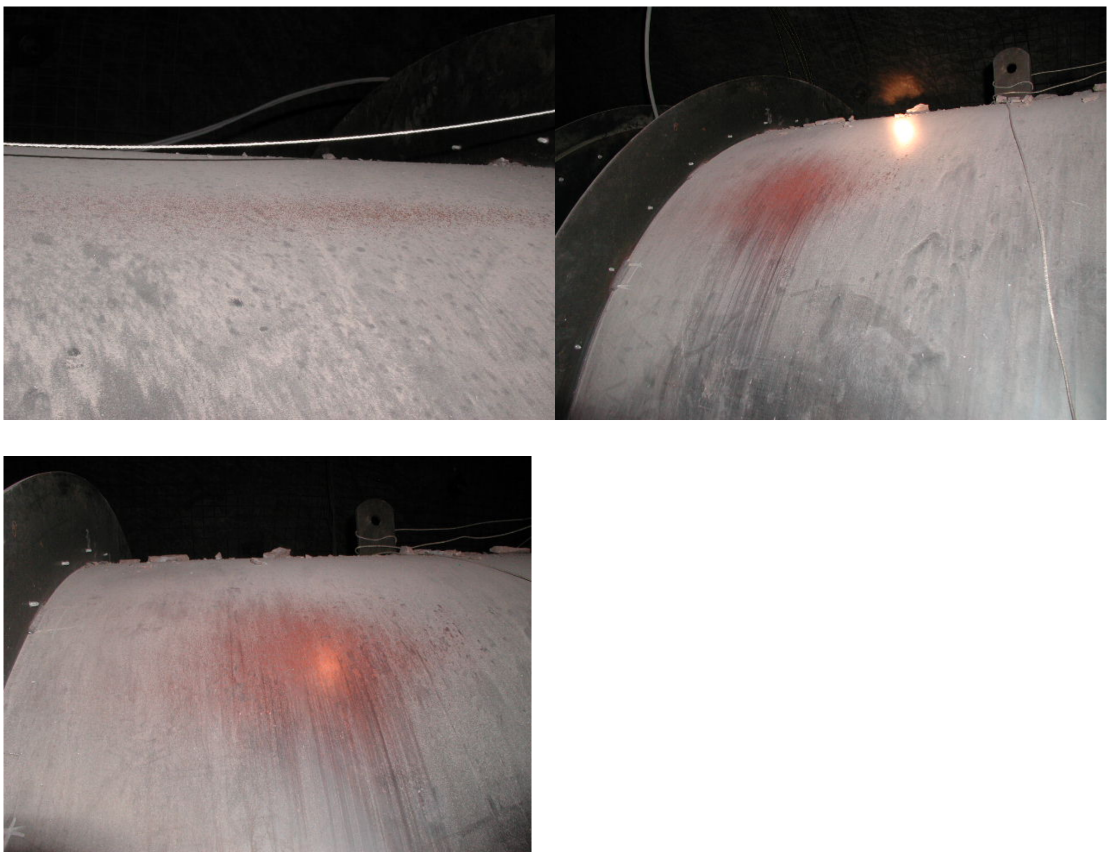


These photos were taken by Kevin Smart on April 18, 2006. These photos document a corrosive precipitate that dripped from the heated drift ceiling onto cables that were located along side the canister heaters. The precipitate is interpreted to be clear evidence of thermal refluxing.

This photo was taken by Kevin Smart on April 18, 2006. The staining from the rock bolt down the side of the drift ceiling and wall are evidence that sufficient water drained down the rock bolt within the rock mass such that the resulting solute had enough mass and enough mineralization to stain a long pathway on the wall.




These photos were taken by Kevin Smart on April 18, 2006. They are indicators of the corrosive effect of waters from the rock mass that encounter borehole materials.



These photos are indications of staining from liquid that dripped onto the surface of a canister heater from the roof of the heated drift.

These photos were taken by Kevin Smart on April 18, 2006 or by Randy Fedors or Jack Parrott during a previous trip several weeks earlier. These are evidence of a sludge-like material that dripped onto the surface of the waste packages from the roof of the heated drift.

These photos were taken by Kevin Smart on April 18, 2006. It is not entirely clear what is illustrated. One interpretation is that precipitate formed on the ceiling of the heated drift and in places was of sufficient thickness and mass to encase the mesh. It is also possible that the photos are misleading and that what appears to be precipitate, may in fact be flaky pieces of rock that spalled away from the intact rock mass and are lying directly onto the mass. The reason it appears to be precipitate may be an illusion because the lack of a photo flash shadow at those locations where the rock lies directly on the mesh. This uncertainty needs to be resolved, preferably by first-hand inspection.

July 3, 2007 Ronald Green

Compilation of Anecdotal Evidence for Thermal Refluxing during Engineered Geologic Heater Tests.

This section summarizes evidence that thermal refluxing may have occurred during the conduct of geologic heater tests. Evidence for thermal refluxing at heater tests can take several forms:

1) In the rock mass

- Temperature excursions (i.e., typically rapid decreases in temperature) detected by thermocouples in the pathway of the downward flow of liquid water.
- Chemistry analyses of water samples collected in the rock mass that indicate elevated concentrations consistent with thermal refluxing and not recent condensate.
- The presence of solute staining on fracture surfaces consistent with evaporated reflux water.
- Corrosion of engineering materials placed in the rock mass during the heater test.

2) In open-air drifts

- Chemical staining at the point where fracture flow drains into the open air space.
- Chemical staining on open-air drift floors, materials that collapsed into an open-air drift, or engineered system.
- Observed thermal refluxing dripping into an open-air drift.
- Corrosion of engineering materials in the open-air drift during the heater test.

Following is a summary of geologic heater tests conducted in the United States that were sufficiently documented to be appropriate for examination for evidence of these indicators of thermal refluxing. Included with each citation is a summary of evidence that supports the possible occurrence of thermal refluxing during the execution of the thermal test.

Section 1: 1977-83 Climax Mine heater tests by LLNL

1.3 1977-78 Climax small-diameter heater tests

- 1.3.1 Heater test H-1
- 1.3.2 Heater test H-2
- 1.3.3 Permeability/heater test P-1

1.4 1980-1983 Climax Spent Fuel Test

Section 2: 1982-84 G-Tunnel heater test series by SNL

2.1 1980 Borehole heater test – *in situ* water migration/heater experiment
2.2 1982-84 Borehole heater test – three tests in different boreholes
2.3 1981-84 Heated block test

Section 3: 1988-89 G-Tunnel borehole heater test by LLNL
Section 4: 1997 Fran Ridge Large-Block Test (LBT) by LLNL
Section 5: 1985 Superior Road Tunnel heater test by the U of AZ
Section 6: 1997 ESF Single-Heater Test (SHT) by LBNL
Section 7: 1997-2005 ESF Drift-Scale Heater Test (DST) by LBNL
Section 8: 1996-97 Lab-Scale Heater Tests (LST) by SwRI

Table x. Summary of heater test with selected test information. Note that temperatures transcribed from graphs may be approximate													
Test	Date	Sponsor	Duration	Max Heater Temp	Max Rock Temp	Evidence of Thermal Refluxing							
						1	2	3	4	5	6	7	8
Climax small borehole H-1	1977	LLNL	68 days	n.a.	175 C	y	x	x	n	n	x	x	n
Climax small borehole H-2	1977-78	LLNL	62 days	n.a.	150 C	y	x	x	n	n	x	x	n
Climax small borehole P-1	1978	LLNL	83 days	n.a.	419.3 C	x	x	x	n	n	x	x	n
Climax Spent Fuel Test	1980-83	LLNL	3 yrs	145 C	80 C	x	y	x	y	x	x	n	n
G-Tunnel water migration/heater	1980	SNL	63 days	473 C	240 C	n	n	n	n	x	x	n	n
G-Tunnel single borehole series - IWa	1982	SNL	21.7 days	460 C	240 C	y	x	x	x	n	n	n	n
G-Tunnel single borehole series - IWb	1982	SNL	7.1 days	460 C	240 C	n	n	x	x	n	n	n	n
G-Tunnel single borehole series – IN	1982	SNL	35.0 days	360 C	175 C	n	x	x	x	n	n	n	n
G-Tunnel single borehole series – IIWc	1984	SNL	7.8 days	325 C	100 C	n	n	x	n	n	n	n	n
G-Tunnel single borehole series – IIWd	1984	SNL	8.1 days	460 C	195 C	y	n	x	n	n	n	n	n
G-Tunnel single borehole series – IIWe	1984	SNL	7.9 days	500 C	240 C	y	n	x	n	n	n	n	n
G-Tunnel single borehole series - IIWf	1984	SNL	11.2 days	530 C	310 C	y	n	x	n	n	n	n	n
G-Tunnel heated block, thermal cycle 1	1983	SNL	15 days	95.2 C	78 C	n	n	n	n	n	n	n	n
G-Tunnel heated block, thermal cycle 2	1983-84	SNL	21 days	250.7C	95 C	n	n	n	n	n	n	n	n
G-Tunnel heated block, thermal cycle 3	1984	SNL	46 days	360 C	145 C	n	n	n	n	n	n	n	n
G-tunnel single borehole heater test	1988-89	LLNL	195 days	355 C	237 C	n	n	n	n	n	n	n	y
CNWRA lab-scale heater test 1	1996	CNWRA	140 d	510 C	202 C	y	y	y	n	y	y	y	y
CNWRA lab-scale heater test 2	1997	CNWRA	215 d	485 C	175/452	y	y	x	n	x	y	y	y
Fran Ridge large-block test	1997-98	SNL	375d + 203d	?	142 C	y	n	n	n	n	n	n	n
ESF single-heater test	1996-97	LBNL	9mth + 7mth	430 C	165 C	?	n	y	n	n	n	n	y
ESF drift-scale heater test	1997-2005	LBNL	4 yr + 4 yr		255 C	y	n	n	y	y	y	y	y

1) Temperature excursions (i.e., typically rapid decreases in temperature) detected by thermocouples in the pathway of the downward flow of liquid water.
2) Chemistry analyses of collected water samples that indicate elevated concentrations consistent with thermal refluxing and not recent condensate.

3) The presence of solute staining on fracture surfaces consistent with evaporated reflux water.
4) Corrosion of engineering materials placed in the rock mass during the heater test.
5) Chemical staining at the point where fracture flow drains into the open air space.
6) Chemical staining on open-air drift floors, materials that collapsed into an open-air drift, or engineered system.
7) Observed thermal refluxing dripping into an open-air drift.
8) Corrosion of engineered materials placed in the open-air drift during the heater test.

y denotes the phenomenon was observed. n denotes the phenomenon was not observed. x denotes the experiment was not conducted in a manner to permit the phenomenon to be observed. Phenomena such as water chemistry and fracture staining would only be observed if active detection was undertaken. Phenomena such as corrosion of heaters or equipment is assumed to be reported, even if such phenomena were not included as part of the objective of the test.
n.a. denotes not available.

Summarize in terms of temperature gradient, times of occurrence, locations, and coordinating temp excursions with locations and times.

July 6, 2007 Ronald Green

The following draft outline was prepared for a document of the thermal refluxing issue.

Assessment of Thermal Refluxing at a HLW Geological Repsository

Introduction

The first objective of this analysis is to examine the results from field- and laboratory-scale heater tests and evaluate whether the test results provide evidence that thermal refluxing may have occurred during the conduct of the test. Because the objectives of the heater tests were not typically to observe thermal-hydrological outcomes, evaluation of test results tended to emphasize processes other than thermal-hydrological mechanisms such as thermal-mechanical or thermal-chemical. Nonetheless, close examination these test results provide valuable insights on thermal-hydrological processes active during the tests. This report provides a summary of an examination of twenty field-scale tests in addition to two laboratory-scale tests for evidence that would indicate whether thermal refluxing may have occurred during the conduct of the tests.

The second objective of this analysis is to evaluate whether two thermal refluxing analytical models (i.e., Phillips model and Birkholzer model) can adequately replicate or represent the phenomena observed during the heater tests. This exercise will reduce uncertainty and increase confidence in repository performance assessment by either demonstrating that the analytical models accurately capture the thermal refluxing phenomenon or disqualifying the analytical models as representative of thermal refluxing.

Background – Description of thermal refluxing and its relevance to repository performance.

Heat and Mass Transfer (Thermal Refluxing) Conceptual Model

.

Limitations in Direct Observation of Thermal Refluxing

Evidence of Thermal Refluxing in Heater Tests

Description of Relevant Heater Tests

Criteria Potentially Indicative of Thermal Refluxing

Heater Tests Evidence of Thermal Refluxing

Analytical Models of Thermal Refluxing

Description of Analytical Models

Phillips Model

Birkholzer Model

Assessment whether analytical models explain Heater Tests Evidence

Phillips Model

Birkholzer Model

Discussion

Conclusion

August 9, 2007 Ronald Green

The final report will appear as follows:

Introduction

The objective of this analysis is to examine the results from field- and laboratory-scale heater tests and evaluate whether the test results provide evidence that thermal refluxing may have occurred during the conduct of the test. Because the objectives of the tests were not typically to observe thermal-hydrological outcomes, evaluation of test results tended to emphasize processes other than thermal-hydrological mechanisms such as thermal-mechanical or thermal-chemical. Nonetheless, close examination these test results provide valuable insights on thermal-hydrological processes active during the tests. This report provides a summary of an examination of twenty field-scale tests in addition to two laboratory-scale tests for evidence that would indicate whether thermal refluxing may have occurred during the conduct of the tests.

Background

Emplacement of heat-generating high-level nuclear waste (HLW) in a geologic repository will redistribute water in the geologic media near the repository and in the emplacement drifts. The presence of liquid water and water vapor in HLW emplacement drifts is of particular concern because it is this water that will greatly determine HLW waste canister failure rates and affect the subsequent transport of radionuclides from emplacement drifts to the accessible biosphere after waste canister failure. Typically numerical models are used to simulate the heat and mass transport mechanisms expected to be important in water redistribution near the repository. These models are used to predict when water will enter emplacement drifts and how this water will interact with the engineered barrier systems. Heat and mass transport mechanisms that govern redistribution of water in geologic media are inherently complex and are further complicated by naturally occurring heterogeneities in geologic media that can vary by orders of magnitude (in particular permeabilities). As a result, the level of uncertainty in the heat and mass transport models used to predict water redistribution in the geologic media surrounding a repository can be undesirably high.

There are many multiphase models used to simulate various aspects of heat and mass transport expected to occur near a HLW repository. Of particular interest to this evaluation is the potential propensity for liquid water to enter an emplacement drift by thermal refluxing during the heating phase. Multiphase analyses performed to evaluate the thermal refluxing phenomenon have attempted to be as representative and realistic as possible (Phillips, 1997; Birkholzer, 2004), but are predicated on simplifying assumptions necessitated by the complexity of the processes involved, physical setting, and scaling issues. Temporal and spatial scales of moisture redistribution expected near an emplacement drift render assessing the accuracy of these analyses problematic. As a consequence, predictions made using these analytical approaches have not been rigorously tested to ascertain whether the analyses sufficiently represent reality.

Uncertainty in complex models of this sort can be reduced by benchmarking the model results with results from other similar models, comparing the model results with natural analogs, or conducting physical tests to replicate the processes in question. This analysis focuses on assessing results from relevant physical tests during which heat and mass processes were active.

On occasion, natural analogs can provide physical evidence of phenomena expected to occur at a geologic repository. When available, natural analogs can provide an opportunity to evaluate and observe the heat and mass transfer processes in a natural setting under, at least in part, controlled conditions. Properly conducted and interpreted testing can provide valuable insight when constraining numerical models used to simulate heat and mass transfer.

Heat and Mass Transfer Conceptual Model

The conceptual model of moisture redistribution during the heating phase of a HLW repository is that water will vaporize near emplacement drifts when and where temperatures are above boiling. The ensuing water vapor will be transported away from the heat source via fractures by diffusion until reaching the boiling isotherm at which point water vapor will condense. Of concern is whether sufficient water will condense above emplacement drifts to instigate downward flow of liquid water through fractures to penetrate into rock with above-boiling temperatures. The process where downward flowing water penetrates into rock at above boiling temperatures is referred to as thermal refluxing.

The magnitude and importance of thermal refluxing will be rate dependent, ostensibly a function of temporal and spatial scales. This scale dependency and natural heterogeneity renders assessment of the importance of thermal refluxing particularly vexing. Numerical simulators are informative, but predictions are predicated on assumptions inherent in the assumed conceptual model. Numerical simulators are further complicated by the complexities of the natural environment and simplifications necessary when characterizing the environment.

Limitations in Direct Observation of Thermal Refluxing

Direct observation of thermal refluxing in geologic media is problematic for a multitude of reasons. Some reasons are:

(i) Thermal refluxing does not occur under normal geologic conditions. An anthropogenic heat source with sufficient power is needed to vaporize water and create a dryout zone for thermal refluxing to occur. In the absence of a sufficiently large heat source, water may be redistributed, but a scenario appropriate for thermal refluxing would not exist.
(ii) Similar to other heat and mass transfer phenomena occurring in geologic

media, thermal refluxing is highly dependant on the large spatial heterogeneity evident in fractured tuff. It is extremely difficult to identify which fractures would be candidates for thermal refluxing.

(iii) Similar to other heat and mass transfer phenomena occurring in geologic media, the temporal scale during which thermal refluxing might occur could be 100s or 1,000s of years. It is difficult to effectively characterize what will be the changes in the environment over such long time periods and how these changes would potentially affect thermal refluxing.

(iv) Combining spatial and temporal scales increases the challenge of knowing when and where to look for thermal refluxing.

(v) Indirect indicators of thermal refluxing are possible. One possible indicator is temperature. Rapid declines and fluctuations in above-boiling temperature are an indication that liquid water is penetrating into rock that was previously above boiling. The challenge in measuring temperature as an indicator is that refluxing water is believed to occur in fractures. Although thermistors and other temperature measurement devices can be relatively easily inserted into rock matrix, it is difficult to insert thermistors in fractures located in the bulk rock. There are several issues related to this challenge. Attempting to insert instrumentation into a fracture will surely alter the hydraulic properties of the fracture possibly causing water to bypass the instrumentation. Fluid flow has been shown to follow a circuitous path down fractures (Or et al.; Glass et al.). It is difficult to know where to place temperature measurement instrumentation in a fracture in order to detect thermal refluxing liquid water and even if such a location were known, it would be challenging to place the instrument at the precise location to detect the pulse of thermal refluxing water. There is an additional problem with detecting the downward flow of refluxing water. Most temperature instrumentation measures at discrete time intervals. It is possible that a thermal refluxing pulse could pass undetected if the temperature measurement is taken at a time other than when the pulse is present.

(vi) The spatial scale of an experiment may be insufficient to comprise a REV [representative elemental volume]. For example, refluxing will occur in fractures, not the matrix of rock. An experiment that has insufficient size to interact with a sufficient sampling of fractures, may not encounter fractures in which thermal refluxing is active. The URL at Stripa provides evidence supporting this assertion. This evidence is that 80% of the water seeping into the drift occurs in 5% of the drift. A sampling of the drift that did not include this 5% would provide a much different assessment than a sampling that included this 5%.

(vii) Evidence for thermal refluxing that was collected during a post mortem evaluation of a heater test will typically not provide conclusive information on the time at which the event associated with the thermal refluxing evidence occurred.

August 14, 2007 Ronald Green

Evidence of Thermal Refluxing in Heater Tests

Documents describing the conduct and results of 19 heater tests were evaluated in search of evidence of potential thermal refluxing. The heater tests were conducted between 1977 and 2005.

Description of Relevant Heater Tests

Many national HLW repository programs utilize underground testing facilities to serve a multitude of purposes: facility siting and disposal-system design; safety evaluations; site characterization; analog testing; and technology development (NEA report). The underground testing facilities are referred to as Underground Research Laboratories (URL). URLs have been historically developed both at sites considered for potential geological repository development and at sites chosen for strictly research and testing purposes. Qualitative and quantitative results from the analog tests allow for critical assessment of the numerical simulators used for long-term assessment of the repositories.

Of interest to the potential DOE HLW repository at Yucca Mountain are approximately twenty field-scale non-isothermal tests conducted since the late 1970s at Ranier Mesa, Busted Butte, and Yucca Mountain in southwest Nevada and Apache Leap in Superior, Arizona (Table 1). Because the US DOE has chosen unsaturated volcanic tuff as the geologic medium of its potential HLW repository, international analog testing performed in a phreatic environment or in geologic media other than volcanic tuff (i.e., granite, salt, clay) has limited applicability and interest when assessing thermal refluxing in volcanic rock under partially saturated conditions. Although most of these twenty tests were not conducted for the explicit purpose of evaluating for thermal refluxing, ancillary observations or evidence from these tests could provide corroborative support that thermal refluxing may have occurred during the tests.

Test	Date	Sponsor
Climax small borehole H-1	1977	LLNL
Climax small borehole H-2	1977-78	LLNL
Climax small borehole P-1	1978	LLNL
Climax Spent Fuel Test	1980-83	LLNL
G-Tunnel water migration/heater	1980	SNL
G-Tunnel single borehole series - IWa	1982	SNL
G-Tunnel single borehole series - IWb	1982	SNL
G-Tunnel single borehole series – IN	1982	SNL
G-Tunnel single borehole series – IIWc	1984	SNL
G-Tunnel single borehole series – IIWd	1984	SNL
G-Tunnel single borehole series – IIWe	1984	SNL
G-Tunnel single borehole series - IIWf	1984	SNL

G-Tunnel heated block, thermal cycle 1	1983	SNL
G-Tunnel heated block, thermal cycle 2	1983-84	SNL
G-Tunnel heated block, thermal cycle 3	1984	SNL
G-tunnel single borehole heater test	1988-89	LLNL
CNWRA lab-scale heater test 1	1996	CNWRA
CNWRA lab-scale heater test 2	1997	CNWRA
Fran Ridge large-block test	1997-98	SNL
ESF single-heater test	1996-97	LBNL
ESF drift-scale heater test	1997-2005	LBNL

Tests considered for evaluation had the following characteristics in common.

- Conducted in the vadose zone,
- Conducted in fractured rock,
- Did not use backfill material, such as bentonite clays,
- Heat source,
- Conducted for sufficiently long durations with sufficiently high heating to redistribute moisture in the rock proximal to the heat source,
- Temperature was monitored,
- Evidence of thermal refluxing was potentially available for evaluation.

With the exception of tests conducted at the Climax Mine complex, all tests were conducted in volcanic tuff. The Climax Mine tests were conducted in granite. Only one test had a heater temperature that did not exceed boiling (95.2 C measured at the G-tunnel heated block, cycle 1 test). Two other tests had no temperatures measured in the rock that exceeded boiling, but because the heater temperatures were sufficiently high for sufficiently long periods (i.e., 145 C in the 3-yr long Climax Spent Fuel Test and 250.7 C in the 21-day long G-Tunnel heated block, cycle 2 test) above boiling temperatures were likely experienced in the rock at locations where temperature was not measured.

Criteria Potentially Indicative of Thermal Refluxing

The 19 heater tests evaluated as part of this study were neither designed nor conducted to test for thermal refluxing. Nonetheless, it is believed that results and evidence from the tests may shed light on whether thermal refluxing occurred during the conduct of the tests. Documents describing these tests were evaluated and examined for any indication that thermal refluxing may have occurred during the tests. Eight specific phenomena were identified as being indications that thermal refluxing could have occurred during the tests. The first four criteria occurred mainly in the rock and the second four criteria occurred mainly in the heater chamber, whether it is a borehole or a drift. Following are the eight criteria:

1. Temperature excursions (i.e., typically rapid decreases in temperature) detected by thermocouples located in the pathway of the downward flow of liquid water.

2. Chemistry analyses of collected water samples that indicate elevated concentrations consistent with thermal refluxing and not recent condensate.
3. The presence of solute staining on fracture surfaces consistent with evaporated reflux water.
4. Corrosion of engineering materials placed in the rock mass during the heater test.
5. Chemical staining at the point where fracture flow drains into the open air space.
6. Chemical staining on open-air drift floors, materials that collapsed into an open-air drift, or engineered system.
7. Observed thermal refluxing dripping into an open-air drift.
8. Corrosion of engineering materials placed in the open-air drift during the heater test.

Results from each of the 19 heater tests were evaluated to ascertain whether there was evidence that any of the eight criteria occurred. Results from the evaluations are compiled into a summary table.

August 15, 2007 Ronald Green

Heater Tests Evidence of Thermal Refluxing

Each of the 19 selected heater tests is described in this section. Included in the description is a description of the test environment, heat source, duration of the test, temperature regime, and phenomenological evidence of the eight target criteria.

Climax Stock Mine Heater Tests

The earliest *in situ* heater tests of interest to evaluating for thermal refluxing at a HLW geologic repository were initiated in 1977 at the Climax mine located in the Climax Stock quartz monzonite at the Nevada Test Site, Nevada. There were two sets of *in situ* heater tests performed by LLNL in the Climax Stock mine: (i) a series of three tests performed in small-diameter vertical boreholes (Montan and Bradkin, 1984) and (ii) the Spent Fuel Test performed with 11 spent fuel assemblies and six electric heaters placed in vertical boreholes (Patrick, 1986 and Weiss et al., 1985). All tests were conducted in the SFT-C facility at a depth of about 420 m below ground surface at the Climax Stock Mine. The tests were conducted as part of the DOE Nevada Nuclear Waste Storage Investigations.

1.1 Climax Small-Diameter Borehole Heater Tests

The three *in situ* small-diameter borehole heater tests were conducted in 1977-78 to obtain information on *in situ* thermal conductivity, thermal diffusivity, and permeability of quartz monzonite (Montan and Bradkin, 1984). Of greater interest were the first two tests (referred to as H-1 and H-2), conducted to measure the effect of heat on the thermal diffusivity of the Climax Stock quartz monzonite. A plan view of borehole locations is illustrated in Figure 1.1a. The third test (P-1) was conducted to measure the effect of temperature changes on rock permeability. The tests were conducted in 9 to 12-m vertical boreholes with diameters that varied from 48 to 76 mm. Temperature was recorded at four depths (A - below the heater, B and C at the heater midplane, and D – above the heater) in a series of boreholes during H-1Boreholes were instrumented with spring activated thermocouples designed to press them firmly against the rock wall. After thermocouple installation, the boreholes were backfilled with loose Perlite insulation. . Temperature was reported in terms of temperature rise over the ambient (23 C) (Montan and Bradkin, 1984). Therefore, boiling (96 C at the Climax mine horizon) would be a rise of about 73 C above ambient.

The first heater test, H-1, operated for 68 days in late 1977. There were two outages in power and one equipment malfunction during H-1. The first power outage occurred after nine days of heating. The project team inferred that a small amount of water, probably circulating fluid lost to the fracture system during drilling, entered the heater hole as vapor and began refluxing in a region near the top of the heater. They concluded that refluxing eventually caused a short circuit in the power leads leading to the power outage. Heating was discontinued for three days to repair the heater apparatus. After seven more days of heating, there was a second short circuit in a heater lead, this time locking the heat source at full open. No additional discussion on these corrosion events was provided by Montan and Bradkin (1984). Chemical analysis of refluxing water was not determined. There is little opportunity to discern whether there was any evidence that the refluxing waters had elevated ionic concentrations or that the refluxing waters were relatively clean condensate water.

Evidence of development of a heat pipe was observed during H-1 in three boreholes, J-01, I-02, and I-01. Boreholes J-01, I-02, and I-01 are located about 0.4 m, 0.5 m, and immediately adjacent to the heater borehole. All three had evidence of temperature excursions where temperatures above boiling were rapidly decreased to the boiling temperature, although the evidence in I-01 was subtle (Montan and Bradkin, 1984). The temperature excursions are evidenced by rapid decreases in temperature from temperatures as high as 130 C down to the temperature of boiling. Back filling the boreholes with loose Perlite insulation was apparently insufficient to prohibit the rapid downward flow of refluxing water

The second heater test, H-2, operated for 62 days in late 1977 and early 1978. Evidence of a heat pipe was observed in three boreholes, I-10, I-11, and J-02. Montan and Bradkin (1984) reported an unanticipated rise in temperature at the bottom of the heater and an anomalous temperature rise in temperature above the midplane of the heater during test H-2. Montan and Bradkin (1984) attributed the anomalous temperatures to an accumulation of fine quartz monzanite dust at the bottom of the heater borehole. Similar to test H-1, Montan and Bradkin (1984) noted there was indication of refluxing water above the heater. Boreholes I-11 and J-02 had evidence of temperature excursions where temperatures above boiling were rapidly decreased to the boiling temperature. Boreholes J-02, I-10, and I-11 are located about 0.4 m, 0.5 m, and immediately adjacent to the heater borehole. Of interest is that borehole I-11, which is located immediately adjacent to the borehole, did not register temperatures above boiling, instead, temperatures at the heater midplane remained at boiling for essentially the entire test duration when the heater was energized. This indicates that the midplane of I-11 was probably dominated by a heat pipe or, less likely, that liquid water at the boiling temperature was present during this entire time.

1.2 Climax Spent Fuel Test

The Climax Spent Fuel Test was conducted in the Climax stock quartz monzonite at the Nevada Test Site. The heating phase of the Spent Fuel Test-Climax was initiated in April-May 1980 and terminated in March-April 1983. The heat source was 11 spent fuel canisters and six electric simulators. The test was conducted at a depth of 420 m below ground surface. The zone of saturation is at an elevation of about 945 m above mean sea level, which is about 145 m below the horizon of the Climax Spent Fuel test (Patrick, 1986). The Climax Spent Fuel Test was conducted in the same underground facility as the Climax small-diameter borehole heater tests.

The heater boreholes were vertical and located in the drift floor in the Climax Spent Fuel Test facility. A carbon steel liner was placed in each heater borehole. The fuel assemblies and electric heaters were then placed in the lined borehole. Thermocouples were placed throughout the heater test domain to monitor temperature change during the test (Patrick *et al.,* 1984). Of principal interest to this evaluation are thermocouples that were placed in vertical boreholes located next to the large heater boreholes, between the borehole liner and the heater, and within the heater. During the 3-yr heating phase, canister temperatures exceeded boiling, liner temperatures approximately attained boiling, but rock temperatures did not achieve boiling (Montan and Patrick, 1986; Patrick, 1986).

Consequently, neither heat pipes nor temperature excursions were observed during the tests.

Water Chemistry

Of interest to in the Climax Spent Fuel Test was the presence of water observed in canister borehole Climax Emplacement Hole #1 (CEH#1) during the heating phase of the test (Weiss *et al*., 1985). Fuel assembly number D34 was placed in CEH#1. Although the test horizon was 145 m above the poteniometric surface, CEH#1 apparently intersected a fracture zone with mobile water allowing water to pool in the liner-rock annulus (Weiss et al., 1985).

The evolution of liquid water in CEH#1 was interpreted by Weiss *et al*. (1985) using temperature measurements. Weiss *et al*. (1985) noted that the temperature of D34 at mid-height attained a maximum of between 135 and 140°C for a period of approximately two months. Based on temperatures recorded at other boreholes (Patrick, 1986), this two-month period was interpreted to be immediately after the onset of heating. Temperatures of the liner and of the canister near the bottom of the canister are illustrated in Figure 1 (taken from Figure 3 in Weiss *et al*., 1985). Temperatures in the bottom of the borehole were less than those measured at mid-height and did not exceed boiling. Weiss *et al*. (1985) surmised that a leak in the liner allowed water to enter the liner cavity. As a result, the bottom portion of the canister was submerged in water for at least the first eight months of the heater test, thereby keeping temperatures below boiling.

The canister temperature increased until 3.1 years out of core, after which the temperature exhibited a slight decline. Liner temperature increased monotonically until 3.0 years out of core, at which time a there was an additional increase in temperature for 0.1 years. Weiss *et al*. (1985) interpreted that the jump in liner temperature at the 3-yr mark occurred when water in the liner-rock annular space was lost, either through evaporation or percolation through the rock. The absence of water resulted in poorer thermal conductance in liner-rock annular space and heat transport changed from conduction-convection to radiation. Canister temperatures, which gradually increased up to 3.0 years, did not rise at 3.0 years. Weiss *et al*. (1985) inferred that a gradual increase in solute concentration of the water in the liner-canister annular space was the cause for the slight temperature rise leading up to 3.0 years out of core. The decline in canister and liner temperatures after 3.1 years is interpreted to be caused by a decline in decay-heat generation.

The liner leak is interpreted to have sealed from precipitation of solute minerals present in the liner-canister, annular-space water. Weiss *et al*. (1985) asserted that sealing occurred prior to 3.0 years out of core. There was no water present inside the liner when the canister was briefly removed in August 1982 or 2.4 years out of core.

Although the source of water that seeped into the liner-rock annulus was interpreted to originate from a fracture that was free flowing prior to the test, there exists the prospect that the chemistry of the collected water could have been altered by refluxing. Fortunately, Weiss *et al*. (1985) analyzed the chemical composition of water sampled from the liner-rock annulus and compared it with the chemical composition of water sampled from two locations in the Climax complex. The major ion concentrations of water from the annulus (CEH#1) and two samples of ambient rock water (NH-01 and UG-02)(from Table I, pg 12 of Weiss *et al*., 1985) are summarized in the following table.

Comparison of water analyses from the Climax facility and well J-13 (mg/L)

Species	NH-01	UG-02	CEH#1	Well J-13
Na	229.	214.	273.	43.9 ± 1.19
Ca	240.	114.	16.0	12.5 ± 0.77
SiO_2	22.5	23.9	1.4	57.7 ± 1.0
K	3.8	4.7	538.	5.11 ± 0.32
SO_4	850.	480.	193.	18.7 ± 0.47
Cl	160.	70.	30.	6.9 ± 0.21
HCO_3	65.	165.	1322*	136. ± 8.1
F	N.D.	N.D.	3.8	2.2 ± 0.32
NO_3	N.D.	N.D.	2.5	9.6 ± 3.63

*calculated from ionic balance
NH-01 and UG-02 were collected from two locations in the Climax Mine complex.
CEH#1 was collected from the liner-rock annulus.

In summary, the water chemistries were as follows. The ambient water (two samples) was relatively high in Na, Ca, SO_4, Cl, and HCO_3. Water from the liner-rock annulus was significantly higher in K and lower in Ca, SO_4, and Cl. Unfortunately HCO_3 was not measured in the liner-rock annulus of CEH#1, but an ionic balance would dictate a HCO_3 concentration in excess of 1300 mg/l.

Weiss *et al*. (1985) commented that they did not understand the details of the processes that led to the differences in compositions. They suggested that factors such as variation in equilibria with temperature, concentration by distillation, contact with the zinc-coated steel liner, interaction with the grout, radiolysis, and ion exchange with the rock probably contributed to the differences in measured species concentrations. They also noted that it was possible that contamination by detergent used in drilling the nearby access hole also occurred. Weiss *et a*l. (1985) did not identify that thermal refluxing could have led to the anomalous ionic concentrations of the liner-rock annulus water sample.

August 20, 2007 Ronald Green

Evidence of Corrosion

No corrosion was evident on the canisters at the conclusion of the Climax Spent Fuel Test (Patrick, 1986, pg 280). Of interest is that the rod extensiometer transducers, extensiometer connecting rods, and vibrating wire stressmeters failed during the heating phase of the test. The source of the failure of the transducers was complex and not attributed to a single source (Patrick *et al*., 1981). Hygroscopy of the resistive element was identified as a potential source of failure. The source for water was not identified. Corrosion of the vibrating wire was experienced in the vibrating wire stressmeters (Patrick *et al*., 1981). Patrick *et al*. (1981) noted the source of the water was elusive because gauges were O-ring sealed, coated, and foamed in place in relatively dry holes.

A total of 10 extensiometers failed during and after the Climax Spent Fuel Test (Patrick *et al*, 1984). Examination indicated that all extensiometers failed due to stress-corrosion cracking. The presence of calcium carbonate at the roots of the corrosion cracks indicated that extensiometer seals had leaked allowing water to enter, because calcium carbonate could only have transported to the corrosion site as a solute in water. Subsequent laboratory analyses (Patrick, 1986) indicated that the extensiometer connecting rods were most susceptible to corrosion when in the presence of chloride ions.

Post-heater test confirmatory testing in the laboratory confirmed that corrosion of the extensiometer connecting rods would not occur when exposed to ambient Climax stock water at 50 C. Corrosion failure of the extensiometer rods did occur, however, when $CuCl_2$-$2H_2O$ was added to the ambient Climax stock water to increase the chloride ion concentration. Inspection of the extensiometer connecting rods fracture surface during the confirmatory testing detected the presence of chloride ions. It was also noted that the type of corrosion fracturing observed in the presence of $CuCl_2$-$2H_2O$ was similar to the type of fracturing observed during the heater test (i.e., a combination of intergranular- and transgranular fracturing). This evidence and analysis indicated that the water that infiltrated past the failed seals on the extensiometers did not have the benign chemistry peculiar to the naturally occurring water in the Climax mine area, but instead had a more aggressive chemistry, apparently with elevated concentrations of chloride ions.

2.1 1980 SNL G-Tunnel Water Migration/Heater Test

A series of heater tests was conducted by SNL in the G-Tunnel Underground Facility at the Nevada Test Site in 1980-84. The G-tunnel test facility is located in the welded Grouse Canyon tuff, a member of the Belted Range tuff at Rainier Mesa. The tuff in the vicinity of the experiment at the G-tunnel facility had a measured porosity of 22 to 28% and liquid saturation > 85%.

The first test in the SNL series was the1980 G-tunnel water migration/heater test. The objectives of the migration/heater test were (Johnstone et al., 1985):

- Assess water generation/migration behavior in welded tuff
- Support thermal/thermomechanical code development
- Support instrumentation development
- Measure *in situ* thermal conductivity

Of these, the primary goal of the experiment was to assess the water behavior.

The water migration/heater test facility consisted of one heater borehole, one stress borehole, two thermocouple boreholes, and three water migration boreholes. The seven boreholes were parallel. The test heater consisted of two resistive heating elements placed in a 10.2 cm diameter, 1.22-m long borehole. Power level was set at a level to heat the rock to the highest temperature possible with assurance that the rock would not fracture, disintegrate, or respond in some other manner that would interfere with the observation or confuse the interpretation of the water behavior. Based on these criteria, Johnstone et al. (1985) specified a maximum operating temperature of 220 C with an accompanying operating power level of 1,000 W.

The heater test was initiated on February 5, 1980 and continued for 63 days. Rock temperatures increased at a rate that exceeded pretest thermal analysis predictions. The operating power was eventually decreased from 1,000 W to about 800 W to keep rock temperatures from exceeding 220 C. Regardless of this adjustment, actual rock temperatures exceeded 240 C in the heater borehole. The discrepancy between pretest predictions and actual temperatures suggests that: (i) actual heat-transfer mechanisms differed from those represented in the pre-test analyses or (ii) the thermal conductivity or specific heat of the rock was lower than the values assigned in the pretest analyses. Rock-wall temperatures did not exceed 78 C in the water collection boreholes and 88 C in the thermocouple boreholes during the heater test. Although the temperature of the heater elements was relatively high, a large dryout zone did not develop around the heater borehole.

Three adjoining parallel water migration boreholes (WM-1, WM-2, and WM-3) and the heater borehole (HH-1) were instrumented to collect water. Water was collected from

HH-1, WM-1, WM-2, and from well #8 and analyzed. Water collected from Well #8, which provided water used in drilling the boreholes, is considered to represent ambient water. No water was collected in WM-3 located about 30 cm above and 20 cm to the side of the heater borehole. During the migration/heater test, a total of 61.7 liter of water was removed from the four boreholes (Zimmerman et al., 1986a, pg 8-19). The highest rate of flux was during the first three days of heating, after which the rate of flux declined (Zimmerman et al. (1986a). Chemical analyses of samples collected during the water migration/heater test are illustrated in Table x.

Table x. Anion concentrations at different times in water samples from HH-1, WM-1, WM-2, and well #8 (Johnstone et al., 1985)

Sample No.	Date (J-day)	F (ppm)	C^{1-} (ppm)	PO_3^{4-} (ppm)
HH-1				
HH-3	37.05	1.5	2.1	
HH-12	38.2	1.9	1.2	
HH-19	39.23	0.3	N.D.	
HH-136	80.4	0.1	0.9	N.D.
HH-158	98.36	0.3	0.6	N.D.
WM-1				
WM-129	73.4	2.7	1.4	4.1
WM-160	99.36	0.8	5.6	
WM-2				
WM-28	38.4	9.2	10	15
WM-124	70.4	2.1	8.4	4.6
WM-161	99.38	1.8	5.0	
Well #8	1.5	8.3	2.5	

Date is in terms of Julian date from start of year.

The decrease in ion concentrations in the collected water is interpreted to reflect the contribution of condensate with low ionic concentrations. This observation is consistent with the fact that most water was collected soon after onset of heating. Assessment of the impact of refluxing water in this heater test was obscured because water was both injected into boreholes prior to energizing and periodically removed from boreholes during heating. There was no evidence in the temperature measurements that would indicate thermal refluxing occurred during the experiment, however, this lack of evidence may have been obscured by the water removal.

September 4, 2007 Ronald Green

2.2 1982-84 SNL G-Tunnel Heater Tests

The next set of heater tests in the G-Tunnel complex were conducted by SNL in 1982-1984. The objective of these tests was to evaluate the thermal and hydrothermal response of welded and non-welded tuff to heating. The set consisted of three borehole heater tests (Zimmerman, 1986a) and one heated block test (Zimmerman, 1986b). The tests were conducted in two alcoves; Alcove 1 is located in a welded tuff, the Grouse Canyon member, and Alcove 2 is located in a nonwelded tuff, referred to as Tunnel Bed 5. The Grouse Canyon member has a porosity of 12 to 25% and the Tunnel Bed 5 has a porosity of approximately 45%. There was significant water present in both units. The elevation of the test location was approximately 1,894 m msl.

Two borehole experiments (i.e., IW and IIW) were conducted in Alcove 1 and one borehole experiment was conducted in Alcove 2 (i.e., IN). IW and IN were vertical and IIW was horizontal. The borehole tests were conducted in parts. There were two tests conducted in borehole IW (a and b) and four tests conducted in borehole IIW (c through f). The heated borehole tests are described in Table x.

Table x. G-Tunnel Small-Diameter Borehole Heater Tests

Test	Date	Sponsor	Duration	Max Heater Temp	Max Rock Temp
G-Tunnel single borehole series - IWa	1982	SNL	21.7 days	460 C	240 C
G-Tunnel single borehole series - IWb	1982	SNL	7.1 days	460 C	240 C
G-Tunnel single borehole series – IN	1982	SNL	35.0 days	360 C	175 C
G-Tunnel single borehole series – IIWc	1984	SNL	7.8 days	325 C	100 C
G-Tunnel single borehole series – IIWd	1984	SNL	8.1 days	460 C	195 C
G-Tunnel single borehole series – IIWe	1984	SNL	7.9 days	500 C	240 C
G-Tunnel single borehole series - IIWf	1984	SNL	11.2 days	530 C	310 C

The letter subscripts are added to be able to differentiate among the tests.

Each heater unit consisted of a 114.9 cm long heater unit and a 76.2 cm cool extension. The heater units were hermetically sealed from the alcoves. The alcoves are located 600 m above the regional water table. The ambient temperature of boiling at this elevation is 94 C.

The heater units were equipped with one of two types of thermocouples to measure the temperature of the rock wall of the emplacement holes (i.e., tipout thermocouples and thermocouples bonded directly into the rockwall) to directly measure the rockwall temperature (Zimmerman et al., 1986a). Experiments in IIW only used thermocouples bonded directly into the rockwall. Heater boreholes IW, IN, and IIW were equipped with seven, six and five thermocouples, respectively. The thermocouples were placed at different levels. In all three heater boreholes, 3 thermocouples were in the heater section of the borehole. The remaining thermocouples were set between the heater section and the alcove wall. Test IIW also had a satellite borehole with six thermocouples placed near potential hydraulic-conducting fractures. There is no mention whether the boreholes were grouted.

Test IW and IIW were conducted to detect for the presence of pooled water. Sensors were placed at 2.5 cm increments in borehole IIW from the bottom to a height of 38 cm to detect electrolytes as an indication of liquid water. Data were collected at 5-minute to 30-minute intervals.

2.2.1 Test IW

The first component of test IW (IWa) operated at a constant power level of 800 W for a period of 21.67 days. Heater element temperatures exceeded 450 C. Emplacement hole temperatures approached 240 C. The thermocouple located at the bottom of the heater borehole was the only thermocouple to record a thermal refluxing event during IWa. Two rapid temperature excursions were observed during the first day of heating (Figure 6.1.5) (Zimmerman et al., 1986a). Temperature at the thermocouple at the base of the heater borehole decreased from about 175 C to about 90 C during the first excursion and from about 160 C to 105 C during the second excursion. Water collected in the heater emplacement hole during early heating. There was no mention of water chemistry analysis, but it is likely the water was mostly condensate because it occurred soon after the onset of heating. The temperature excursions are likely indicators of thermal refluxing of low TDS condensate water. 15 days after Test IWa was concluded, the heater was re-energized for an additional 7.1 days (Test IWb). No temperature excursions and no water were detected during this experiment.

2.2.2 Test IN

A component to the heater, referred to as the handling pipe at the top of the heater, was full of water when the emplacement hole was opened at the end of the test. The volume of water was estimated to be 0.5 liter (Zimmerman et al., 1986). The bottom of the heater pressure unit had a few drops of water at its base when opened. There is no mention of water chemistry analysis. There is no mention of corrosion. No temperature excursions were observed during IN.

2.2.3 Tests IIW

The four IIW tests were conducted at four power levels that were ramped up during the 35 day long test: 400W (7.8 days)(IIWc), 800W (8.1 days)(IIWd), 1,000W (7.9 days)(IIWe), and 1200W (11.2 days)(IIWf). Each power level is referenced here as a separate test. Maximum heater internal temperatures were 325 C, 460 C, 500 C, and 530 C. Maximum rock temperatures of 100 C, 195 C, 240 C, and 310 C were measured in the heater boreholes. Temperature excursions, as evidenced by rapid decreases in temperature to boiling (i.e., 94 C at the elevation of the tests), were observed during all four tests (i.e., IIWd,e,f). As indicated in Figure 6.3.7 of Zimmerman et al. (1986a), the temperature excursions occurred immediately after power was ramped up suggesting any refluxing water was low TDS condensate. No water was detected by pressure transducers located in the bottom of the borehole indicating that either the amount of refluxing water was not large or that downward flowing water was diverted prior to arriving at the bottom of the borehole.

No other refluxing event was observed although a heat pipe was observed at the 1.80-

1.85 m depth in the satellite borehole during test IIWf. Similar to the IWa,b heater tests, there was no evidence in the temperature measurements that would indicate thermal refluxing occurred during the experiment, however, this lack of evidence may have been obscured by the periodic water removal that occurred during testing.

2.2.4 Heated-Block Test

The heated-block test was conducted in the Grouse Canyon member of the Belted Range tuff in the G-Tunnel Underground Facility at Rainier Mesa at the same location as tests IW, IN, and IIW. The tuff is welded at this location. The block was 2 m x 2 m at the surface an extended to a depth of 3 m, although the tested portion was the upper 2 m so that the volume of tested tuff was 8 m^3.

There were three thermal cycles in the test: October 5, 1983 to November 22, 1983; November 22, 1983 to January 17, 1984; and April 5, 1984 to August 16, 1984. Each had a heating cycle and a cooling cycle. The three tests are considered separate tests and were assigned individual designations, heated block test: thermal cycles 1, 2, and 3.

The heaters were placed outside the block in the intact rock. Temperatures were measured in the block, in the cut slots (i.e., in the flat jacks), and in the intact rock surrounding the block. There was minimal remarkable data. Of limited interest was that development of a heat pipe was indicated by temperatures maintained at the boiling temperature for extended durations. The basic test design (i.e., no rock above the heated block) and insufficient measurement resolution resulted in minimal meaningful thermal reflux information.

September 6, 2007 Ronald Green

3. 1988-89 G-Tunnel heater test by LLNL

The LLNL heater test was conducted in 1988-89 in the G-Tunnel Underground Facility at Rainer Mesa at the Nevada Test Site. The test facility was located in the Grouse Canyon tuff. The test was located in the small-diameter heater alcove in the Mechanics Drift of the G-Tunnel Underground Facility. The heater borehole was inclined slightly upward and crossed a significant vertically oriented fracture. The 3-m long heating unit was energized at 3.3 kW on November 7, 1988. The heating phase lasted for 128 days after which power was ramped down in 20 steps over 67 days (Ramirez and Wilder, 1991; Ramirez, 1991; Lin et al., 1991).

There were seven horizontal neutron probe boreholes, three combined psychometric/thermocouple boreholes, and one thermocouple-only borehole. In addition, thermocouples were also installed in the neutron probe boreholes. Microwave coaxial resonators were installed in the pressure boreholes as part of a system that was developed and installed to measure water-vapor partial pressure in the boreholes at temperatures up to 250 C. A capacitance sensor (Humicap) was installed in the heater borehole in front of the packer. The resonator was behind a packer and could not be removed during testing

(Lin et al., 1991).

The microwave resonators were not tested prior to installation and operated erratically soon after installation. The source for the erratic behavior was hypothesized in the 1988 progress report by Ramirez and Wilder (1991). The resonator was thought to be cooler than the surrounding environment causing water to condense inside the resonator and that This water did not dry out, eventually causing corrosion inside each resonator rendering the system inoperative. A similar response was replicated in the laboratory. This replicated test was cited as verification of their explanation of why the resonator failed. The system apparently never worked. There was no discussion of the microwave system in the final report (Ramirez, 1991).

It is possible that there is an alternative explanation for the resonator equipment failure, although the Ramirez and Wilder (1991) explanation is plausible. The presence of corrosion on the resonator electronic components observed at the conclusion of the G-Tunnel Heater Test and a similar response observed during the laboratory-based test support the premise that the presence of liquid water on the components led to the equipment failure. One factor in the Ramirez and Wilder (1991) explanation that is questionable is that the resonator was sufficiently cooler than the borehole environment to cause water to condense on the resonator and for that water to indefinitely remain on the resonator even after thermal equilibrium of the resonator with the borehole environment. Once shut in, the sensor environment would have quickly equilibrated to the ambient temperature and the close to 100% relative humidity.

It is possible that a heat and mass transfer mechanism other than condensation due to a cold trap could have led to water accumulation on the resonator. In particular, thermal refluxing could have contributed to liquid water accumulation in the borehole cavity. Supporting this hypothesis is the presence of a vertically oriented fracture in the borehole which could have provided an opportunity for refluxing back to the resonator (Ramirez and Wilder, 1991).

One additional observation from Ramirez and Wilder (1991) was that the resonator began to malfunction immediately after the borehole was grouted. This observation suggests that the mechanism that led to water accumulation on the resonator occurred soon after the instrument was shut in by grouting. It is unlikely that thermal refluxing would have occurred immediately after grouting. However, in the absence of detailed examination of corrosion products, condensate water, CO_2 partial pressure, fracture location and orientation relative to the resonator, and the specific timing of events, it is difficult to conclusively identify which heat and mass transfer mechanism led to the corrosion and which mechanisms can be categorically dismissed.

September 19, 2007

Following are emails from NRC requesting minor changes to a DST Modeling status report. The requested changes were minor, programmatic in nature, and easily incorporated.

Randy,

I reviewed the changes. I agree that they are programmatic in nature and do not affect the technical merit of the report. Gordon is to have Jackie make the changes and he will make sure the changes are implemented as indicated. It should be done in short order, but the bureaucratic wheels do turn slowly. We will complete it as quickly as possible.

Ron

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-----Original Message-----
From: Randall Fedors [mailto:RWF@nrc.gov]
Sent: Thursday, August 30, 2007 1:41 PM
To: Gordon Wittmeyer
Cc: Ronald Green; Robert Lenhard
Subject: Fwd: Making old report publicly available

Gordon,

Please arrange to have the Green and Painter 2002 report revised per the word perfect file I left on the shared drive. All changes were made in strikeout/red font format in the file.

.\RFedors\GreenPainterRevision\GreenPainter2002LETTER REPORT_01402.661.240_RevisedAug07.wpd

I do not think the center will disagree any of the changes, though feel free to editorialize OGC's or my implementations of their markup if the intent remains the same. There are no changes to the technical content.

I am presuming that you will resubmit the report without a review process (except for a review of the NRC requested changes). I would appreciate that this be done in the next week or two. I have already requested (via Bret Leslie) a change in the TPA User Guide relevant to the new title and year for this report. Let me know if you have any questions.

Thanks,
Randy

This scientific notebook was closed on June 19, 2008 by Ronald Green.

This scientific notebook was revised on July 18, 2008 by Ronald Green. All revisions were related to adding the explicit document from which figures were taken. All figures not cited are original and developed as part of work documented in the scientific notebook.