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STRATEGIES FOR THE HIJIORI LONG TERM FLOW TEST

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ABSTRACT

This paper describes analyses being performed to aid in the development of operation strategies for the Long Term Flow Test at the Hijiori Hot Dry Rock reservoir, Japan. Testing has shown that the reservoir is dominated by flow in natural fractures that connect the reservoir to the far-field. When the injection flow is doubled, the production flow rate stays approximately constant. Also, during operation, the production downhole pressures are sub-hydrostatic. The challenge is to design an operating strategy that provides adequate production within these constraints. GEOCRACK is being used to predict reservoir performance and guide in the design.

HIJIORI TEST DATA

In 1991, 1995, and 1996, reservoir testing was performed at the Hijiori Hot Dry Rock geothermal reservoir (GERD, 1995; GERD, 1996). This data provides a foundation to help understand flow in the Hijiori reservoir and to then guide in developing strategies for the long term circulation test.

Reservoir Geometry

The Hijiori reservoir is located on the southern boundary of the Hijiori caldera. The reservoir wells intersect two major fractures at depths of about 1800 and 2200 m. The fractures are part of the ring structure around the caldera and strike east-west and dip steeply to the north, at an angle between 25 and 35 degrees from the vertical. A vertical section of the reservoir is given in Figure 1.

In 1991 and 1995/96 the Hijiori reservoir consisted of four wells as illustrated in Figure 2. HDR-1 was open to flow both at the upper fracture and at a depth of 2150-2200 m, while the other wells (KSG-2, HDR-2, and HDR-3) extended to a depth of about 1800 m. In 1991, SKG-2 was used as the injection well, with production from the other wells.

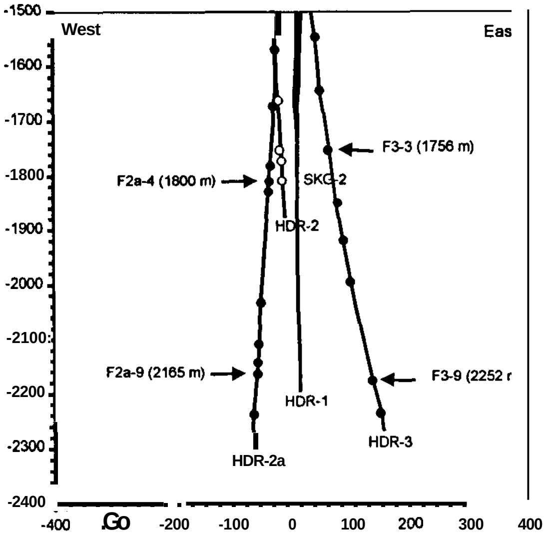

Figure 1: Vertical section of Hijiori reservoir. Dots indicate fracture intersections with wellbores.

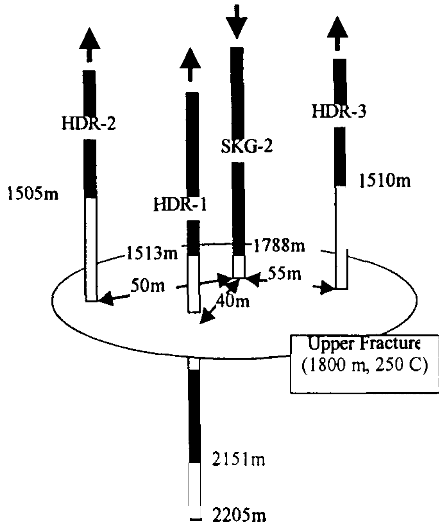

Figure 2: Schematic of wellbores during 1991 testing

Between 1991 and 1995, HDR-2 and HDR-3 were deepened to intersect the lower fracture, as shown in Figure 3. In the 1995 and 1996 testing, HDR-1 was used as the injection well and HDR-2a and HDR-3 as production wells (HDR-2a was closed during part of the 1996 testing).

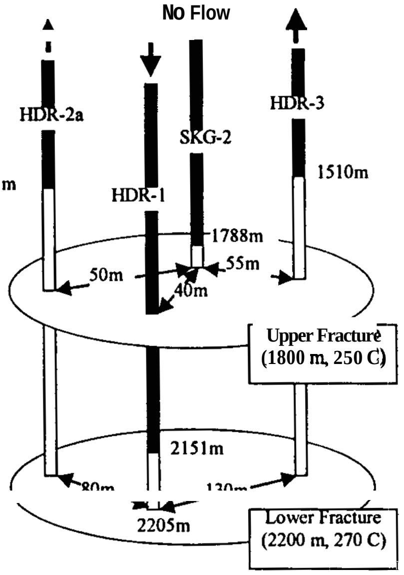

Figure 3: Schematic of wellbores during 1995 and 1996 testing

1991 Testing

The 1991 test started 8/2/91 and lasted 90 days, with SKG-2 injection at a rate of about 16 kg/sec. For the near-steady state conditions of the last 40 days of the test the production is shown in Figure 4. Typical recovery was about 76%.

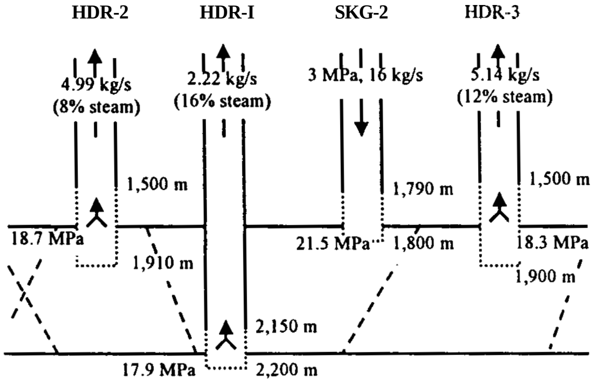

Figure 4: Schematic of conditions near end of 1991 tests

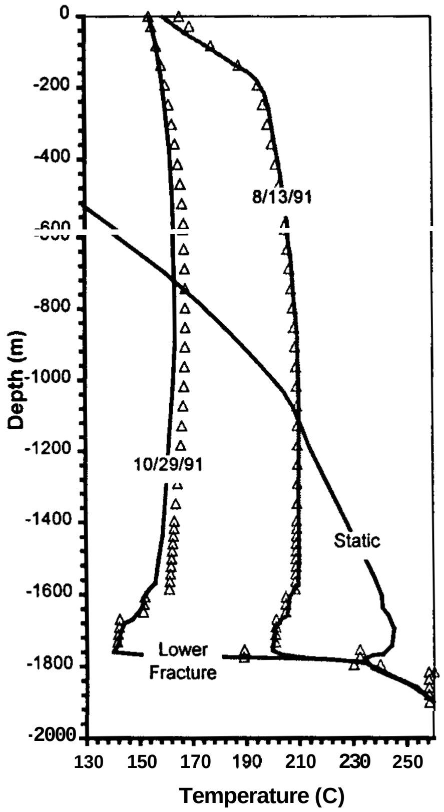

Figure 5: HDR-2 temperatures before and during 1991 testing (triangles are WELF97 results)

Temperature logs taken before and during the 1991 testing show the cooling that occurred at the location of the upper fracture. Figure 5 gives the data for HDR-2; similar data was obtained for HDR-3.

Also shown in Figure 5 are matches of the temperature data calculated using WELF97, a code that uses radial cooling and two phase flow calculations to predict borehole temperatures. Based on the data and the supporting WELF97 calculations, most flow and the corresponding cooling of the well occurred at the upper fracture. Just 11 days after the start of the test, the upper fracture temperature had declined about 60 °C, increasing to a 110 °C reduction by the end of the test.

Drilling between 1991 and 1995

Between 1991 and 1995, HDR-2 and HDR-3 were deepened. When drilling HDR-2 in 1994, it is believed that significant cooling occurred as a result of lost circulation at the upper fracture.

1995 Testing

At the beginning of 1995 testing, the static temperatures in HDR-2 (now called HDR-2a) showed the effects of previous testing and lost circulation. The static profile in Figure 6 shows that

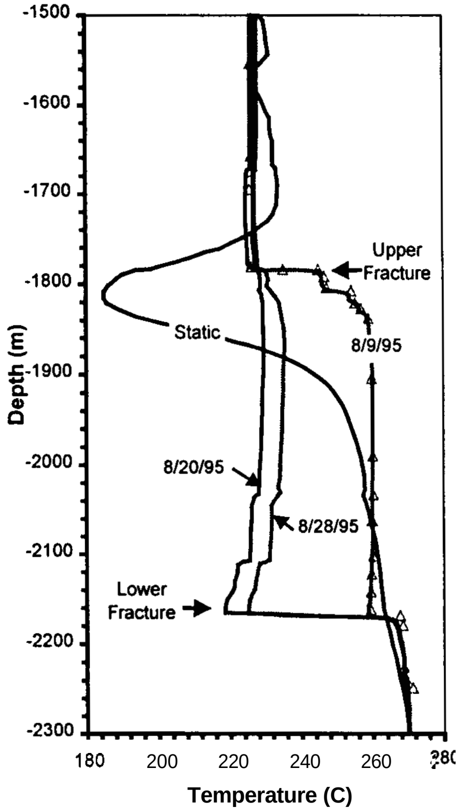

Figure 6:HDR-2a temperatures before and during 1995 testing (triangles are WELF97 results)

in 1995 the upper fracture was still about 70 °C cooler than before 1991.

As illustrated in Figure 7, during the 1995 testing water was injected at the lower fracture depth from HDR-1.

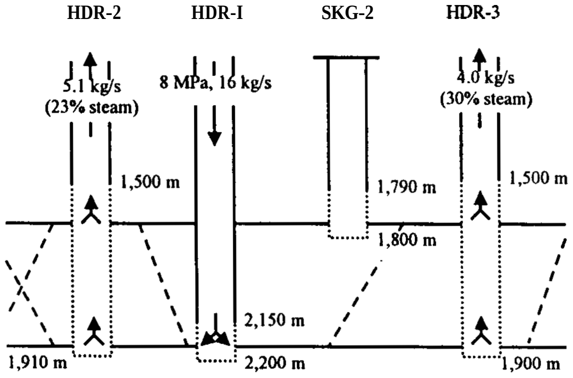

Figure 7: Schematic of conditions during 1995 tests

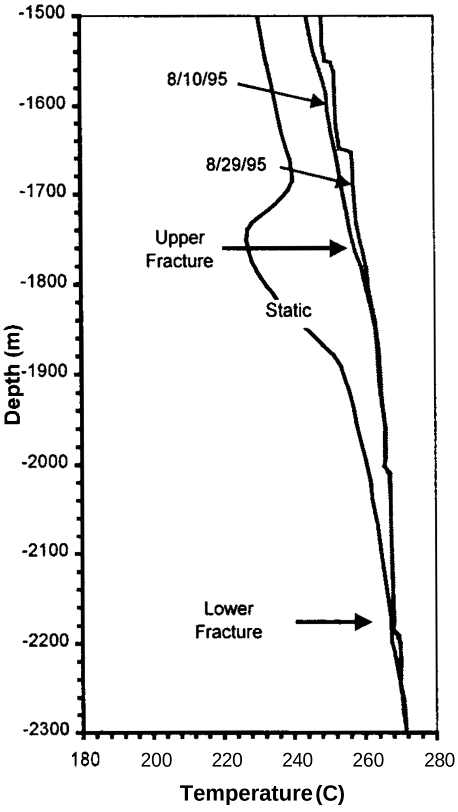

Figure 8:HDR-3 temperatures before and during 1995 testing

Data obtained during testing, Figure **6,** show that HDR-2a has a strong connection to HDR-1. In HDR-2a we see rapid cooling similar to that observed during the 1991 testing. We also see that, although the bottom fracture of HDR-2a is cooling, the temperature produced above the upper fracture is approximately constant. This means that the flow into HDR-2a at the upper fracture must be warming, which is consistent with hot water passing through the cooler upper fracture (and warming it) as fluid is produced from HDR-2a.

To verify this, WELF97 was used to calculate the flow into HDR-2a to match the measured temperature profile. The WELF97 calculation showed that the lower and upper fractures are the major flow paths in HDR-2a and that cooling occurred at the lower fracture and warming of the fluid at the upper fracture.

A completely different behavior is noted for HDR-3, Figure 8. In contrast to the 1991 testing, where cooling occurred at the upper fracture at both HDR-2 and HDR-3, no cooling is observed in HDR-3 during the 1995 testing. One reason for this is the longer distance between HDR-1 and HDR-3, relative to HDR-1 and HDR-2a. **A** second reason, confirmed by both the measured data and the WELF97 calculation is that flow into HDR-3 is distributed over many fractures that intersect HDR-3, rather than principally the lower fracture.

After 12 days of injection at a rate of 16 kg/sec the injection flow was increased to 32 kg/sec for 9 days, then returned to 16 kg/sec for 4 days. The higher injection flow rate did not result in a corresponding higher production rate. In fact, the production from HDR-2a initially dropped then recovered to approximately the same as an injection rate of 16 kg/sec.

1996 Testing

The 1996 testing lasted 30 days, with 25 days of injection into HDR-1 with HDR-2a closed followed by 5 days of injection producing from both HDR-2a and HDR-3. Figure 9 shows a schematic of the conditions during the test when HDR-2a was shut. One point of interest is that although HDR-2a was shut at the wellhead, there was significant flow into HDR-2a at the lower fracture that exited at the upper fracture. There was not any significant cooling in HDR-3.

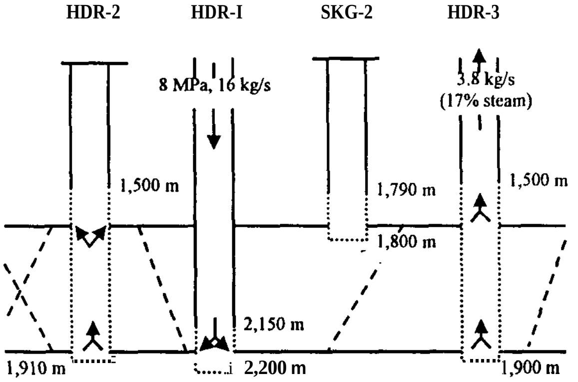

Figure 9: Schematic of conditions during 1996 tests

RESERV SIMULATION FRC 1 T 1996

To help understand **flow** and heat removal in the Hijiori reservoir a model of the reservoir was developed using GEOCRACK. The focus of the analysis was on the flow and temperature responses of the reservoir under the approximately steady state conditions **of** the tests. Since GEOCRACK is a two-dimensional code, it is unrealistic to expect perfect comparison to the actual three-dimensional case. Instead, the **goal** is to capture the essential features of the reservoir and use the results to guide in preparation for the long term flow test.

The analysis included:

- 1991 testing, where water was injected into the upper fracture using SGK-2.
- Thermal recovery after the 1991 upper fracture experiments.
- Additional cooling of the reservoir due to lost circulation during deepening of HDR-2a in 1994.
- 1995 Short Term Circulation Test (STCT) experiments (including interaction of Upper and Lower Fractures).
- 1996 Short Term Circulation Test (STCT) experiments.

The GEOCRACK finite element code was developed to solve coupled structure/fluid/thermal problems where the flow is on fractures (Swenson, 1997). **A** GEOCRACK model consists of rock blocks with nonlinear contact and discrete fluid paths between the blocks. Heat transfer occurs by conduction in the rock blocks and transport in the fluid. The user interactively defines the finite element mesh, the material properties, boundary conditions, and solution controls. All user interaction with the analysis is through the graphic display and a menu.

The GEOCRACK model that we used to perform the analyses is shown in Figure 10. This figure shows the rock blocks (rectangles), fractures/flow paths (blue paths), and well locations (circles and squares) in the model. Figure 10 shows the injection and production points for the 1995 and 1996 testing, in 1991 and 1992 injection was at the upper fracture level.

In the actual reservoir, the upper and lower fractures are know to dip steeply. This 2-D representation should be viewed as section of the reservoir in which the fractures have been rotated to remove the dip. In the model, a uniform thickness (depth normal to the vertical plane of the model) **of** 50 m was used.

The GEOCRACK model represents a vertical section of the reservoir, extending from a depth of 1500 to 2500 m. The horizontal extent is 1000 m, with the wells approximately centered within the model. The vertical section used for the model was chosen to bound the known volume of the reservoir. A uniform depth (normal to the vertical section) of 50 m was used for the entire model. This is an estimate of the participating depth of flow on the steeply dipping fractures known to exist at Hijiori. It was selected to be on the same order as the spacing between the wells.

The horizontal spacing of the fractures is 75 m with a vertical spacing of 100 m (these values are for the region in the center of the model). The spacing used for these fractures was based on the approximate number of known fractures that intersect the wells (Figure 1). Also, the pattern of the fractures was chosen to enhance the vertical connection between the upper and lower Fractures, since there is a known connection between them.

In Figure 10, the upper and lower fractures are shown by dashed lines. These fracture systems are known to dominate flow. A dual path was used, since the flow data (and WELF97 calculations) indicates flow feeds at spacings of about 50 m. The fracture opening in the upper and lower fractures was increased over the nominal values of the reservoir. This represents the increased conductivity of these fractures.

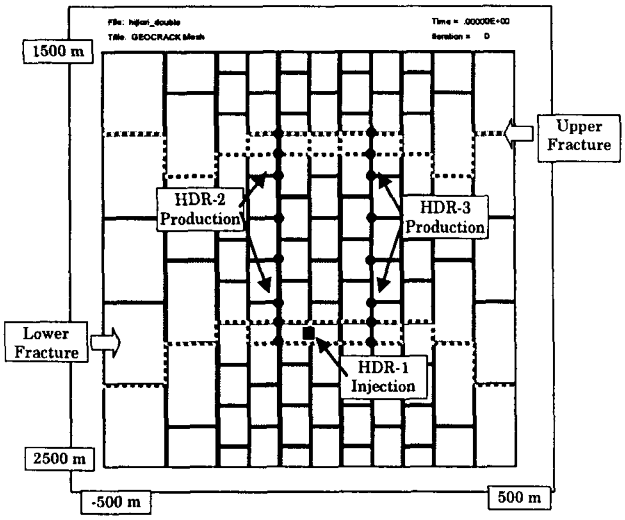

Figure 10: GEOCRACK model representing vertical section of reservoir

The actual finite element mesh that is used to develop the solution is a discretization of the block geometry. Triangular elements with quadratic shape functions are used for the blocks, with quadratic flow and contact elements between the blocks.

Material Properties

Since GEOCRACK solves the coupled fluid/thermal/structure problem, all associated properties must be specified. The in-situ stresses at Hijiori are 43.2 MPa horizontal, 54.0 MPa overburden, and 32.4 MPa minimum horizontal. The hydrostatic pressure at a depth of 2000 m is about 18.5 Mpa. In the model, all other pressures were adjusted to the same depth, so that the relative values would be correct.

Rock and Water Properties

Standard properties for granite and water were used in the analysis. The water viscosity was specified as a function of pressure and temperature.

Nonlinear Fracture Contact Stiffness

Since the rock blocks contact, it is necessary to specify a fracture contact stiffness. We used a Gangi model, with a fracture closure stress of 75 MPa, complete opening at 0.25 mm, and an exponent of 0.33:

$$a = 0.25\left[1.0 - \left(\frac{\sigma_{eff}}{75}\right)^{0.33}\right]$$

This gives a nonlinear stiffness between opening and effective stress on the fracture. For example, at an effective stress of 35.5 MPa (54 MPa in-situ – 18.5 MPa hydrostatic), the fracture opening is 0.05468 mm. The same contact behavior was used for all fractures in the model.

Fluid Flow

In GEOCRACK, the problem is defined in an initial equilibrium state. The conductivity of the joint elements is calculated using the cubic law, $k_p = \frac{a^3}{12\mu f}$, where a is the joint opening, μ is the dynamic viscosity, and f is an adjustment factor (assumed 1.5 in all calculations). The user specifies the initial opening at the equilibrium state, and then any displacements are added to that value when calculating the conductivity, $a = a_0 + a_{displacement}$. If we strictly use the Gangi model the initial opening would be 0.055 mm at an effective stress of 35.5 MPa, however, for the flows to match the data and because of the known increased fracture conductivity at the upper and lower fractures, the values of the initial openings were specified as shown in Table 1.

Fracture	Initial Opening (mm)
Horizontal	0.075
Vertical	0.125
Horiz. Upper and Lower	0.200
Vert. Upper and Lower	0.250

Wellbore and Far-Field Boundarv Conditions

In the Hijiori reservoir, the upper and lower fractures are conceived to be high conductivity fractures. The wellbores intersect this fracture. When water is injected into HDR-I, some of the water is recovered in HDR-2a and HDR-3, but some water flows past the production wells and into the far-field A two-dimensional model of a vertical section of the reservoir cannot accurately represent both the flow into the producing wells and flow past the wells.

To improve our representation of this flow condition, the concept of a conductivity from the fractures to the wellbores and far-field was introduced. The user specifies a pressure in the wellbore (or far-field) and a corresponding conductivity from the fracture to the wellbore (or far-field). The flow into the wellbore is then calculated using this conductivity and the pressure difference between the wellbore and fracture, or,

$$Q = K_{well}\left(P_{fracture} - P_{well}\right)$$

This approach makes it possible to model the high conductivity upper and lower fractures and also to represent the partial flow of the water into the wellbores. Figures 12 and 13 show the values used in 1991 and 1995/96.

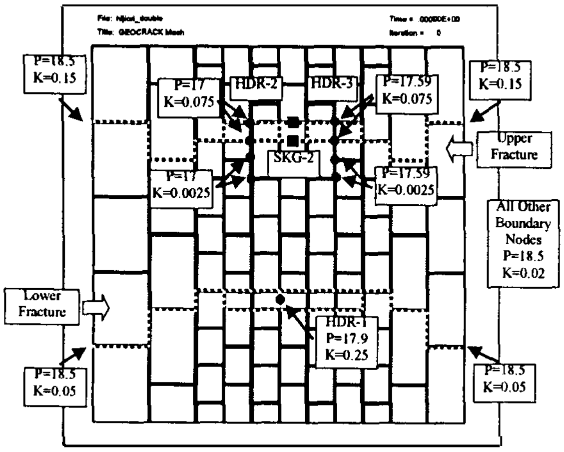

Figure 12: 1991 test conductivities and pressures in wellbores (units of pressure are MPa, units of conductivity are kg/day-Pa)

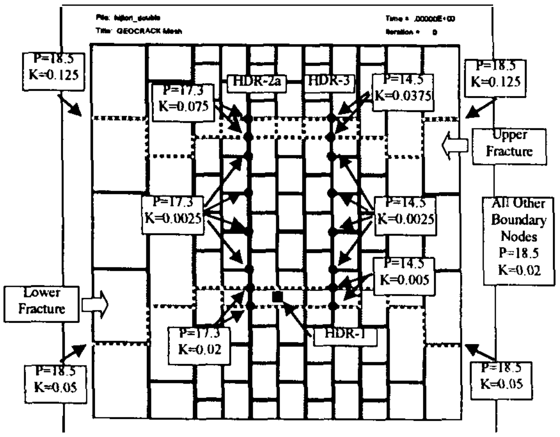

Figure 13: 1995 and 1996 STCT conductivities and pressures in wellbores for all cases except for HDR-2a shut-in (units of pressure are MPa, units of conductivity are kg/day-Pa)

GEOCRACK RESULTS

Temperature Distribution in Reservoir

A good way to obtain an overall understanding of the analysis is to look at temperatures contours in the reservoir. Figure **14** shows the temperature in the reservoir at the end of the 1991 testing. In this test, water was injected in the upper fracture through SKG-2. What is seen in the contours, and confirmed by the rapid cooling observed in HDR-2 and HDR-3 is that flow is primarily on the upper fracture and that cooling is localized to this region.

Figure 15 shows the temperatures contours at the end of testing in 1996. This figure shows the thermal recovery that has occurred at the upper fracture and the cooling at the lower fracture (again confirmed by measured temperature contours).

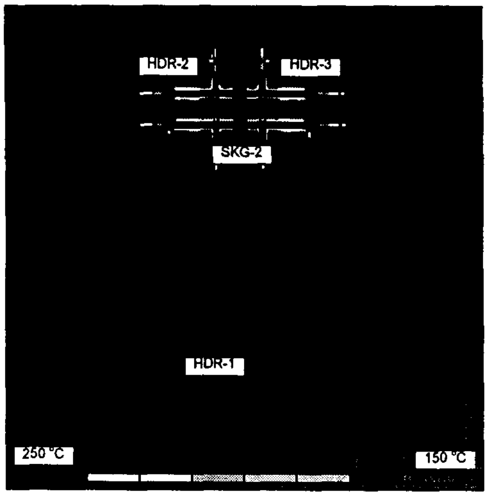

Figure 14: Temperatures at 90 days, at end of 1991 testing

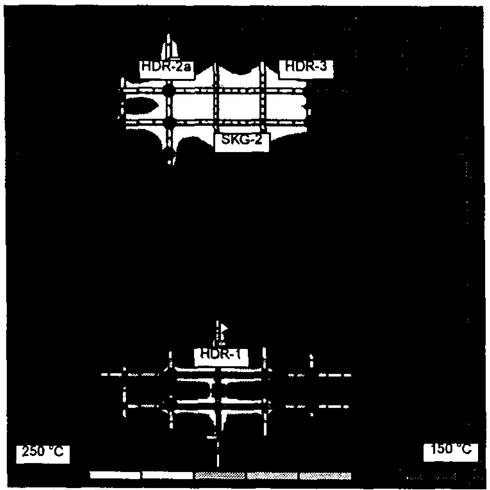

Figure 15: Temperatures at 1830 days (after 1996 testing)

Comparison of GEOCRACK and Static Temperature Data

One way to compare the GEOCRACK calculations with experimental data is with the static temperature logs, which provide temperatures along a line in the reservoir. Figure 16 shows the measured and predicted static temperatures in HDR-2a. (Recall that in the GEOCRACK model the upper fracture is displaced vertically and assumed two fractures at a 50 m spacing.) In 1992, GEOCRACK predicts **80** °C of cooling, while the data shows 80 "C; in 1995 GEOCRACK predicts 140 °C, while the data shows 120 "C; and in 1996 GEOCRACK predicts **90** "C, while the data shows 100 "C. The measured profile is somewhat more diffuse than the GEOCRACK profile. One difference between the calculations and measured temperatures occurs at the lower fracture, where the 1996 data shows cooling extending from the upper fracture to the lower fracture. In contrast, the GEOCRACK analysis shows only local cooling at the lower fracture. This could be the result of circulation between the fractures even while the wells are shut-in.

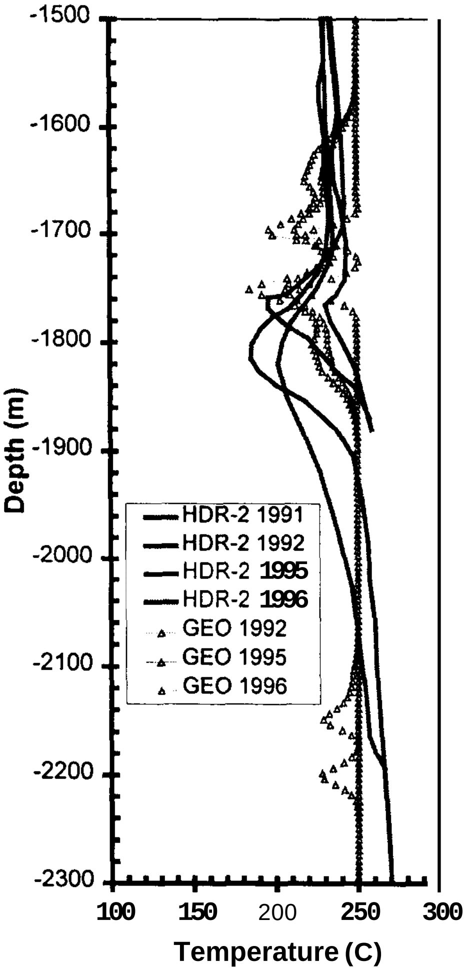

Figure 16: Comparison of HDR-2 static temperature data with GEOCRACK

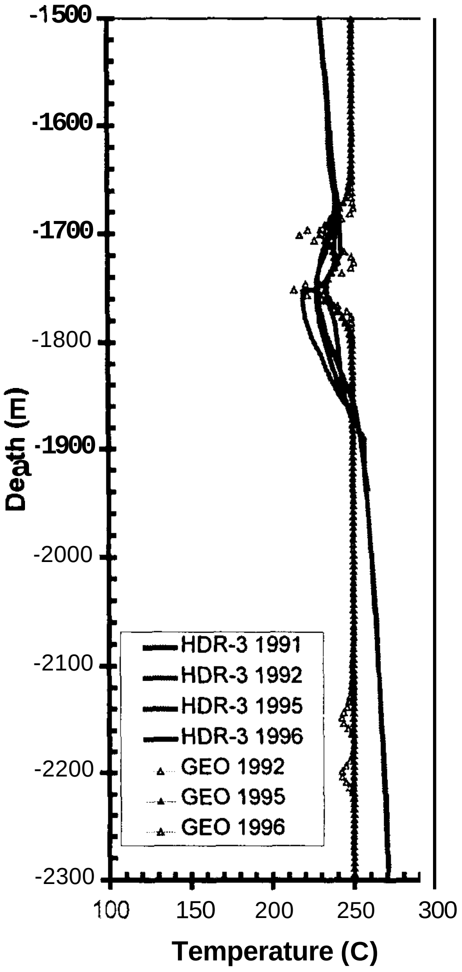

Figure 17: Comparison of HDR-3 static temperature data with GEOCRACK

This data and the temperatures during production confirm general agreement between the GEOCRACK analysis and measured data. The match would be improved by using one flow fracture in GEOCRACK with an increased local rock conductivity to represent the more diffuse flow near the fracture.

DISCUSSION OF GEOCRACK ANALYSES

The analysis captured many of the features of the reservoir. The model did a reasonable job of representing thermal behavior, however, it could be improved in representing the pressure sensitivity of flow in the reservoir. Some of the results include:

- The rapid appearance of cooler water in the production wells. This shows that flow is primarily on a the fractures, as simulated in GEOCRACK.
- The thermal recovery shows that cooling during the tests was limited to a region near the fracture.
- The model required a large conductivity between the upper fracture and the wells to obtain reasonable flow results. However, the conductivity between the lower fracture and the wells is much smaller. This is especially true for HDR-3.

IMPLICATIONS FOR LONG TERM CIRCULATION TEST

This study again re-emphasizes a critical fact about the Hijiori reservoir – the fact that the reservoir intersects two fractures and that these fractures dominate the reservoir flow. There are two main consequences to this fact:

- Cooling of the production wells occurs soon after injection is started. This is a result of flow on the fractures that provides a strong connection between the injection and production wells.
- The reservoir is "open." If the injection pressure is raised to about 14 MPa (2000 psi) surface, flow is lost to the far-field. Therefore, the production pressure must be reduced below hydrostatic pressure to maintain flow.

This is a work in progress and we have not completed a GEOCRACK analysis of the Long Term Circulation Test, our best estimate of what would occur if the current well connections remain the same and HDR-I is used as the injection well is:

- HDR-2a would rapidly cool at the lower fracture.
- HDR-3 will not cool as rapidly at the lower fracture, in fact, cooling is not be expected for about 200 days.
- The connection between the lower and upper fractures could result in lower temperatures at the upper fracture. We expect a delayed cooling at the upper fracture on the order of 100 days.

As world-wide experience with Hot Dry Rock and conventional geothermal reservoirs accumulates, it **is** clear the reservoir engineer must remain flexible and adjust the engineering approach to reflect the characteristic of any particular reservoir. For Hijiori, this means addressing the rapid cooldown of HDR-2a and the relatively low recovery rates.

One engineering approach is to consider blocking the connection between HDR-2a and the Lower Fracture. This would force the flow between HDR-1 and HDR-2a to follow **a** longer path, increasing heat removal and increasing the time for high temperature production from HDR-2a. **As** a result, the flow to HDR-2a would be similar to the flow to HDR-3, which has a poor connection at the lower fracture, but a good connection at the upper fracture. Similarly, since HDR-3 has seen little cooling, the same behavior could be expected at HDR-2a.

A second engineering approach would be to examine the use of a downhole pump in HDR-2a. The pump would ensure that sub-hydrostatic pressures could be maintained in HDR-2a, even if the produced fluid cooled, raising the flash point and increasing downhole pressure. Additionally, the pump could be used to reduce (or eliminate) two-phase flow in the HDR-2a production well. This would afford better control of the well.

REFERENCES

GERD, "FY 1995 Summary of Hot Dry Rock Geothermal Power Project in Japan," New Energy and Industrial Technology Development Organization, Tokyo, Japan, September, 1996.

GERD, "FY 1996 Summary of Hot Dry Rock Geothermal Power Project in Japan," New Energy and Industrial Technology Development Organization, Tokyo, Japan, November, 1997.

Swenson, Daniel, "User's Manual **for** GEOCRACK: **A** Coupled Fluid Flow/Heat Transfer/Rock Deformation Program for Analysis of Fluid Flow in Jointed Rock," Manual Release 3.11b, Kansas State University, Manhattan, KS, 66506, March, 1997.

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