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THE NUMERICAL MODELING STUDY OF THE HIJIORI HDR TEST SITE

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ABSTRACT

The Hot Dry Rock (HDR) electric power generating system, considered a clean energy system because it scarcely generates greenhouse gases such as CO_2, would greatly benefit humankind. Since the idea was first proposed at the Los Alamos National Laboratory in 1972, several field tests have been conducted in locations such as Fenton Hill (U.S.A.), Cornwall (U.K.), Soultz (France), Hijiori (Japan), and Ogachi (Japan). Although extensive studies have been performed at these test sites, the HDR electric power generating system is still under investigation due to some technical and economical difficulties. The development of a numerical simulation system, which could be utilized to optimize the resource development and management, is one such technology.

This study investigates the possibility of modeling the Hijiori HDR test site with the numerical simulator TOUGH2. Through history matching studies on preliminary short term circulation tests at the Hijiori HDR test site, it is found that the numerical model, coupled with the double porosity model, can simulate the temperature performance at inflow points of production wells in the HDR reservoir. Following history matching studies, long term temperature performances are predicted for both constant production and constant bottom hole flowing pressure cases. These history matching and prediction studies suggest for the Hijiori HDR test site: (1) The permeability between HDR-1 and HDR-2a may be 7.5 times larger than that between HDR-1 and HDR-3; (2) the temperature at the inflow point of F2a-9 in HDR-2a shows maximum decrease, while the temperature at other inflow points does not show a distinct decrease; (3) the temperature decrease at the inflow point is strongly related to injection rates at the injection well and the distance between injection and production wells.

1. INTRODUCTION

In various countries, geothermal energy is utilized as an electric power generation source as well as a local heat source. This type of energy scarcely produces greenhouse gases in generating electrical power; therefore, it is expected to increase the utilization for the solution of the problem of global warming. In Japan, there are eighteen geothermal power stations located in the Kyushu, the Tohoku, and the Hokkaido areas. In total, the geothermal electric power of these stations reaches up to 500 MW. All of the power stations are so called conventional type geothermal power stations; in other words, they use only the original underground hot water or steam as a heat source.

On the other hand, the Hot Dry Rock (HDR) power generation system utilizes heat in hot rock where water or steam is not originally available. In this system, water is circulated between some wells drilled in hot rock areas and extracts heat for the generation of electric power. The New Energy and Industry Technology Development Organization (NEDO) estimates that the HDR power generation system could generate electric power equivalent to 29,000 MW x 20 years even if limiting the hot rock areas to temperatures higher than 250℃ and depths shallower than three kilometers.

As soon as the idea of the HDR power generation system was proposed at the Los Alamos National Laboratory, the field experiment was started in Fenton Hill, U.S.A. in 1972. In Japan, the research of the HDR power generation system started at the foot of Mt. Yakedake in the Gifu Prefecture in 1978 as part of the Sunshine Project, which was conducted by the Agency of Industrial Science and Technology. NEDO also participated in the HDR development program of field experiments in Fenton Hill under an IEA agreement during 1981 and 1986. Following these experiences, NEDO began field experiments at Hijiori in the Yamagata Prefecture in 1985.

Up to the present, several field tests have been conducted in locations such as Fenton Hill (U.S.A.), Cornwall (U.K.), Soultz (France), Hijiori (Japan), and Ogachi (Japan). However, the HDR power generation system is still under investigation due to some technical and economical difficulties. The development of a numerical simulation system, which could be utilized to optimize the resource development and management, is one such technology. This study investigates the possibility of modeling the Hijiori HDR test site using the numerical simulator TOUGH2 through history matching studies on preliminary short term circulation tests at the test site. Long term temperature performances at inflow points of wells at the test site are also discussed.

2. THE HIJIORI HDR TEST SITE

The Hijiori HDR test site is located on the southern edge of the two-kilometer diameter Hijiori caldera in Okura Village in the Yamagata Prefecture. The underground structure of the Hijiori HDR test site consists of two reservoirs that are at the different depth: an upper reservoir at a depth about 1,800 m, and a lower reservoir at a depth of about 2,200 m. The history of technical development at the Hijiori test site is roughly divided into two periods. The first period is from 1985 through 1991, focusing on the development of the upper reservoir and the exploration of various techniques for the HDR power generation system, and the second period is from 1992 and after, starting the development of the lower reservoir (NEDO, 1997). The following paragraphs summarize the technical development at this site.

At the beginning of the first period, SKG-2 (bottom hole depth: 1802 m; bottom hole temperature: 253℃), which had been drilled before the HDR project for the investigation of geothermal resources at this area, was hydraulically fractured to create an upper reservoir at a depth around 1800 m. Subsequently, three wells were drilled towards the reservoir: HDR-1 was drilled to a depth of 1805 m in 1987, HDR-2 was drilled to 1910 m in 1989, and HDR-3 was drilled to 1907 m in 1990. The communication between these three wells was tested in 1988, 1989, and 1990. These tests indicate a good communication between the wells.

As for the final experiment using the upper reservoir, a circulation test was conducted for 90 days, specifying SKG-2 as an injection well and HDR-1, HDR-2, and HDR-3 as production wells in 1991. Hot water and steam were continuously produced from all production wells at a temperature from 150 to 180℃. The total thermal recovery was calculated to be about 8.5 MW, and the recovery rate was estimated to be about 80 %. This result shows that the multi well system is effective for the development of the HDR power generation system.

At the beginning of the second period, HDR-1, which was re-drilled to 2205 m in 1988, was hydraulically fractured in the interval of 2150-2200 m to create a lower reservoir. HDR-3 was re-drilled to 2300 m in 1993, and HDR-2 was sidetracked and re-drilled to 2300 m in 1994. After the sidetrack, HDR-2 was renamed as HDR-2a. At the end of 1994, the multi-well, double-reservoir circulation system was established at the Hijiori HDR test site as shown in Figure 1.

A preliminary short term circulation test at the lower reservoir was conducted in 1995 for 25 days, specifying HDR-1 as an injection well and HDR-2, and HDR-3 as production wells. During the preliminary test, water was injected at a rate of 60-120 t/h, and hot water and steam at a temperature around 180℃ were produced with rates of 14-15 t/h. The recovery rate was estimated to be 40 %, and it was found that the permeability between HDR-1 and HDR-3 was not so good as that between HDR-1 and HDR-2a. Following this circulation test, a flow enhancement test was conducted for 30 days, specifying HDR-1 as an injection well and mainly HDR-3 as a production well to improve the permeability between HDR-1 and HDR-3 in 1996. However, no remarkable improvement was observed. A long term circulation test is planned from 2000 to 2002.

3. A MATHEMATICAL MODEL FOR THE HIJIORI HDR TEST SITE

This section describes a mathematical model for the Hijiori HDR test site, which is constructed with the numerical simulator TOUGH2 (Pruess, K., 1991). TOUGH2 is the upgraded version of TOUGH (Pruess, K., 1987), which abbreviates 'transport of unsaturated ground water and heat'. TOUGH is a multi-dimensional numerical simulator which deals with water, steam, and air flow, and heat transfer through porous or naturally fractured media. On the other hand, TOUGH2 can handle multi-component, multi-phase fluid flow and heat transfer. TOUGH2 neglects thermal shrink of rock; therefore, it cannot deal with dynamic fracture permeability change. TOUGH2 has two distinguished features: IFDM and MINC. IFDM (Integrate Finite Difference Method) is a method to set up finite difference equations from partial differential equations which govern fluid flow and heat transfer through porous media. IFDM gives more flexibility dividing an investigated area compared to other finite difference methods. MINC (Multiple Interacting Continua) is a matrix subdivision method for modeling fractured media. MINC divides matrix into pieces, which makes it possible to treat fluid flow and heat transfer in matrix in transient conditions. In the case of one matrix subdivision, MINC reduces to the so called KAZEMI model (Kazemi, H., 1976), which is widely used for modeling fractured media.

Figure 2 shows the size of the investigated area and the divisions used for modeling in this study. The modeled area is 3240 m in W-E (X) direction, 2400 m in N-S (Y) direction, and 2850 m in vertical (Z) direction, from the depth of 650 m to 3500 m. The boundary of the modeled area is more than 1000 m away from the wells. The numbers of divisions are 18, 13, 17 in X, Y, Z direction, respectively. Open boundary condition is assumed for all sides, and closed boundary condition is assumed for the top and bottom faces. As for initial conditions, vertical temperature distribution is estimated from the static temperature log analysis, and pressure distribution is obtained by multiplying the grid node depth by the water pressure gradient corresponding to the temperature at the depth.

The modeled area consists of two parts, the low and high permeable zones. The low permeable zone corresponds to the area where fracture is not developed, and the high permeable zone (the meshed area in Figure 3) corresponds to the area where fracture is developed. The area of high permeability is estimated from the acoustic emission map (NEDO, 1996). The high permeable zone is modeled using a double porosity approach, i.e., the MINC one matrix subdivision model or the KAZEMI model, while the low permeable zone is modeled with the conventional single porosity model. In the double porosity fracture model, it is assumed that the fluid flows only through fractures, whereas heat transfers between any two media that are fracture or matrix.

Table 1 lists the reservoir properties of this area, which are estimated based on an analysis by NEDO (NEDO, 1996, 1997). In this table, zone 2 corresponds to the high permeable zone between HDR-1 and HDR-2a where fractures are highly developed, and zone 1 corresponds to other high permeable zones. High permeable zones 1 and 2 are shown in Figure 4. In this figure, fluid inflow and outflow points are also indicated by triangles and circles, respectively, which are estimated from the PTS log analysis (NEDO, 1996).

4. RESULTS AND DISCUSSION

4.1 History Matching Studies

In 1995, a preliminary short term circulation test at the lower reservoir was conducted for 25 days, specifying HDR-1 as an injection well, and HDR-2a and HDR-3 as production wells. During the test, following items were monitored: the injection well head pressure and injection flow rate of HDR-1, the wellhead pressure and temperature of HDR-2a and HDR-3, and the production flow rate at the wellhead of HDR-2a and HDR-3. The PTS (Pressure-Temperature-Spinner) logging was performed for several times to provide information about changes of the vertical temperature profile and the fraction of inflow or outflow rate at each inflow or outflow point.

To investigate the possibility of applying TOUGH2 as a HDR numerical simulator, history matching studies are performed on the preliminary short term circulation test with the model described in Chapter 3, where the fractured zone is modeled as a double porosity model, and the non-fractured zone is modeled as a single porosity model. The strategy of this history matching study is as follows. That is, using measured injection and production data at each well as input data, pressure and temperature are calculated. Then, calculated temperatures at inflow points are compared with measured values, because the analysis of temperature performance is very effective to investigate the fluid flow in a HDR reservoir. The permeability of the high permeable zone 2 is selected as a matching parameter.

Figure 5 shows the comparison of calculated and measured temperature at the inflow point of F2a-9 in HDR-2a. In this calculation, the permeability of X (W-E) and Z (Vertical) direction is 5.0E-15 m^2, 7.5E-15 m^2, and 10E-15 m^2. The permeability of Y (N-S) direction is fixed as 1.0E-15 m^2, which is the same value as the permeability of the high permeable zone 1. From this figure, X and Z direction permeability of the high permeable zone 2 can be estimated to be about 7.5E-15 m^2, which indicates that the permeability between HDR-1 and HDR-2a may be 7.5 times larger than that between HDR-1 and HDR-3. During this simulation period, the injected water stays in single phase condition.

In 1996, a flow enhancement test was conducted for 30 days, specifying HDR-1 as an injection well and mainly HDR-3 as a production well to improve the permeability between HDR-1 and HDR-3. In this test, the fluid flow rate toward HDR-3 was less than expected, but provided indications for higher permeability between HDR-1 and HDR-2a. With the same numerical model used for the history matching study for the 1995 preliminary short term circulation test, the flow enhancement test in 1996 is also simulated. Figure 6 shows the comparison of calculated and measured temperature at the inflow point of HDR-2a. During these circulation tests, maximum temperature changes were observed at the inflow point of F2a-9 in HDR-2a. Figure 7 shows the entire temperature performance of F2a-9 during the period from 1995 to 1996. From these figures, it is suggested that TOUGH2, coupled with a double porosity model, may be used to simulate temperature performances during circulation tests in a HDR reservoir.

4.2 Prediction Studies

With the same numerical model used for the history matching studies of the circulation tests in 1995 and 1996, ten year temperature performances are predicted for supposed circulation cases: constant production and constant bottom hole flowing pressure cases. For both cases, HDR-1 is specified as an injection well and HDR-2a and HDR-3 as production wells.

As for the first prediction case of constant production, the injection rate of HDR-1 and the production rates of HDR-2a and HDR-3 are given almost the same volume as those of circulation tests in 1995 and 1996. Figure 8 shows the temperature performance at the inflow point of F2a-9, where maximum temperature decrease was observed. The temperature is predicted to decrease to around 70℃ after a two year injection, and it is also predicted to reach around 50℃ after a ten year injection. Other inflow points do not show such a significant temperature decrease. For a further investigation of the temperature decrease at this inflow point, various injection rates such as 60 t/h, 30 t/h, 20 t/h, 10 t/h, and 5 t/h are supposed, and calculations are performed for ten years. Figure 9 shows the temperature performance at the inflow point of F2a-9 for these various injection rates. This figure suggests that the injection rate at HDR-1 should be less than 10 t/h to avoid severe temperature decrease during long term circulation tests. This figure also indicates that the temperature decrease depends on the injection rate, in other words, the injected fluid flow rate through fractures between HDR-1 and HDR-2a.

Constant bottom hole flowing pressure cases are also predicted. In these cases, the bottom hole flowing pressure at inflow points is estimated from the combination of the wellhead pressure and static fluid pressure gradient in wells, neglecting the pressure loss occurred during vertical fluid flow through a wellbore. Negative skin factors, which are estimated so that the initial production volume from HDR-2a and HDR-3 coincides with the last measured volume during the circulation test in 1996, are introduced to reflect fractures near inflow points. Figure 10 shows the temperature performance at the inflow point of F2a-9 for constant bottom hole flowing pressure cases. This figure also indicates that the temperature decreases significantly at the inflow point of F2a-9 for constant bottom hole flowing pressure cases. This may indicate that most of the fluids injected from HDR-1 flows toward HDR-2a due to higher permeability between HDR-1 and HDR-2a. It may also be said that the distance between HDR-1 and HDR-2a is too short for the injected fluid to get hot enough.

To investigate the relation of the distance between injection and production wells to the temperature decrease at a production well, the following simulation test is performed: fluid is injected from HDR-2a at a rate of 60 t/h, and produced from HDR-1 or HDR-3 at a rate of 10 t/h. In this calculation, it is also supposed that the permeability between HDR-1 and HDR-3 is the same as that between HDR-1 and HDR-2a to see the effect of the distance between injection and production wells on the temperature performance at a production well. As shown in Figure 1, the distance between HDR-1 and HDR-2a is approximately 90 m, and that between HDR-2a and HDR-3 is approximately 220 m. Figure 11 shows the temperature performance at the inflow points of HDR-1 and HDR-3. After a ten year circulation test, the temperature at the inflow point of HDR-3 is about 190℃, while the temperature at the inflow point of HDR-1 decreases to 50℃. This shows that the distance between injection and production wells is one of key factors for the temperature performance of a production well.

5. CONCLUSIONS

The HDR electric power generating system, considered a clean energy system because it scarcely generates greenhouse gases such as CO_2, would greatly benefit humankind. Although intensive studies and field experiments have been performed, HDR systems are still under investigation due to some technical and economical difficulties.

In this study, the possibility of numerical modeling of the HDR reservoir with TOUGH2 is investigated through history matching studies of preliminary short term circulation tests at the Hijiori HDR test site. It is shown that the numerical model, coupled with the double porosity model, simulates the temperature performance at inflow points of production wells to a certain degree. It is also indicated that the permeability between HDR-1 and HDR-2a may be about 7.5 times larger than that between HDR-1 and HDR-3. After history matching studies, long term circulation tests are investigated for various cases, specifying HDR-1 as an injection well and HDR-2a and HDR-3 as production wells. Temperature performances at inflow points of production wells are predicted for several constant production and constant bottom hole flowing pressure cases. In all cases, the most significant temperature decrease is observed at the inflow point of F2a-9, which indicates most of injected fluid at HDR-1 flows toward HDR-2a due to high permeability between HDR-1 and HDR-2a. Some additional calculations show that this decrease is strongly related to injection rates and the distance between injection and production wells.

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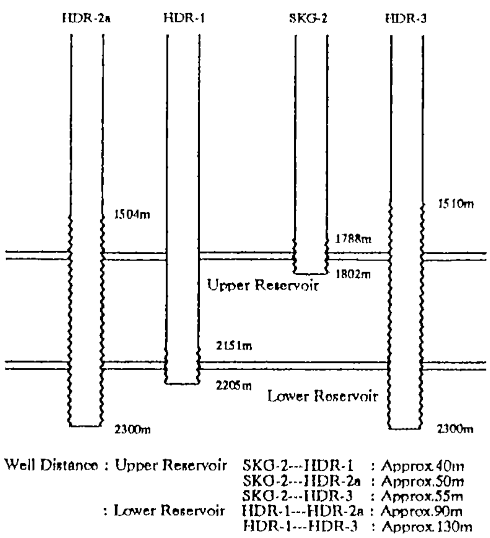

Figure 1. Reservoir and Well Configuration at the Hijiori HDR Test Site

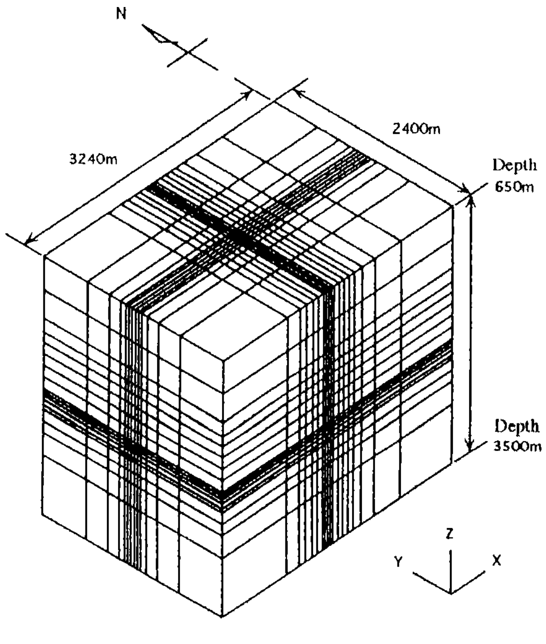

Figure 2. The Investigated Area and Grid Division of the Model for the Hijiori HDR Test Site

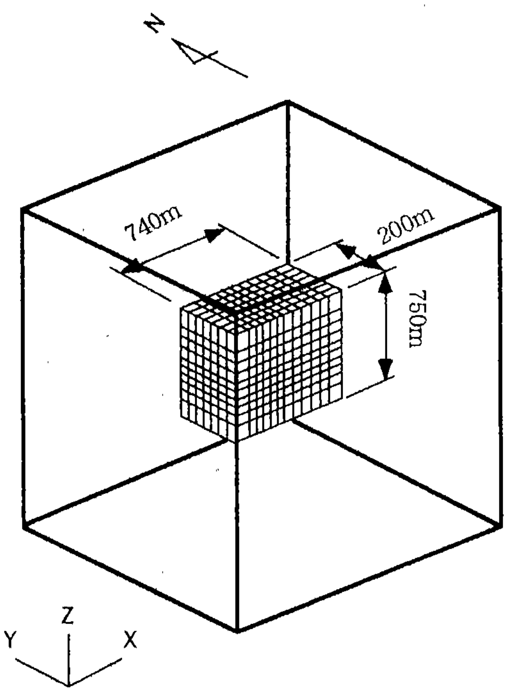

Figure 3. The High Permeable Zone in the Investigated Area

Table 1. Reservoir Properties of the Hijiori HDR Test Site

Rock Density (kg/m^3)	2700
Rock Specific Heat (J/(kg K))	1000
Rock Thermal Conductivity (W/(m K))	3.0
Porosity (fraction)	
Low Permeable Zone	0.05
High Permeable Zone	0.1
Permeability (m^2)	
Low Permeable Zone	1.0 E-16 (0.1 md)
High Permeable Zone 1	1.0 E-15 (1.0 md)
High Permeable Zone 2	1.0 – 10.0 E-15 (1.0 – 10.0 md)

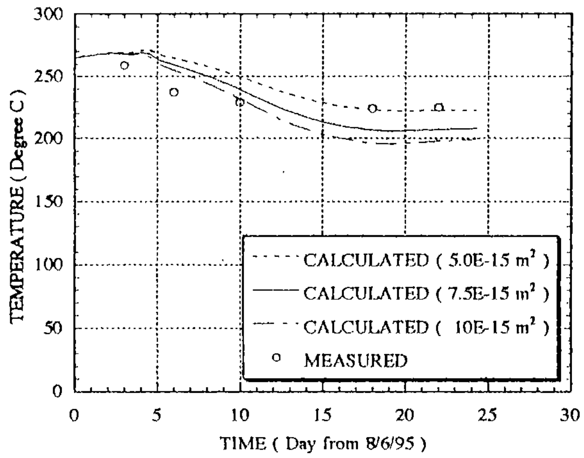

Figure 5. Comparison of Calculated and Measured Temperature at the Inflow Point, F2a-9 (The Preliminary Circulation Test in 1995)

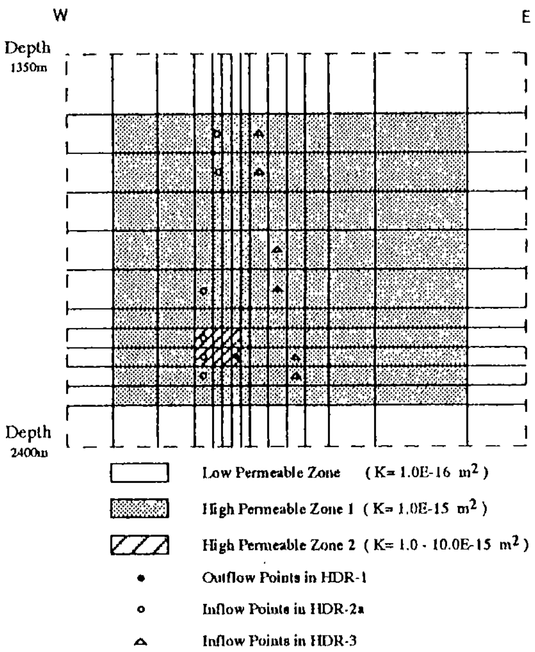

Figure 4. East-West Cross Section at the Center of the Model

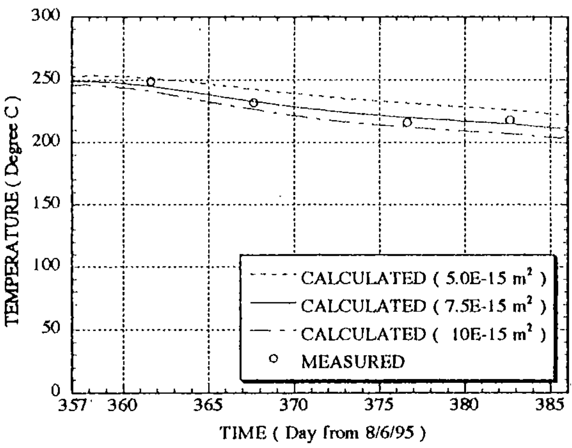

Figure 6. Comparison of Calculated and Measured Temperature at the Inflow Point, F2a-9 (The Flow Enhancement Test in 1996)

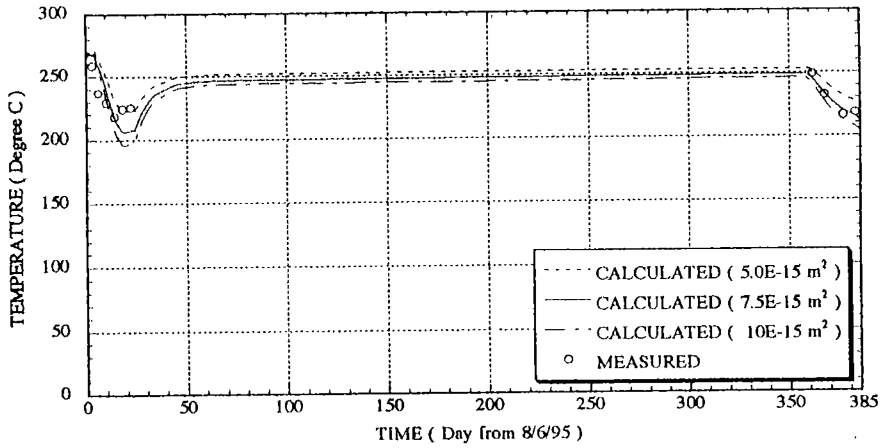

Figure 7. Comparison of Calculated and Measured Temperature at the Inflow Point, F2a-9 (During the Period from 1995 to 1996)

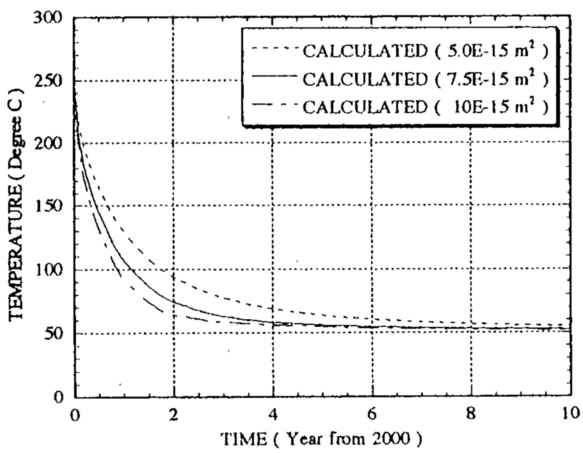

Figure 8. Temperature Performance at the Inflow Point, F2a-9 for the Constant Production Case at the Injection Rate of 60 t/h

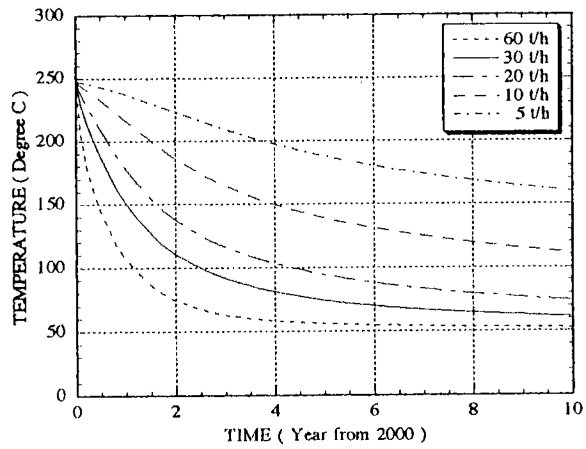

Figure 9. Temperature Performance at the Inflow Point, F2a-9 for Various Injection Rates

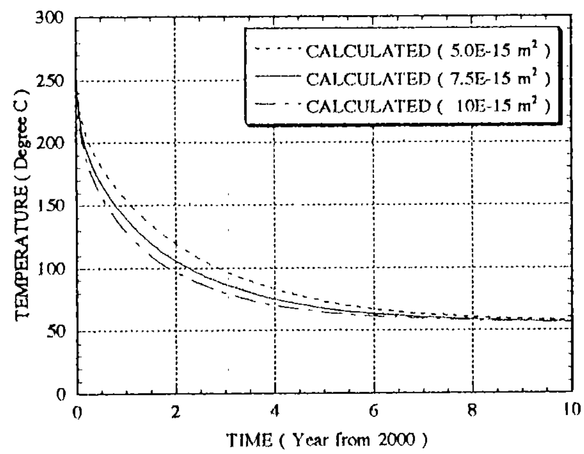

Figure 10. Temperature Performance at the Inflow Point, F2a-9 for the Constant Bottom Hole Flowing Pressure Case

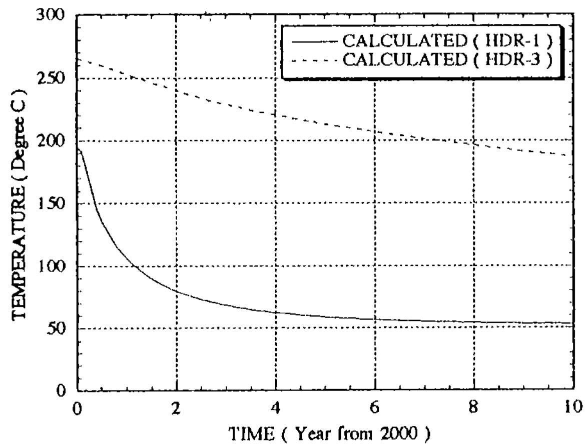

Figure 11. Temperature Performance at the Inflow Points of HDR-1 and HDR-3