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ANALYSIS IN PREPARATION FOR HIJIORI LONG TERM CIRCULATION TEST

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ABSTRACT

In preparation for the Long Term Circulation Test (LTCT) at the Hijiori geothermal reservoir, analyses have been completed to evaluate different operating strategies. Seven cases are discussed, including different injection rates in the same configuration as the 1995-1996 testing, blocking the lower production of HDR-2a, and the use of downhole pumps.

The analyses were performed using WELF98 and Geocrack2D. WELF98 is a wellbore flow simulator that is used to determine flows in individual fractures by matching Pressure-Temperature-Spinner (PTS) data. The Geocrack2D finite element code was developed to solve coupled thermo-hydro-mechanical problems where the flow is on fractures. The models were validated by analyzing 1991-1996 testing and matching the measured data. Based on the LTCT analyses, it is expected that although cooling will occur during the two years of testing, the mixed production temperatures will remain sufficiently high for a successful test. Work is proceeding on 3D analyses.

1. INTRODUCTION

A Long Term Circulation Test is planned for the Hijiori Geothermal Reservoir. The test is expected to run for two years. To prepare for the test, analyses have been performed to evaluate different operating strategies for the test. Since short term tests were performed in 1991, 1995, and 1996, a large amount of data has been gathered from the reservoir. This data and the configuration of the reservoir (well locations and depth) constrain the possible operating regimes. The data also provide benchmarks with which to validate models of the reservoir.

1.1 Reservoir Geometry

The Hijiori reservoir is located on the southern boundary of the Hijiori caldera. The reservoir wells intersect fractures that are part of the ring structure around the caldera and strike approximately east-west and dip steeply to the north, at an angle of about 70 degrees from the horizontal. The intersections of these fractures with the wells is shown in Figure 1. HDR-2a and HDR-3 are production wells that are open (not cased) below about 1500 m. HDR-1 is the injection well and is presently cased to a depth of about 2150 m. At the lower fracture, the separation distance is about 80 m between HDR-1 and HDR-2a and about 130 m between HDR-1 and HDR-3.

Pressure-temperature-spinner (PTS) data show the distribution of flows in the fractures, Figure 2 (GERD, 1996; GERD, 1997). In HDR-2a, two fractures dominate the flow: F2a-2 at 1655 m and F2a-9 at 2165 m. In HDR-3, the flow is more uniformly distributed over some additional fractures, but significant flows occur at F3-1 at 1550 m and F3-7 at 2005 m. These depths are commonly called the upper and lower reservoirs, or fractures.

Examination of the data shown in Figure 2 suggests that common fractures are intersected by both wells. If the HDR-3 data is offset downward by 155 m, there is alignment with at least four of the fractures in HDR-2a: F2a-9 and F3-7, F2a-7 and F3-6, F2a-3 and F3-2, and F2a-2 and F3-1 (Figure 2). This is strong evidence of continuous fractures. If we assume the fractures dip at 70° from the horizontal and use the separation distance of 155m at the F2a-9/F3-7 fracture, the vertical separation corresponds to a strike direction of N70°E. This is consistent with estimations (GERD, 1997) that the major connection fracture forming a shallow reservoir is a fracture plane with a strike of N77°E and an inclination of 70°N. A 3D visualization of such fractures is given in Figure 3, where the bounding box is oriented with the compass, and it can be seen that the strike of the fractures gives different depths of intersection with HDR-2a and HDR-3 for the same fracture.

Figure 4 illustrates a model with the four major fractures that intersect HDR-2a and HDR-3. This figure also includes three fractures that intersect and link the four major fractures. These intersecting fractures are based on BHTV images of the wellbores. Such a model will be used for the 3D analysis of the reservoir.

1.2 Computer Codes Used for Analysis

WELF98 (Schroeder, 1998) is a wellbore flow simulator used to convert PTS data to individual fracture data. Geocrack2D was used to simulate the reservoir. This finite element code was developed to solve coupled structure/fluid/thermal problems where the flow is on fractures (Swenson, 1997). An illustrative Geocrack3D analysis is also given, although this work is still in progress.

2. 1991-1996 TEST DATA

The tests performed from 1991 to 1996 have previously been discussed in GERD (1996), GERD (1997), and Schroeder, et al. (1998), so only a brief summary of 1995 testing will be given here (the configuration in 1995 and 1996 is similar to that expected in the LTCT).

2.1 1995 Testing

In 1995, HDR-2 (renamed HDR-2a) and HDR-3 had been extended past the lower fracture, so these wells received production from both the lower and upper fractures. The injection well was now HDR-1, which was cased to 2050 m to insure injection at the lower fracture depth. The test ran for 25 days.

Figure 5 and Figure 6 show PTS data taken during testing. The temperature profiles are markedly different in HDR-2a and HDR-3. HDR-2a is unusual in that the mixed fluid temperature at the lower fracture depth cools as expected, due to a relatively direct flow path from HDR-1. However, at the upper fracture depth, the initial flow is relatively cool but then the flow into HDR-2a warms as the test proceeds, keeping the mixed temperature above the upper fracture approximately constant. This is consistent with initially hot rock at the lower fracture, but initially cooler rock at the upper fracture, as shown in the static temperatures. Then, flow from the lower injection point is warmed as it moves from the lower fracture through the reservoir before being produced (and warming) the upper fracture. The WELF98 calculation gives a cooling from about 264 °C to 217 °C at the 2165 m fracture in HDR-2a. Essentially no cooling was observed in HDR-3. The 1996 test data is similar to the 1995 data.

2.2 Summary of Test Data

The test data indicate that:

1. Flow in the reservoir is dominated by the upper and lower fractures. This is consistent with common fractures connecting F2a-9/F3-7 and F2a-3 and F3-2.
2. At the lower fracture the intersection of the common F2a-9/F3-7 fracture is 160 m lower with HDR-2a than with HDR-3. This may cause preferential flow of the more dense cold injected water to the lower connection with HDR-2a at F2a-9. This is consistent with the observed cooling of F2a-9.
3. Significant connections between the upper and lower fractures that allows fluid injected into the lower fracture to be produced at the upper fracture.

3. SIMULATION OF 1991-1996 TESTING

Before proceeding to predict the LTCT performance, the existing test data was analyzed to verify that the reservoir model was valid. 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 Geocrack2D is a two-dimensional code, it is unrealistic to expect perfect comparison to the actual three-dimensional case, in particular, the more direct flow paths in the two-dimensional calculation will tend to over-predict cooling at the production well. Instead, the goal of the two-dimensional analysis is to capture the essential features of the reservoir and use the results to guide in preparation for the long term flow test.

3.1 Reservoir Model

The Geocrack2D model that we used to perform the analyses is shown in Figure 7. This figure shows the rock blocks (rectangles), fractures/flow paths (blue paths), and well locations (circles and squares) in the model. Figure 7 also shows the injection and production points for the 1995 and 1996 testing.

The Geocrack2D model represents a vertical section of the reservoir, extending from a depth of 1475 to 2475 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. In the actual reservoir, the upper and lower fractures are known 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.

In Figure 7, the upper and lower fractures are shown by dashed lines. These fracture systems are known to dominate flow. 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. The enhanced conductivity lower fracture does not extend to connect with HDR-3.

The actual finite element mesh that is used to develop the solution is a discretization of the block geometry. Other features of the model include nonlinear contact between the rock blocks, material properties consistent with granite and water, the use of the cubic law for flow on the fractures, and the specification of boundary conditions consistent with the operating conditions. Details have been previously discussed in Schroeder, et al., 1998, and will not be repeated here.

3.2 Analysis Results of 1991-1996 Testing

Results for simulation of the 1991-1996 testing have previously been reported in Swenson et al., 1999. In the 1995 testing, the PTS and WELF98 calculations for HDR-2a show a cooling from about 264 °C to 217 °C at the 2165 m depth. In HDR-3 no cooling is observed.

In the Geocrack2D analysis, the HDR-2a fracture at 2175 m cools from about 265 °C to 185 °C (somewhat more than observed) and in HDR-3 the temperatures remain constant. In 1996, similar results were obtained.

4. LTCT ANALYSIS

4.1 Cases Analyzed

Seven cases were analyzed to examine different operating conditions. The specific problem of interest was whether it was possible to maintain reasonable high production temperatures over the two year LTCT. These seven cases are:

1. All data same as 1995-1996 normal conditions. Injection flow into HDR-1 at a rate of 16 kg/sec. Production from HDR-2a and HDR-3. This is the nominal case.
2. Same as 1, except injection flow rate of 8 kg/sec. The purpose of this case was to examine the effect of reduced flow on production temperatures.
3. Same as 1, except injection flow rate of 32 kg/sec. The purpose of this case was to examine the effect of increased flow on production temperatures.
4. Same as 1, except lower fracture production of HDR-2a blocked. Since the lower fracture in HDR-2a cools rapidly, blocking this flow path is a way to keep the production temperatures in HDR-2a higher.
5. Same as 1, except high permeability path added that

connects the lower and upper fractures. This represents a possible path that can be opened under high injection pressures (as in 1995 testing). This is also a conservative calculation, since this could lead to earlier cooling at the upper fracture.

6. Same as 1, except the production pressures in HDR-2a and HDR-3 were reduced by 2.5 MPa to simulate downhole pumps.
7. Same as 1, except the production pressures in HDR-2a and HDR-3 were reduced by 5.0 MPa to simulate the maximum downhole pumping.

4.2 Results for All Cases

The main results of interest are the mixed production temperatures at the top of the reservoir in HDR-2a and HDR-3. These are shown in Figure 8 and Figure 9.

4.3 Discussion of Nominal Case (Case 1)

Figure 10 shows the temperatures in the reservoir after 720 days of operation for the nominal case. Considerable cooling occurs on the fractures, especially those intersecting HDR-2a. The predicted production temperatures from all the fractures for HDR-2a and HDR-3 are shown in Figure 11 and Figure 12. The important points to notice are the significant cooling at the lower fracture (2175 m) in HDR-2a and the relatively small amount of predicted cooling in HDR-3.

The predicted mixed production temperature in HDR-2a declines from about 240 °C to 180 °C, while the HDR-3 production temperature remains at about 240 °C. The reason the HDR-2a production temperature stabilizes and stops declining is that, while the lower fracture has cooled significantly, the upper fracture is still producing at a high temperature, so the mixed temperature stays at about 180 °C. Obviously, continuing the test would eventually lead to cooling at the upper fracture.

4.4 Discussion of Case with Lower Fracture of HDR-2a Blocked (Case 4)

Since the lower fracture in HDR-2a cools and reduces the mixed production temperature, one approach to preventing this is to block the lower fracture (2175 m) in HDR-2a. This forces the flow to go to other fractures, through longer flow paths before production. As a result, even though the lower fracture cools, this cooler fluid does not enter HDR-2a and does not cool the mixed production temperature. By blocking the cold lower flow into HDR-2a, the production temperature remains much higher. At the end of the test, the temperature is still greater than 210 °C. This is significantly better than Case 1.

4.5 Discussion of Case with Downhole Pumps (Case 6)

The effect of the downhole pumps will be to reduce the downhole pressures in the production wells. Based on the depth and temperatures of the wells it was assumed that a pressure reduction of 2.5 MPa was reasonable. All other data was the same as the previous nominal analysis, with injection flow into HDR-1 at a rate of 16 kg/sec. Production was from HDR-2a and HDR-3.

The flow pattern in the reservoir is different than in the previous cases. Since the production pressure has been reduced below the hydrostatic pressure at depth, the fluid flows from the far-field into the reservoir. This means that hot water is brought into the reservoir. In addition, the production from the wells is increased.

The mixed production temperatures are similar to those calculated in Case 1, but the flow rates are larger. Specifically, in Case 1 the combined production was about 10.8 kg/s, while in Case 6 the production rates have increased to about 14.2 kg/s. This is a result of the increased flow due to the lower production pressures. Case 7 showed even greater flows (perhaps unrealistic).

5. 3D ANALYSIS

Work is proceeding on the 3D fracture model of Hijiori. Figure 13 and Figure 14 show results of an initial 3D analysis. What is clear is that there is a strong connection between the injection point at the bottom of HDR-1 and the production at the lower fracture in HDR-2a. Further results of these analyses will be presented at the conference.

6. CONCLUSIONS

There is strong evidence to suggest that common fractures connect HDR-2a and HDR-3. This is consistent with the observed flows. The significantly larger cooling of HDR-2a may be the result of denser cold water flowing to the lower production point on the common F2a-9/F3-7 fracture.

The analyses indicate that a two year Long Term Circulation Test can be successful. While some cooling can be expected in the production wells, the mixed temperatures should remain above about 180 °C.

Blocking the lower fracture in HDR-2a could reduce the production of cold fluid from that fracture and increase the mixed production temperature. Downhole pumps offer the potential of increased control of production, with the ability to ensure that HDR-2a will continue to produce even if the temperatures of the lower fractures cool significantly.

7. ACKNOWLEDGEMENTS

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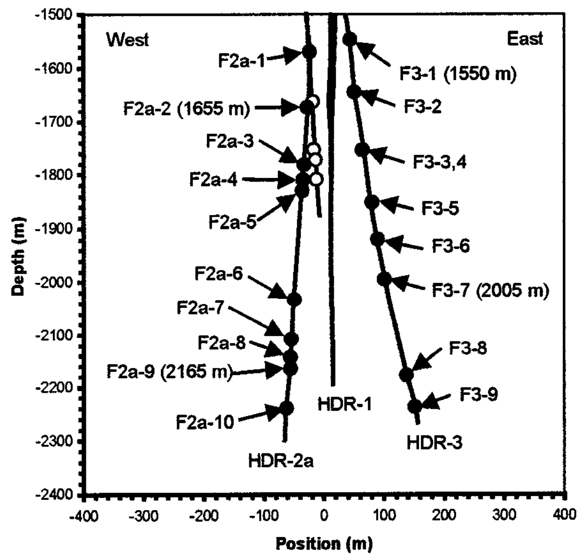

Figure 1: Section of Hijiori reservoir facing North, showing major fractures wellbores (1995 and 1996 testing).

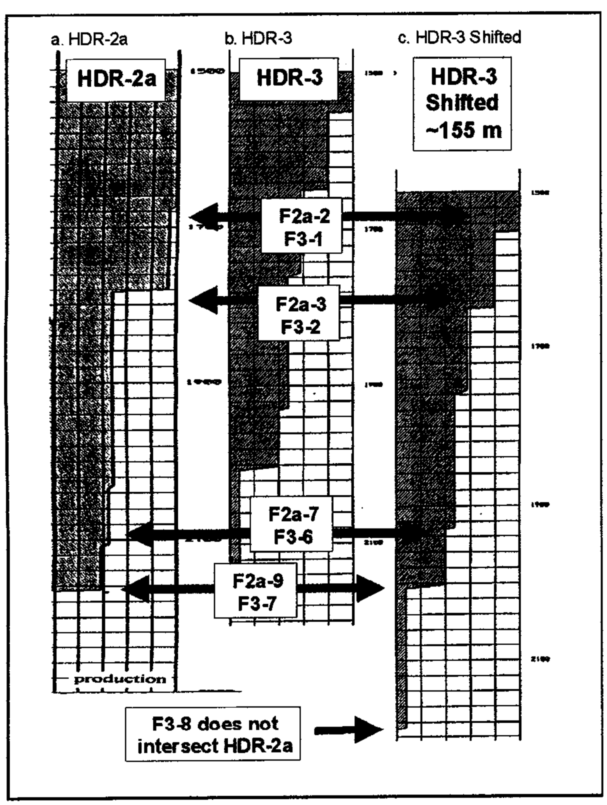

Figure 2: Observed flow fractions in wells showing correlation when HDR-3 data is shifted by 155 m.

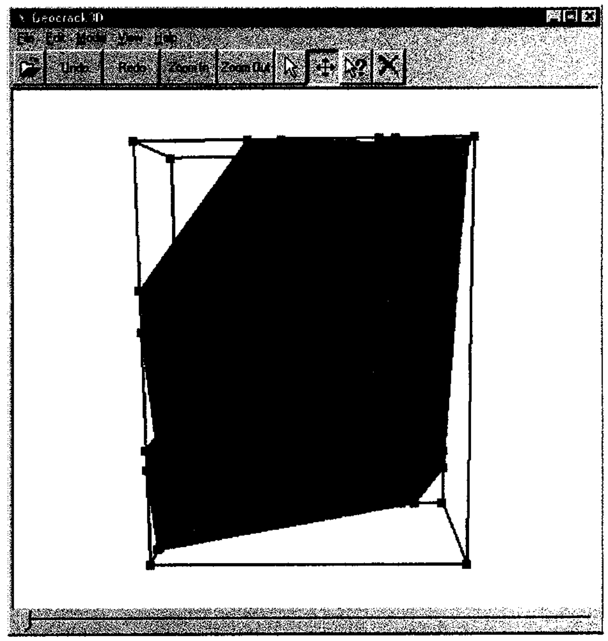

Figure 3: Illustration of the four major fractures at Hijiori, view looking north

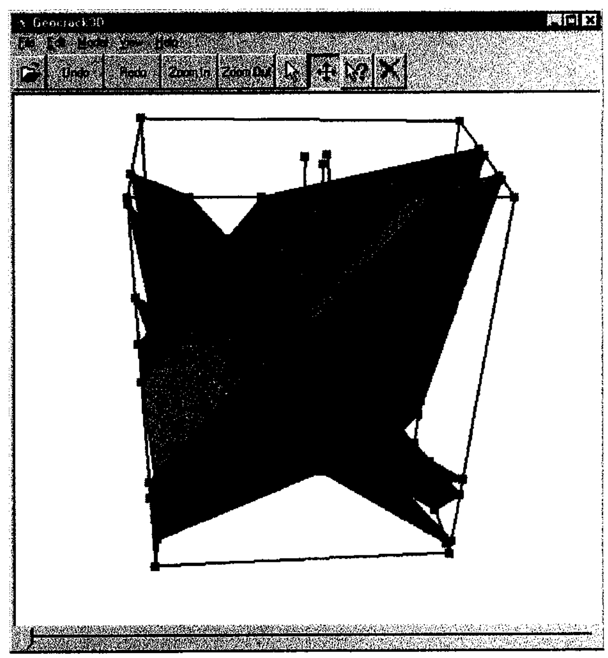

Figure 4: Schematic showing four major fractures and three normal intersecting fractures

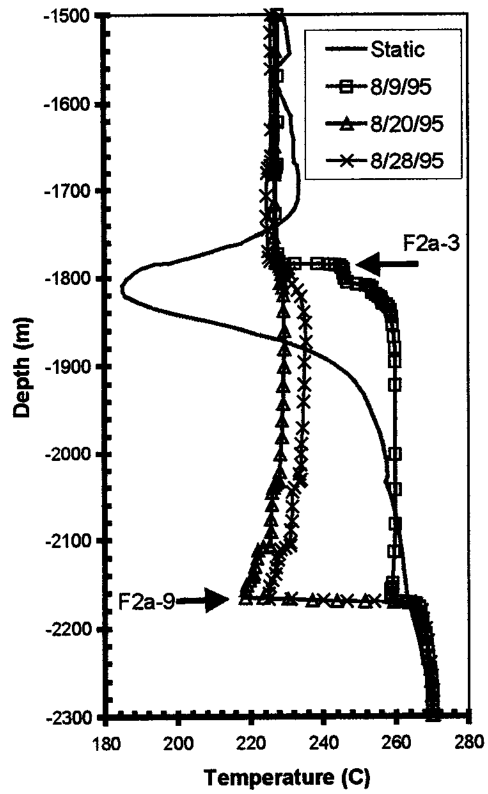

Figure 5: HDR-2a 1995 PTS data

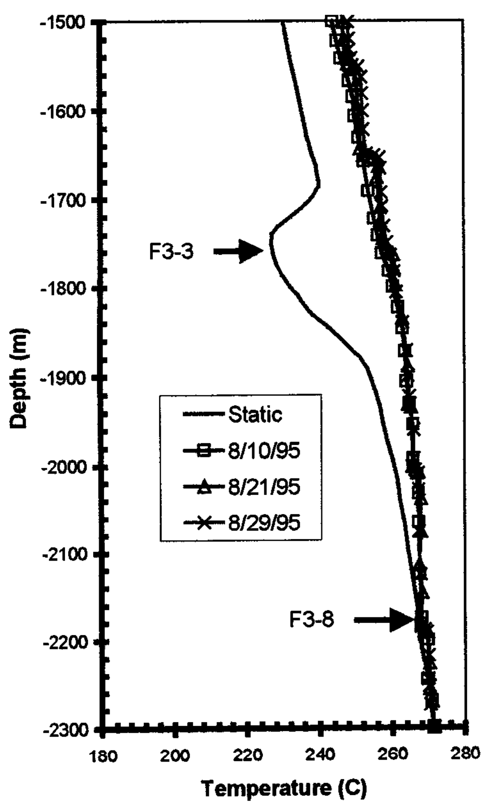

Figure 6: HDR-3 1995 PTS data

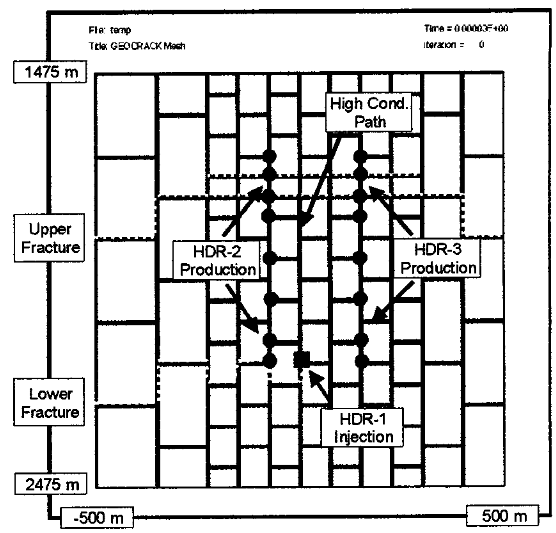

Figure 7: Geocrack2D model representing vertical section of the reservoir

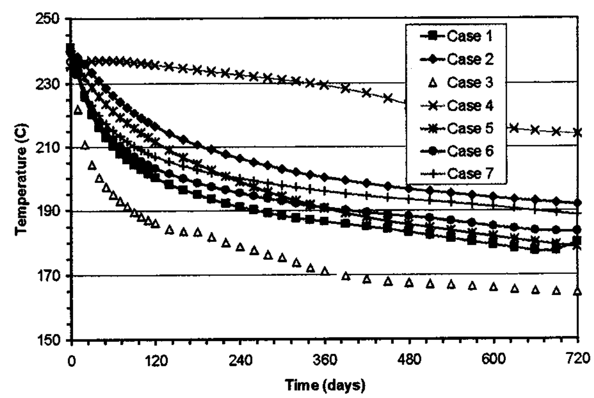

Figure 8: Mixed production temperatures from HDR-2a

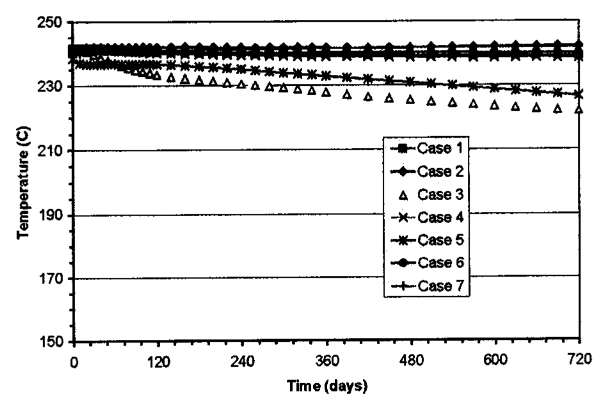

Figure 9: Mixed production temperatures from HDR-3

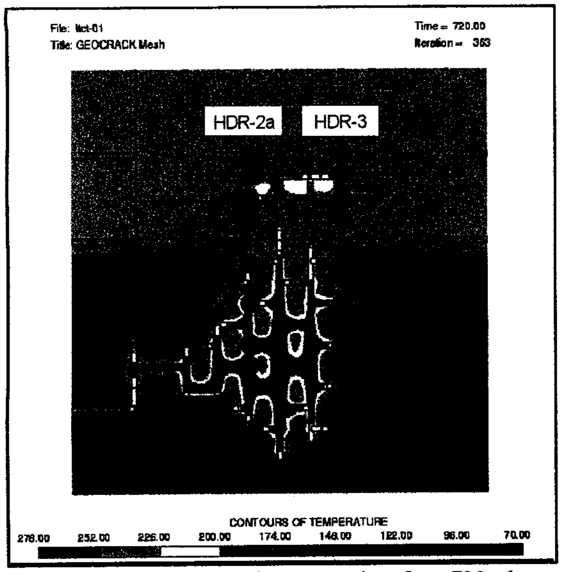

Figure 10: Temperatures in reservoir after 720 days of operation (min=70 °C, max=278 °C)

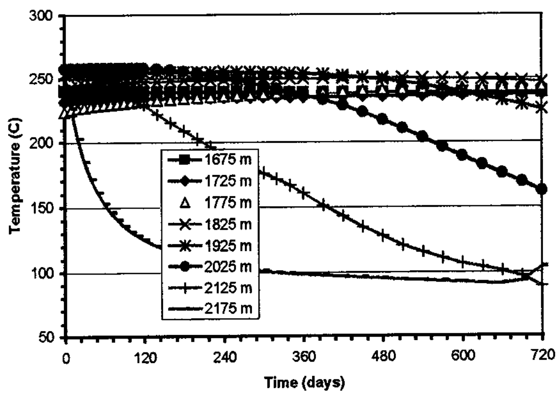

Figure 11: Calculated LTCT production temperatures from HDR-2a

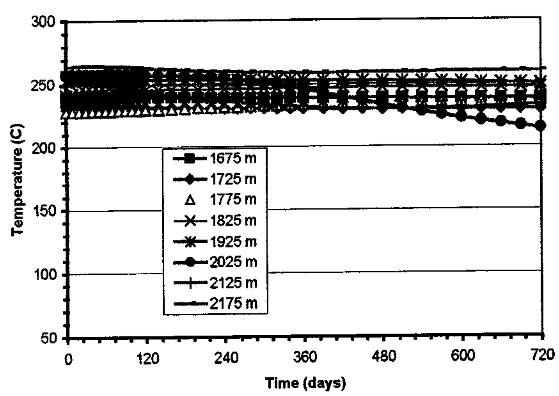

Figure 12: Calculated LTCT production temperatures from HDR-3

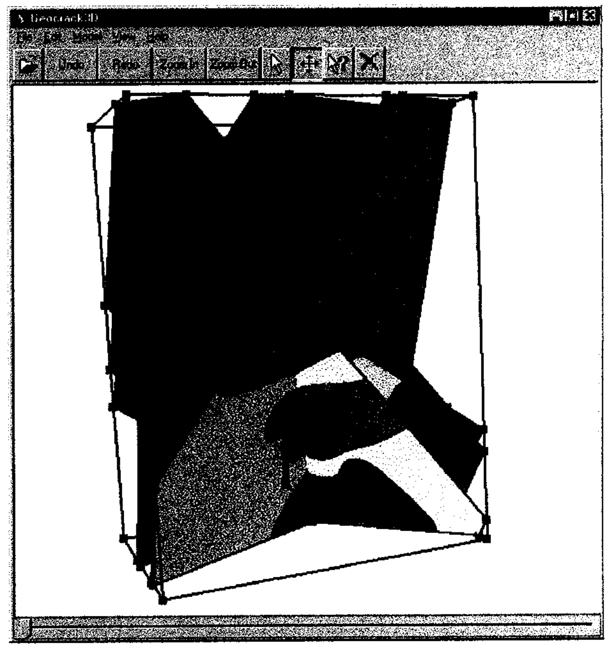

Figure 13: Pressure contours in initial 3D fracture analysis

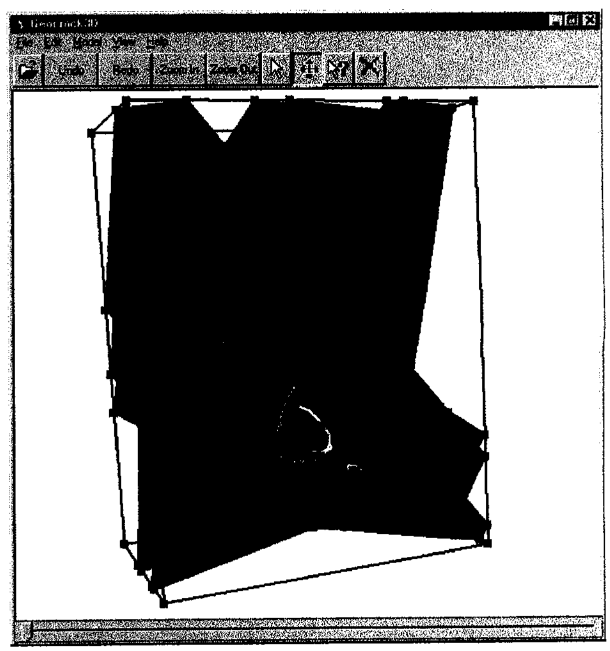

Figure 14: Mass flow rates in initial 3D fracture analysis. Note strong flow from HDR-1 injection to HDR-2a production at lower fracture.