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USING THERMAL DRAWDOWN AND RECOVERY SIGNATURES TO IDENTIFY INJECTION INTERVALS

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ABSTRACT

Geothermal reservoir engineering is an inexact science. The engineer is forced to design and operate the reservoir based on a conceptual model gained mainly by inference, not direct observation. One type of data available to the engineer is temperature logs of the injection and production wells before, during, and after operation.

In this paper, we present analyses of thermal drawdown and recovery at an injection borehole with different fracture spacings. The goal is to identify patterns in the resulting thermal signatures. We discuss data obtained from testing at the Fenton Hill reservoir and compare our calculations to data. We conclude that thermal signatures, especially thermal recovery, can help the engineer identify flow patterns within the reservoir.

BACKGROUND

As cool water is injected into a fracture dominated geothermal reservoir, several effects occur. As the water flows from the surface to the reservoir, it is warmed by heat conducted through the casing wall. This cools the rock, most strongly near the wellbore, but extending radially with time. Over the injection interval, the water cools the wellbore but water also flows into the reservoir, predominantly by means of open joints. The water in the joints cools the faces of the joints and this cooled region gradually extends into the rock by conduction.

At the end of injection, a cooled region will have been established by the flow into the reservoir. If the reservoir is shut-in, thermal recovery will occur. Thermal recovery is expected to be dominated by conduction, but flow may also occur due to natural circulation and residual pressure gradients remaining in the reservoir. The thermal recovery pattern carries the signature of the cooled region and can provide clues as to the flow patterns in the reservoir. We will consider two possible joint configurations: transverse joints (Figure 1) and co-planar joints (Figure 2).

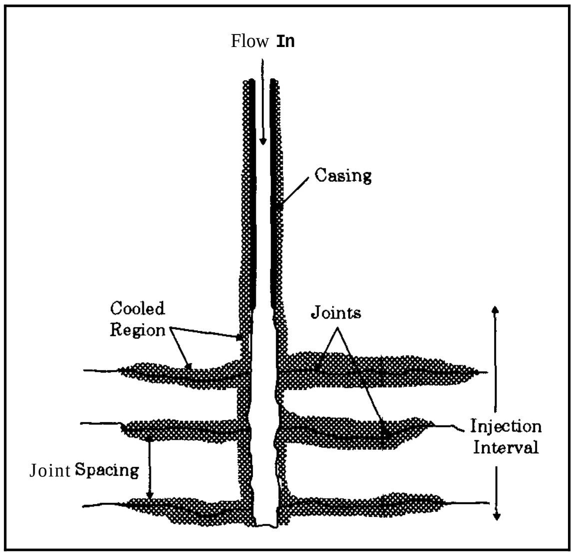

Figure 1: Schematic of transverse cooling

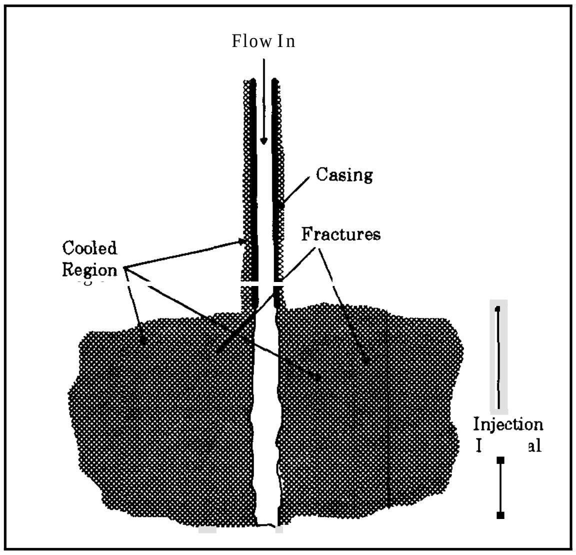

Figure 2: Schematic of co-planar cooling

Our objective is to analytically predict the thermal drawdown and recovery patterns for these joint orientations and a range of fracture spacings. We will then compare these patterns with those observed in the Fenton Hill Initial Closed-Loop Flow Test. These comparisons allow inferences to be made with respect to the active fracture spacing near the Fenton Hill injection borehole.

FENTON HILL DATA

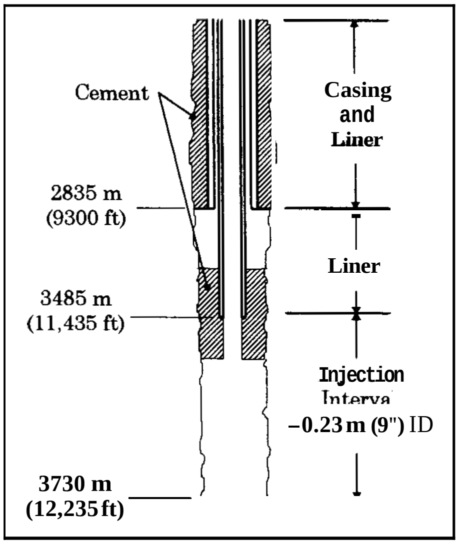

Figure 3: Schematic of injection well (Details of liner not shown)

The data we will use for comparison was obtained before and after the Initial Closed Loop Flow Test (ICFT) performed at Fenton Hill from May **19** through June **18, 1986** (Dash, et al., **1989).** A schematic of the Fenton Hill injection well during the ICFT is shown in Figure **3.**

The ICFT lasted approximately one month **(30** days). The flow rates were nominally **0.0114** m^3/s **(180** gpm) for half the test and **0.0180** m^3/s **(285** gpm) for the remainder of the test. The total injected volume was **37,000** m^3. Based on flowing measurements, the nominal water temperature at the injection interval was **70** "C at a flow rate of **0.0106** m^3/s and **50** °C at **0.0172** m^3/s. Testing prior to the ICFT injected about 32,000 m^3, with the majority of this 2 ½ years before the ICFT.

Temperature logs of the injection well are shown in Figure **4.** The temperature logs measure the water temperature at a thermistor probe mounted in a **0.076** m **(3** inch) outer diameter tool. The accuracy of the measurements is believed to be **1** "C. The measurements were taken as the probe was slowly lowered into the well. The background temperature increased approximately linearly with depth. At the beginning of the ICFT, some residual cooling due to testing and flow is apparent. As shown in the data, significant cooling occurred over the interval from about **3550** m to **3700** m and was still apparent **16** months after the ICFT, at which time temperatures away for the injection interval had returned to approximately the initial background values.

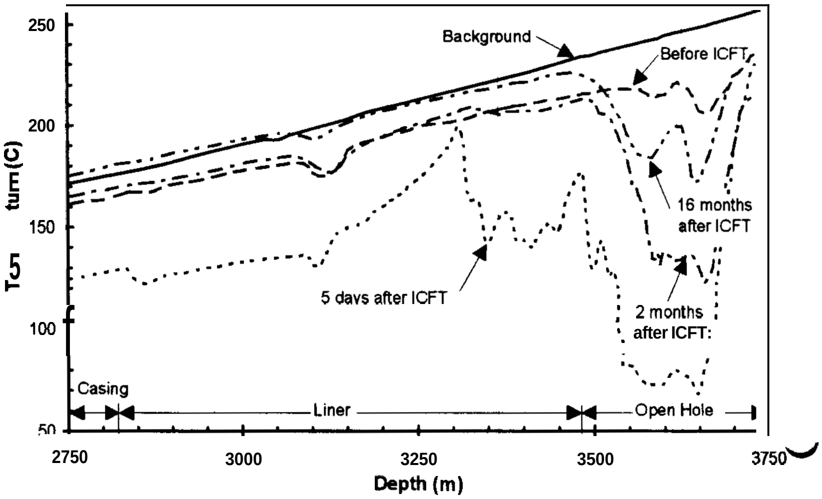

Figure **4:** Temperature log data

ANALYSIS

Our objective is to use the borehole temperature data to infer the orientation and number of joints active during injection. We do this by performing analyses of different fracture spacings and orientations.

The analyses were performed using the GEOCRACK model, a fully coupled fluid flow/rock deformation/heat transfer analysis finite element code (Swenson, et al., **1997).** This code was developed as part of the Hot Dry Rock geothermal energy project at Los Alamos National Laboratory and is available on the world wide web. In this analysis rock deformation was not included, only the fluid and thermal solutions were used.

For the transverse joint analyses, the model represents a **300** m length of the borehole, with injection over a **100** m interval. The model represents an axisymmetric section of the reservoir orehole viewed from side), with an inner radius of .1 m (4") and extends radially 150 m (490 ft). In e model, fluid flows down the central borehole and to axisymmetric (transverse) fractures. Analyses ere performed for geometries of 1, 3, **5**, and 9 actures. Figure **5** shows the mesh for the model at included five joints.

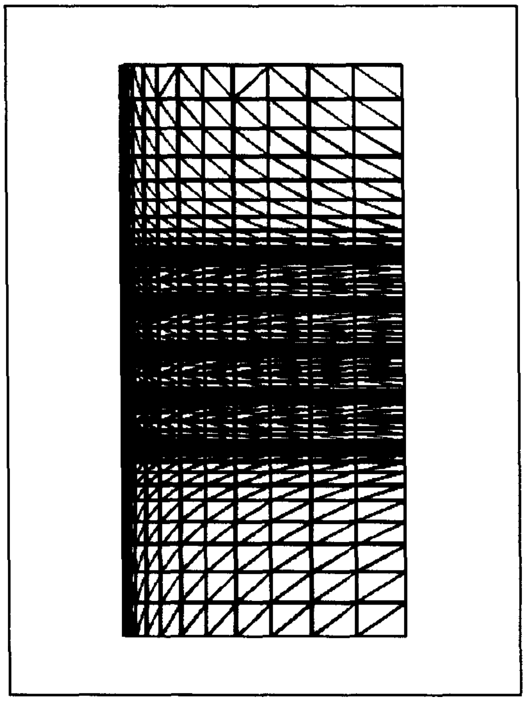

Figure **5:** Mesh for five joint analysis

he analysis for the co-planar joints is a plane model borehole viewed from top). Due to symmetry, only alf of the borehole was modeled. The model had a epth (injection interval) of 100 m and a extended S 0 m from the borehole (Figure 6).

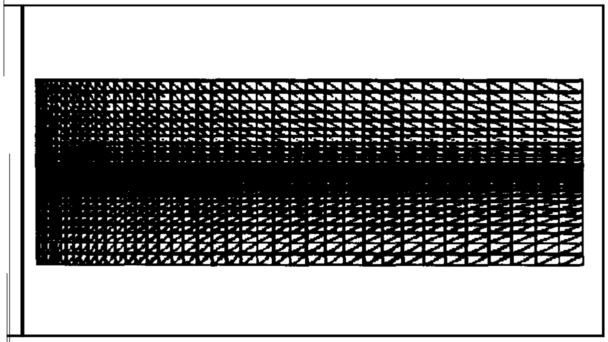

Figure 6: Mesh for co-planar joints

aterial properties of the rock are given in Table 1 nd the water properties in Table 2.

	Value
	85.12E9 Pa
ν	0.25
Density	2,716 kg/m^3
Conductivity	0.22286 J/day-m-C
Specific heat	803 J/kg-C
Thermal expansion	**7.5E-6/C**

Table 1: Rock properties

Property	**Value**
Dynamic viscosity	Table in Pa-day
Joint opening	0.5x10^{-3} m
Density	**950 kg/m^3**
Conductivity	**0.57E5 J/day-m-C**
Specific heat	**4,300 J/kg-C**
Convection coefficient	**0.57E8 J/day-m^2-kg**

Table 2: Water properties

For all analyses, the total injection flow was maintained at the average of the flow in the ICFT experiment, 0.014 m^3/s (222 gpm). This flow was distributed uniformly into each of the fractures in the analysis. The initial temperature of the rock was assumed to be 200 °C and the fluid injection temperature to be 50 "C. Fluid was injected into the borehole for a period of 30 days. The flow was then stopped and the analysis continued for an additional 16 months. For the co-planar joint analysis, the joint opening was changed to 0.5x10^{-2} m.

ANALYSIS RESULTS

An overview of the results can be obtained by looking at temperature contours. Figure 7, Figure 8, and Figure 9 show details of the contours for the top two joints of the five transverse joint model (25 m joint spacing) at 30 days while flowing, at **35** days ***(5*** days after the end of flow), and 2 months after the end of flow. The corresponding result for the co-planar joint model is shown in Figure 10 at **35** days. In all figures, the contours span the temperature range 50 to 200 "C (admittedly somewhat difficult to identify in black and white).

While flowing during injection for the transverse joint cases, the water temperature in the 100 m length of borehole stays at essentially the injection temperature. The water only warms significantly in the joints. Because rock is a relatively poor conductor, the zone cooled by conduction reaches only a 2-3 m into the rock from any cooled surface. As a result, at the end of 30 days, the cooled region surrounds the borehole and extends into the rock at the joints. The bulk of the **rock,** however, remains at the initial temperature. After the flow stops, heat conduction gradually warms the cooled rock, so that most of the rock has recovered the initial temperature 16 months after the test.

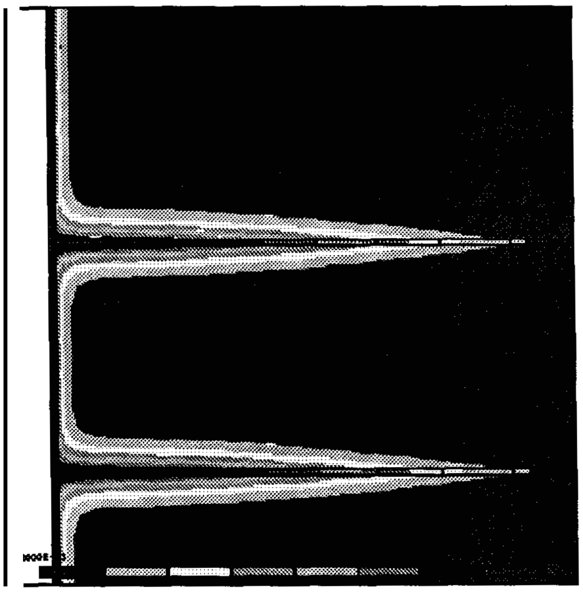

Figure 7: Temperature contours at end of ICFT (30 ays) while flowing, side view of transverse analysis (min temp = 50 C, max = 200 C)

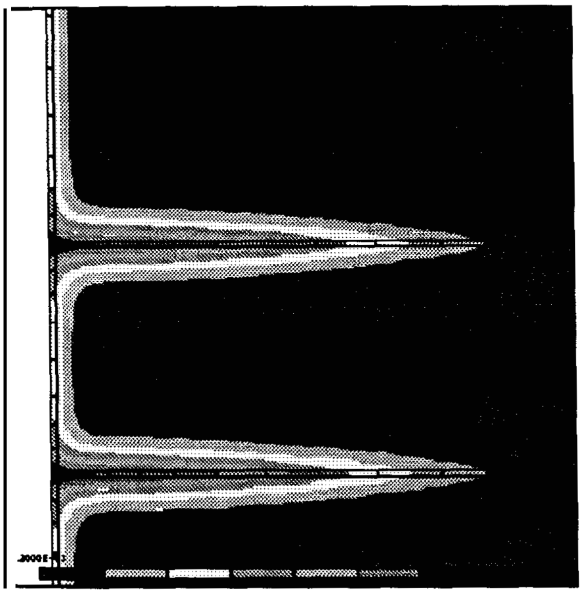

Figure 8: Temperature contours **5** days after ICFT (min temp = 60 C, max = 200 C)

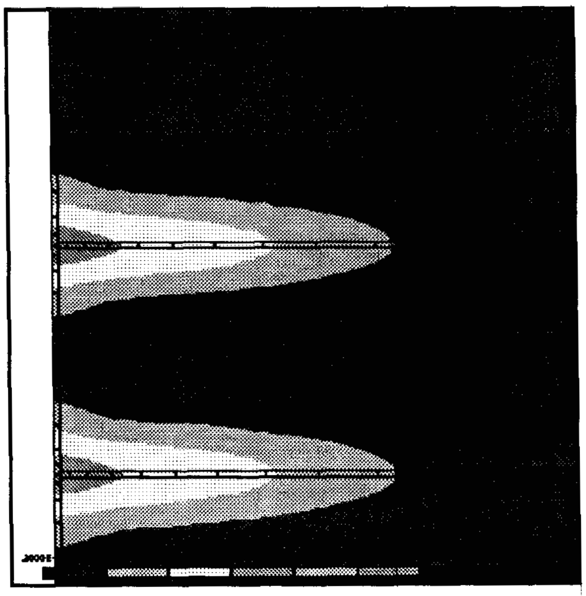

Figure 9: Temperature contours 2 months after ICFT (min temp = 120 C, **max** = 200 *C)*

For the co-planar joint analysis, the cooled region extends further along the joint, but approximately the same distance, 2-3 m into the rock from the joint face.

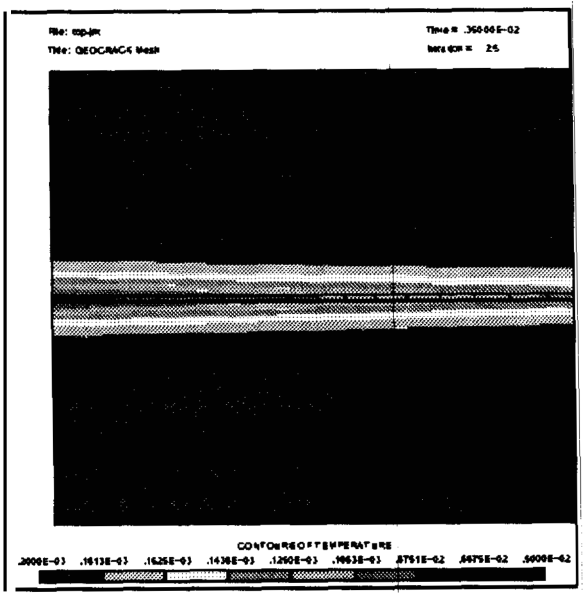

Figure 10: Temperature contours five days after ICFT (min temp = 50 C, max = 200 C)

Another way to look at the results is by plotting temperatures as a function of position. We first look at the radial plots of temperature for the transverse joint analyses. Figure **11** shows the radial cooling

The co-planar joint analysis looks down at the borehole, so there is no variation of the temperature with depth over the injection interval. Figure 15 shows a plot of the borehole temperature (in the injection region) as a function of time.

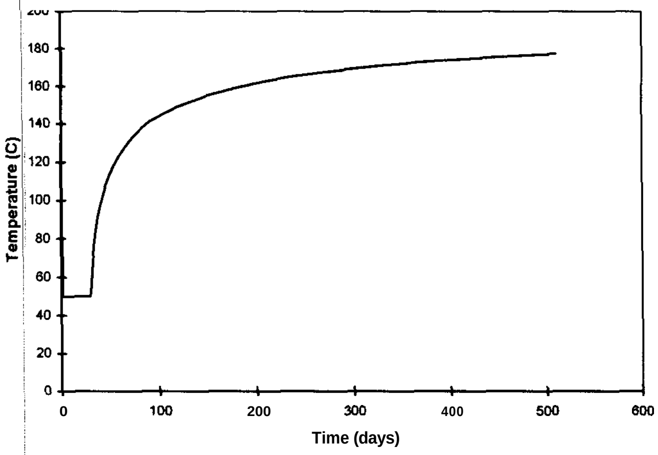

Figure 15: Borehole temperatures for co-planar joint analysis

COMPARISON OF FENTON HILL DATA TO ANALYTICAL RESULTS

The above calculations provide an idealized background. Our task is to now compare with Fenton Hill data and to study the implications.

The easiest comparison to make is the response at the borehole but away from the joints. To do this, a straight line fit was made to the Fenton Hill data from a depth of 2750 to **3500** m. At a depth of **3100** m, the temperatures on this straight fit are **140** °C **five** days after the ICFT, **189 °C** two months after the test, and 200 °C sixteen months after the ICFT. This data is shown in Figure **16** and is compared to analysis results for the disc-shaped joint analyses away from the injection region. The comparison shows that the analyses are consistent with conduction being the primary heat removal method in regions far from the injection joints. The very rapid initial recovery is a strong indication that the cooled region did not extend far into the rock. Similar good comparisons with conduction analysis away from the borehole were reported by Dash, et al., 1989, using the Wellbore Heat Transfer Code (their analysis does not include flow into joints).

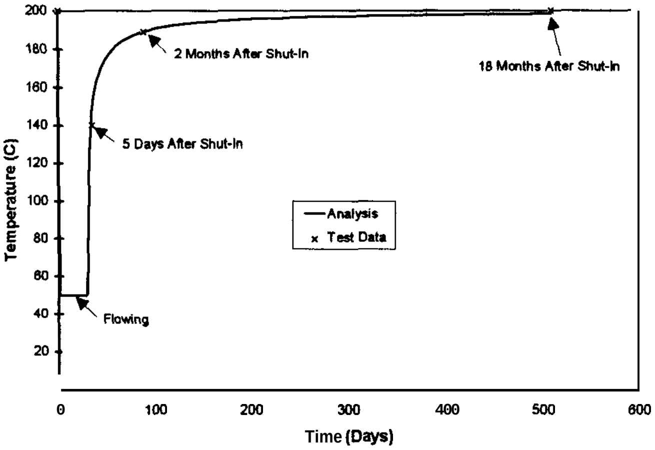

Figure 16: Transient temperature at borehole surface

Let us now examine the data in the jointed region into which fluid was injected. We want to look at broad trends, so the straight line approximations to the data that will be used in the comparisons are shown in Figure **17.**

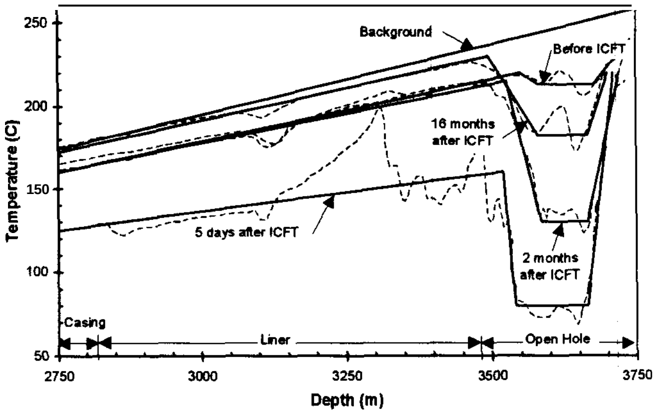

Figure **17:** Approximations to data

One striking difference between the Fenton Hill data and the calculations shown in Figure 12, Figure **13,** and Figure **14** is the relative smoothness of the data. The calculated temperatures have strong dips at joints for injection.

One reasonable hypothesis is that, if in fact the borehole temperatures shown in the calculations were those in the actual borehole, the alternating cold and hot regions would lead to natural circulation cells that would tend to mix the fluid temperature to some average *of* the borehole temperatures. We have performed some simple calculations using the Fluent code and have observed this averaging (the calculations were not for the exact borehole geometry and so are not conclusive).

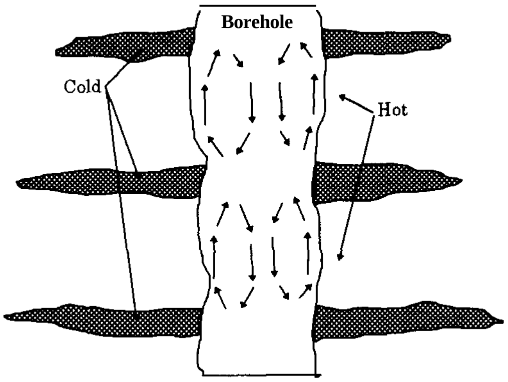

Figure **18:** Schematic of circulation cells in borehole

Because it seems reasonable that the fluid temperature would represent an average borehole temperature, we will use the average drop in temperatures in the injection region relative to the temperatures before the ICFT as a way to compare with Fenton Hill data. This comparison is shown in Table **3.**

Case	5 Days	2 Months	16 Months
1 Transverse Joint	31	11	6
3 Transverse Joint	60	22	12
5 Transverse Joint	68	32	22
9 Transverse Joint	82	52	36
Co-planar Joint	117	59	23
Fenton Data	135	83	31

Because the co-planar analysis included cooling due to flow in the joint, but not the extra cooling due to heat transfer from the borehole surface, the co-planar temperature drops in Table **3** are somewhat smaller than actually expected. Based on this comparison, it appears that it is likely that the major flowing joints in Fenton Hill are aligned with the axis of the borehole (co-planar joints). Such joints (fractures) could be the result of the stimulation used to connect the injection and production wells. Joints aligned predominantly with the borehole axis would also be consistent with the absence of distinct hot and cold regions along the borehole (although temperature averaging could occur in the fluid due to natural circulation).

CONCLUSIONS

Away from injection points, the Fenton Hill data is consistent with cooling of the rock around the borehole by conduction.

In the injection region, cooling of the rock leaves a signature that can help identify the orientation and number of joints actively participating in the flow. Joints normal to the axis of the borehole will introduce local cooled zones associated with each active joint. A joint aligned with the borehole axis will cool the entire borehole and reduce the average temperature at the injection region more than for joints normal to the axis. Based on comparisons with Fenton Hill data, it appears that active joints were aligned with the borehole axis.

If joints are normal to the borehole axis, it is likely that the alternating cooled and hot regions will result in natural circulation cells in the borehole. These cells would spread and smear the local cooling near the joints and mean that the temperature probe measures an averaged borehole surface temperature, not a local rock temperature.

ACKNOWLEDGEMENTS

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REFERENCES

Dash, Zora, et al., **1989,** "ICFT: **An** Initial Closed-Loop Flow Test of the Fenton Hill Phase II HDR Reservoir," Los Alamos National Laboratory, Los Alamos, New Mexico, **87545,** LA-11498-HDR, UC-**251.**

Daniel Swenson, et al., **1997** "GEOCRACK: A Coupled Fluid Flow/Heat Transfer/Rock Deformation Program for Analysis of Fluid Flow in Jointed Rock," Mechanical Engineering Department, Kansas State University, Manhattan, KS, USA, **66506,** code is available at http://www.engg.ksu.edu/–geocrack or by contacting swenson@ksu.edu.