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ANALYSES OF THE HIJIORI LONG TERM CIRCULATION TEST

D. Swenson [(1)], R. Schroeder [(2)], N. Shinohara [(3)], T. Okabe [(3)]

[(1)] Kansas State University
Manhattan, Kansas, USA, 66506
swenson@ksu.edu

[(2)] Berkeley Group Inc.
245 Gravatt Drive
Berkeley, California, USA, 94705
rcsch@slip.net

[(3)] Geothermal Energy R. & D.
Kyodo Bldg.
Chuo-Ku, Tokyo 103, Japan
rd.dep@gerd.co.jp

ABSTRACT

Analyses have been completed to evaluate different operating strategies for the Hijiori Long Term Circulation Test (LTCT). To ensure that the Geocrack2D model used to represent the LTCT was valid, 1991-1996 testing at Hijiori was first simulated. After reasonable matches were obtained with the existing data, the model was used to predict behavior during the two year long LTCT. Five cases were analyzed: (1) a nominal case with injection flow of 16 kg/s, (2) a case with half the nominal flow, (3) a case with double the nominal flow, (4) a case where HDR-2a was blocked at the lower fracture (selected to block the observed cold flow at the lower fracture in HDR-2a), and (5) a case with enhanced connectivity between the lower and upper fracture. In all cases, injection was in HDR-1, with production from HDR-2a and HDR-3.

For the nominal case, the HDR-2a mixed production temperature is predicted to reduce from 240 C to 180 C while the HDR-3 temperature remains approximately constant at 240 C. The highest production temperatures occur for Case 4, when the lower fracture is blocked in HDR-2a, with the final production temperature after two years being 214 C.

BACKGROUND

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.

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 of about 70 degrees from the vertical. A schematic of these fractures is shown in Figure 1.

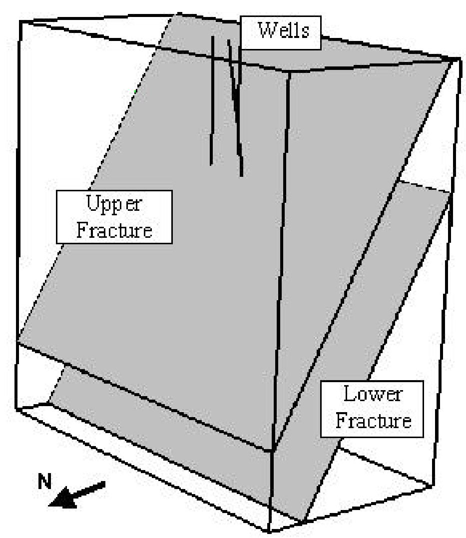

Figure 1: Schematic of the Hijiori reservoir

Three wells intersect the fractures, as shown in Figure 2. 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 2151 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.

As evidenced by test data, the upper and lower fractures are the dominant flow paths in the reservoir. Both HDR-2a and HDR-3 connect to the upper fracture, while at the lower fracture HDR-1 and HDR-2a have strong connections (the HDR-3 lower fracture connection is not as direct).

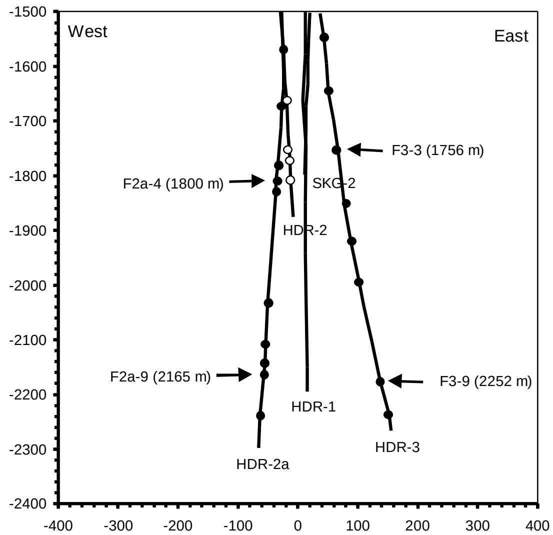

Figure 2: Fracture intersections with the wellbores (1995 and 1996 testing)

Computer Codes Used for Analysis

In the following discussion, two computer codes were used to evaluate test data and predict reservoir performance.

WELF98 (Schroeder, 1998) is a wellbore flow simulator used to convert pressure-temperature-spinner (PTS) data to individual fracture data. WELF98 has a simple mixing model, used at each feed point, that conserves mass and energy. WELF98 solves these equations at each feed point for the new value of h, the mixture enthalpy. The temperature can easily be obtained from the enthalpy, since the downhole fluid in all of these HDR cases is liquid. In this way the pressure, temperature and flow rate for each fracture intersecting the specific wellbore can be calculated.

Geocrack2D was used to simulate the reservoir. The Geocrack2D finite element code was developed to solve coupled structure/fluid/thermal problems where the flow is on fractures (Swenson, 1997). A Geocrack2D 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.

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 will be given here.

1991 Testing

The 1991 test ran for 90 days, with injection into SKG-2 at the upper fracture and production from HDR-1, HDR-2, and HDR-3 at the upper fracture. Based on PTS data and WELF98 calculations, the downhole production temperatures at the upper fracture in HDR-2 decreased from about 200 °C to 120 °C. In HDR-3, a similar decrease from about 220 °C to 120 °C was observed. These results clearly show strong connections between the injection well at upper fracture and the production wells.

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 insure injection at the lower fracture depth. The test ran for 25 days. The 1995 testing is significant, since it was performed in a configuration similar to that expected for the LTCT.

Figures 3 and 4 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. At the lower fracture HDR-3 is not as well connected. Instead of flow from one lower fracture, the flow is dispersed over several fractures. As a result, the production flow from HDR-3 did not cool as quickly as HDR-2a.

The 1996 test data is similar to the 1995 data.

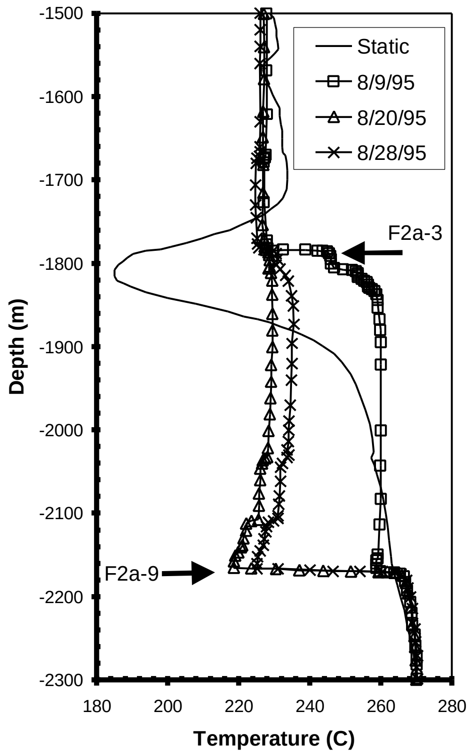

Figure 3: HDR-2a 1995 PTS data

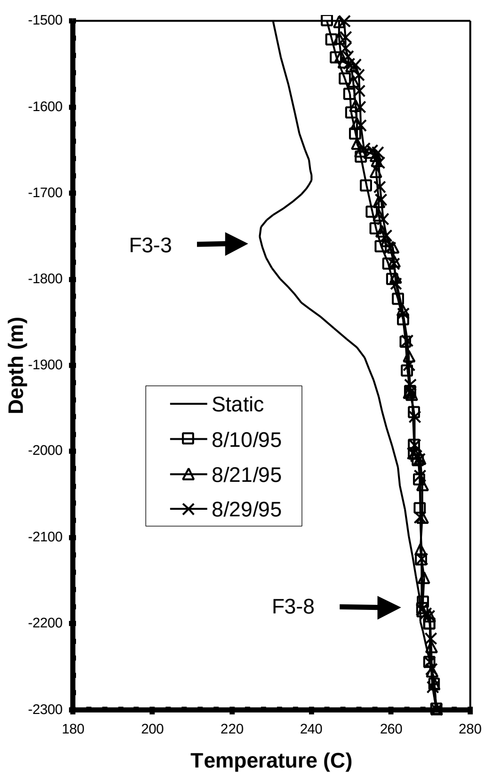

Figure 4: HDR-3 1995 PTS data

Summary of Test Data

The test data indicate that:

1. Flow in the reservoir is dominated by the upper (1800 m) and lower (2200 m) fractures.
2. There are strong connections between all wells at the upper fracture.
3. At the lower fracture, there is a strong connection between the injection well (HDR-1) and one of the production wells (HDR-2a). The connection to HDR-3 is not as direct.
4. Significant connections between the upper and lower fractures that allows fluid injected into the lower fracture to be produced at the upper fracture.

SIMULATION OF 1991-1996 TESTING

Reservoir Model

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 (a three-dimensional model is under development). 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 Geocrack2D model that we used to perform the analyses is shown in Figure 5. This figure shows the rock blocks (rectangles), fractures/flow paths (blue paths), and well locations (circles and squares) in the model. Figure 5 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.

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 2). 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 5, 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.

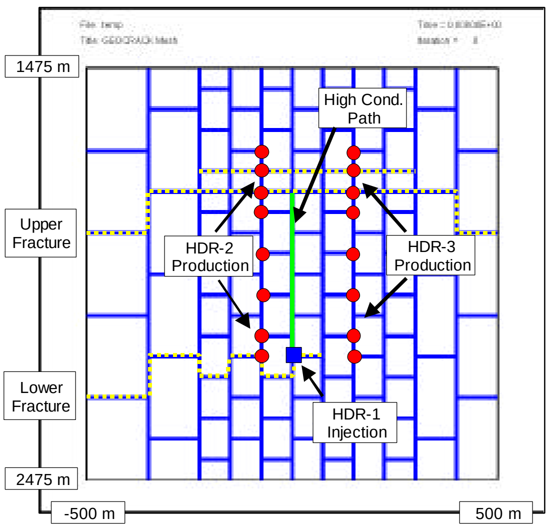

Figure 5: Geocrack2D model representing vertical section of the reservoir

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.

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.

Analysis Results of 1991-1996 Testing

For the 1991 testing, in which injection and production was primarily on the upper fracture, the PTS and WELF98 calculations show a cooling in HDR-2 from about 245 °C to 112 °C at a depth of 1755 m. In HDR-3 the 1754 m fracture cools from about 245 °C to 120 °C.

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.

The corresponding Geocrack2D calculations are shown in Figures 6 through 8. Figure 6 shows the temperatures in the reservoir at the end of 25 days of injection in 1995. Significant cooling occurs along the fractures, but there is little time for the cooling from to progress far into the rock. In addition, the contours show the warmer fluid from the lower regions of the reservoir flowing up to the cooler upper fracture, increasing the temperature there.

Figures 7 and 8 show the temperatures in the producing fractures. In HDR-2a, the fracture at 2175 m cools from about 265 °C to 185 °C (somewhat more than observed) and in HDR-3 the temperatures stay constant. In 1996, similar results were obtained.

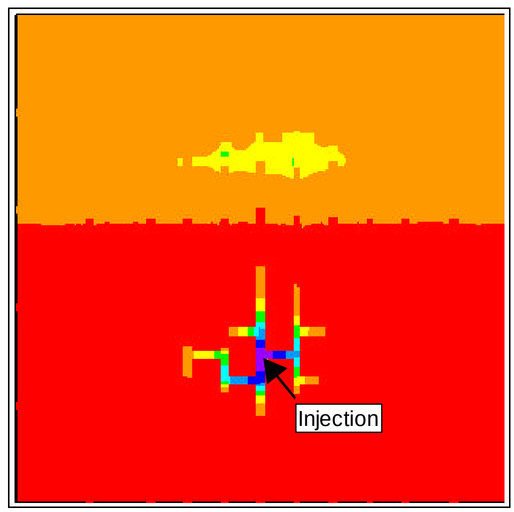

Figure 6: Calculated temperature contours at end of 1995 testing (min=70 ℃, max=278 ℃)

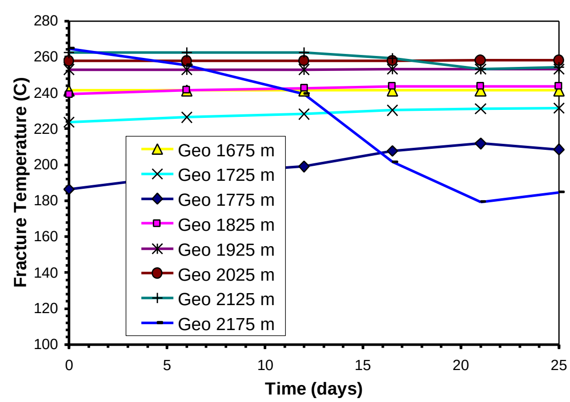

Figure 7:Calculated HDR-2a fracture production temperatures during 1995 testing

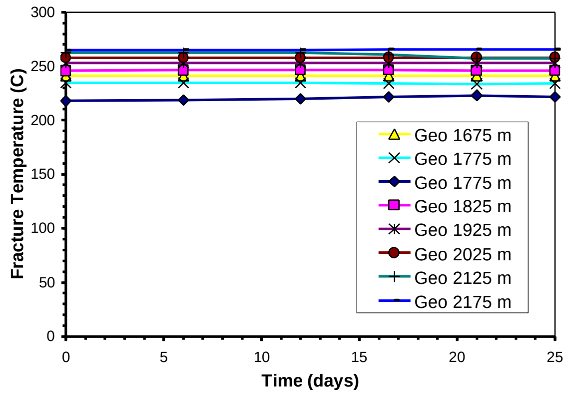

Figure 8: Calculated HDR-3 fracture production temperatures during 1995 testing

Although the correlation between the test data and the model are not perfect, the results were deemed reasonable enough to proceed with analysis of the LTCT. If anything, it can be argued that the Geocrack2D results are conservative, that is, they predict more cooling than will actually occur.

LTCT ANALYSIS

Cases Analyzed

Five cases were analyzed to examine different operating conditions. The specific problem that was of interest was whether it was possible to maintain reasonable high production temperatures over the life of the reservoir. These five 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.

Thermal Recovery

In the analysis, it was assumed that the LTCT would begin in 2001. The reservoir thermally recovers during the interval without production. Figure 9 shows the predicted reservoir temperature distribution at the beginning of the LTCT.

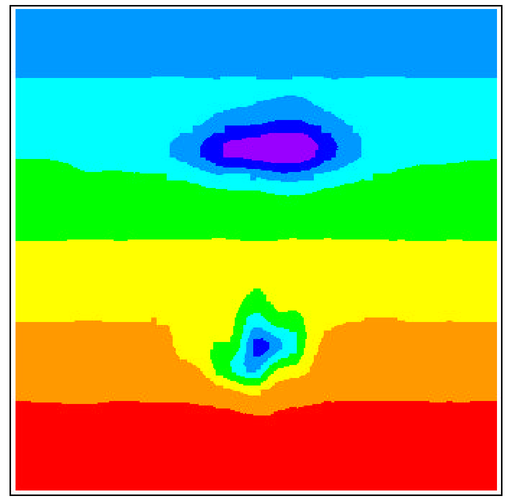

Figure 9: Reservoir temperatures at beginning of LTCT (min = 215 ℃, max=278 ℃)

Results for Nominal Case (Case 1)

Figure 10 shows the temperatures in the reservoir after 720 days of operation. As can be seen, considerable cooling has occurred on the fractures, especially those intersecting HDR-2a.

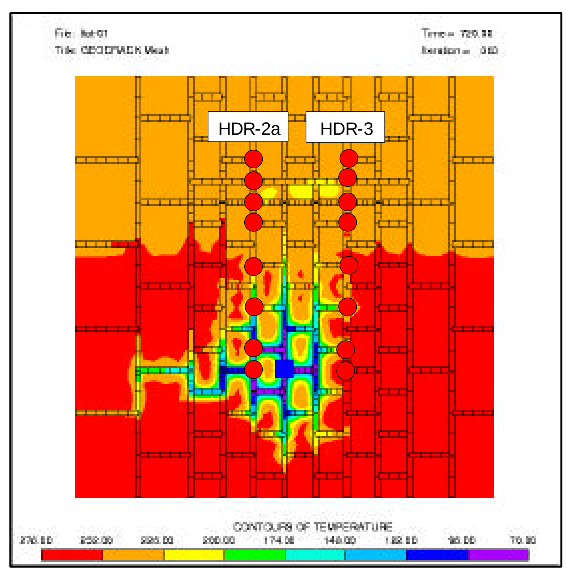

Figure 10: Temperatures in reservoir after 720 days of operation (min=70 ℃, max=278 ℃)

The predicted production temperatures from all the fractures for HDR-2a and HDR-3 are shown in Figures 11 and 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.

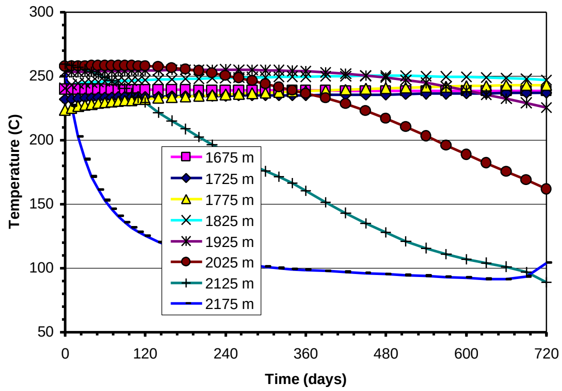

Figure 11: Calculated LTCT production temperatures from HDR-2a

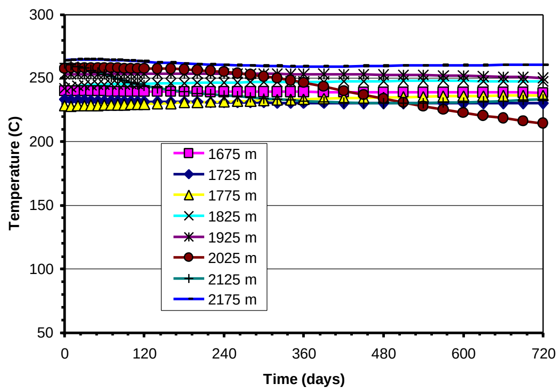

Figure 12: Calculated LTCT production temperatures from HDR-3

The mixed production temperatures are shown in Figure 13. This shows that 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.

Figure 14 shows the production flow rates. The total production is about 11 kg/s, for a recovery rate of about 68%.

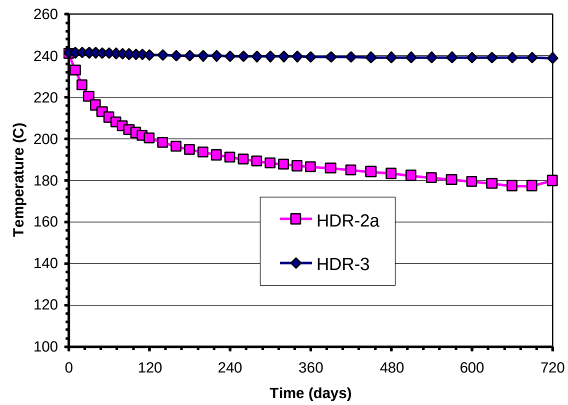

Figure 13: Mixed production temperatures for LTCT, nominal case (Case 1)

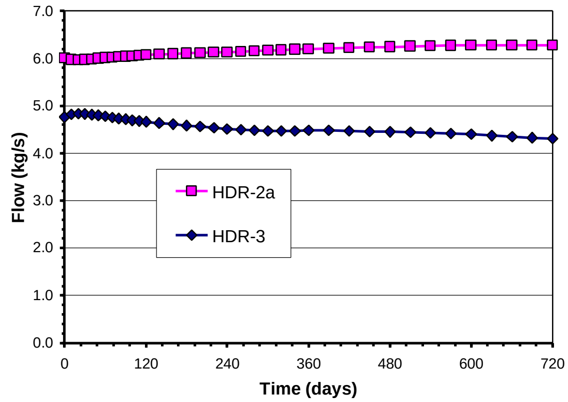

Figure 14: Production flow rates for LTCT, nominal case (Case 1)

Results 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. As for the other cases, water was injected at a rate of 16 kg/sec into HDR-1 at the lower fracture, and production was in HDR-2a and HDR-3. The analysis was continued for two years.

In general, the individual fracture Figure 47 and Figure 48 show the mixed production temperatures and flow rates in the wells. 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. Thus, by blocking the cold flow into HDR-2a and forcing the flow to take a longer path, the production temperatures are significantly improved.

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