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Variation of the Characteristics of the Shallow Reservoir at the Hijiori Test Site between 90-days Circulation Test and Long-Term Circulation Test Using FEHM Code

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ABSTRACT

At the Hijiori Hot Dry Rock (HDR) field in Yamagata prefecture, a deep reservoir and a shallow reservoir have been created by hydraulic stimulation. A Long-Term Circulation Test (LTCT, Term 2 and Term 3) of the Hijiori system was conducted from December 23, 2001 to August 31, 2002. The test used two injection wells SKG-2 and HDR-1, and two production wells HDR-2a and HDR-3. At the beginning of this test, water was injected at a constant flow rate of 8.35 kg/s into both injection wells. After 15 weeks of flow, the injection rate of HDR-1 (completed only in the deep reservoir) was increased to 12.53 kg/s and the injection rate of SKG-2 (completed only in the shallow reservoir) was decreased to 4.17 kg/s, yielding an injection ratio of 3:1. In response to this change in injection distribution, the production flow rate of HDR-2a decreased from 8 to 6kg/s, while the production rate in HDR-3 remained almost constant during the test. Both production wells are open to both reservoirs.

Also, 90 days circulation test (Exp.9102) was carried out in1991. This test was used with the shallow reservoir. Aiming to grasp the variation of the characteristic of the shallow reservoir between Exp.9102 and LTCT, we developed a numerical model of Hijiori reservoir and simulated the test data using the FEHM (Finite Element Heat and Mass transfer) code developed at Los Alamos National Laboratory. The model provided a reasonable match to the observed pressure, temperature and flow data collected during the LTCT and Exp.9102. We compare with the model parameters of Exp.9102 and LTCT. As the results, permeability of the shallow reservoir of LTCT is higher than that of Exp.9102.

1. INTRODUCTION

Under the New Sunshine project administrated by the Ministry of Economy, Trade and Industry (METI), field tests have been conducted to develop a heat extracting system in hot dry rock (HDR) at Hijiori caldera in Yamagata Prefecture from 1984 to 2002. This HDR test site is located on the southern edge of the 2 km diameter Hijiori caldera, which was formed about 10,000 years ago. Topographic effects extend underground, and the predominant fracture orientation is E-W, with a high dip angle to the N. The Hijiori HDR system consists of a shallow reservoir and a deep reservoir and four wells (SKG-2, HDR-1, HDR-2a and HDR-3). Well SKG-2 is completed in the shallow reservoir only, well HDR-1 is completed in the deep reservoir only, while the remaining two wells (HDR-2a and HDR-3) are open to both reservoirs.

The Hijiori HDR geothermal energy R&D project is divided into two phases. The first phase was 1985 to 1991, when the shallow reservoir was created and various technological developments were carried out. The second phase was 1992 to 2002. The Long Term Circulation Test (LTCT) was the final test of the second phase, and consisted of three test periods or "terms." During Term 1 (November 27, 2000 to November 15, 2001), the circulation test was conducted utilizing deep injection well HDR-1 and production wells HDR-2a and HDR-3 (*Oikawa et al., 2001, Tenma et al., 2002*). During Term 2 (December 23, 2001 to April 28, 2002), a dual circulation test was carried out, using both HDR-1 and SKG-2 as injection wells; and HDR-2a and HDR-3 as production wells. During Term 3 (June 1, 2002 to August 31, 2002), a small binary power plant was used to demonstrate electric power generation from this HDR system, using the same well configuration of Term 2.

With two reservoirs and four wells with various completion depths, the Hijiori HDR system is an ideal site for evaluating the characteristics of a multi-reservoir system. The interference between the shallow and the deep reservoirs using the variations in downhole pressure has already been examined (*Tenma et al., 1997*). This paper presents additional analyses of the multi-reservoir system at Hijiori test site using by the results of LTCT, Term 2 and Term 3.

2. OUTLINE OF LTCT TERM 2 AND TERM 3 (DEC. 23. 2001 – AUG. 31. 2002) AND EXP.9102

The LTCT is divided with three periods by the different of injection rate as shown in Table 1. This test was carried out with two injection wells (HDR-1 and SKG-2), and two production wells (HDR-2a and HDR-3). The purpose of conducting this test was to estimate the productivity of multi-reservoir system when injecting successively into each reservoir and to provide data to calibrate the numerical model of the system. A total of 191,409 tons of water were injected into HDR-1, and the total injected into SKG-2 was 191,409 tons. The total amount of steam and hot water produced from HDR-2a was about 124,765 tons, and that from HDR-3 was 43,792 tons, yielding an overall fluid recovery rate of about 54 %.

The histories of injection and production rate, wellhead temperature and wellhead pressure are shown in Figure1a - 1c. As noted in Figure 1a, water was injected at a constant flow rate of 8.35 kg/s into SKG-2 and HDR-1 during Run Segment 1. During Run Segment 2, the ratio of injection flow rate into wells HDR-1: SKG-2 was changed from 1:1 to 3:1. The amount of steam and hot water produced from HDR-2a was greater than that from HDR-3. In the beginning of Run Segment 2, when the rate of injection into each reservoir changed, the production rate of HDR-2a decreased from 8 kg/s to 6 kg/s.

As shown in Figure 1b, the wellhead temperature of HDR-3 decreased from about 170°C to 160°C and the wellhead temperature of HDR-2a decreased from about 150°C to about 130°C during Run Segments 1 and 2.

As shown in Figure 1c, injection wellhead pressure of HDR-1 started at about 2 MPa, and increased to 4 MPa when the injection rate was increased during Run Segment 2. Also, the wellhead pressure of well SKG-2 decreased about 1.2 MPa when its injection rate was decreased. Production wellhead pressure of HDR-2a temporarily increased about 2 MPa because of wellbore scaling during Run Segment 1. The scaling stopped by the effect of the long-term circulation, HDR-2a was maintained at approximately 1 MPa throughout the test. Wellhead pressure of HDR-3 was fairly constant at about 1 MPa during Run Segments 1 and 2.

Also, Exp.9102 was a three-month circulation test with injection well SKG-2, and three production wells HDR-1, HDR-2 and HDR-3 in 1991 (*Kruger and Yamaguchi, 1993*). The heat was successfully extracted from the shallow reservoir created at a depth about 1800m from August 6 to November 3, 1991. Most of the pumping was done at a rate of 16.7 kg/s except an initial period of the test. At the period, the injection flow rate was increased for short time to twice or three times to improve the connectivity of fractures between the injection and production wells and to promote AE generation for detecting the flow paths in the reservoir. Single production tests were also conducted to estimate the productivity from each production well. In this test, a wellhead valve of one production well was kept open, while valves of other production wells were closed. Therefore, there was no production from two wells whose valves were closed during this test.

3. RESERVOIR MODELING

As described in Tenma et al. (2002), a numerical model of the Hijiori reservoir was developed using the conceptual model of the two reservoirs and the data of the LTCT. As discussed above, the Hijiori HDR system has two reservoirs (the shallow reservoir and the deep reservoir) and four wells (SKG-2, HDR-1, HDR-2a and HDR-3). Also, there are two main fractures in the shallow reservoir and four main fractures in the deep reservoir as shown in Figure 2 (*from Tenma et al., 2002*). On the basis of Acoustic Emission (AE) data, these main fractures are thought to be inclined planes (*Tezuka et al., 1998*); however, to simplify the model calculations, we have assumed that the fractures are horizontal. To estimate the behavior of the reservoir in response to pressure variations, we used Gangi's bed-of-nails model as shown in Figure 3. Also, relation between the aperture of the fracture W and the effective pressure P is revealed as follows;

$$W = W_o\left\{1-\left(\frac{P}{P_\alpha}\right)^{\frac{1}{n}}\right\} \quad (1)$$

$$P = \sigma - P_w \quad (2)$$

$$P_\alpha = E\frac{A_r}{A} \quad (3)$$

In these equations, σ is the earth stress normal to the fracture, and P_w is the pressure within the fracture. A is the total area of the fracture, A_r is the total cross sectional of the nails.

Also, the exponent of the distribution of nail's heights n is shown in equation (4). In this equation, α, β are control value and Q is total amount of injection flow.

$$n = \frac{Q+\beta}{Q+\alpha} \quad (4)$$

The relation between fracture aperture W and permeability k was derived from the cubic law for laminar flow as follows.

$$k = \frac{W^2}{12f} \quad (5)$$

In this equation, f is a friction factor for flow and the Lomize's friction factor (*Whiterspoon, 1980*) was adopted in the simulation. The Lomize's friction factor was defined as a follows.

$$f = 1+17\left(\frac{a}{2W}\right)^{1.5} \quad (6)$$

In this equation, a is the representative height of asperity shown in Figure 3.

The simulation code FEHM (Finite Element Heat and Mass Transfer), developed at Los Alamos National Laboratory (*Zyvoloski, 1992*), was used for the analysis of the Hijiori multi-reservoir system. In the FEHM code, the conservation equations of heat and mass in a porous media are solved using the control volume finite element method. Properties and parameters used for the simulation are shown in Table 1. We referred to the parameter set used to calculate hydraulic fracturing (*Yamaguchi et al., 1997*), and we determined these parameters comparing with the measured data by trial-and-error (*Tenma et al., 2004*).

4. RESULTS

The results of calculation of the LTCT, Term 2 and Term 3 are shown in Figure 4a (injection pressure in HDR-1 and SKG-2), 4b (temperatures in HDR-2a and HDR-3) and 4c (production rates for HDR-2a and HDR-3). The ratio of the production rate from the shallow and the deep reservoir for the total amount of hot water and steam produced by HDR-2a and HDR-3 is shown in Figure 5a and 5b. The upper graph on these figures shows the ratio of production rate from the shallow reservoir, and lower presents that from the deep reservoir. For example, a value of 100 % in the upper graph of Figure 5a means that production is being derived only from the shallow reservoir. Also, ratios derived from PTS logs are shown for the shallow reservoir with an open triangle (Δ) and for the deep reservoir with an open square (□).

Also, the results of calculation of Exp.9102 are shown in Figure 6a (injection pressure in SKG-2), 6b (temperatures in HDR-2 and HDR-3) and 6c (production rates for HDR-2 and HDR-3). Model parameters of the shallow reservoir are shown in Table 2.

5. DISCUSSION

As noted in Figure 4a - 4c, the model closely matches the measured pressure, temperature and flow rate throughout the LTCT, Term 2 and Term 3, suggesting that our simple multi-reservoir model correctly represents the observed behavior during the LTCT. Figures 5a and 5b show a good match between the calculated production ratio of HDR-2a and HDR-3 and the results of PTS logging.

As discussed above, the relative amounts of fluid injected into the two injection wells was changed at the end of Run Segment 1. This led to a change in the production rate of HDR-2a during Run Segments 2 and 3, as explained below.

During Term 1, injection was directed only to the deep reservoir, and only cold water flowed from the shallow reservoir (*Tenma et al., 2004*). However, steam and hot water was produced from the shallow reservoir during Term 2 and Term 3, because part of the injection was directed to the shallow reservoir. At the start of Term 2 (Run Segment 1), the ratio of production rate from the shallow reservoir was about 75 % (Figure 5 a). Figure 1b shows that the wellhead temperature of well HDR-2a was initially about 125°C, and then increased to nearly 150°C. After about 70 days of circulation, temperature of HDR-2a was gradually decreasing thereafter. We infer that these temperature changes result from the influence of the heat extraction from the shallow reservoir as shown in Figure 4b.

Also, the ratio of the production rate from the shallow reservoir decreased when the distribution of injection between the shallow and deep reservoirs was changed during the test. As the total production rate during Run Segment 2 is lower than that during Run Segment 1, we suppose that the increase of the productivity from the deep reservoir is less than that lost from the shallow reservoir after more injected was diverted to the deep reservoir.

In contrast, the production rate from the shallow reservoir in well HDR-3 remained more constant at 70 – 80% of the well's total flow during Run Segments 1 and 2, despite the fact that more injection was diverted to the deep reservoir during Run Segment 2. We conclude from this that the connection of SKG-2 and HDR-3 of the shallow reservoir is better than that of the HDR-1 and HDR-3 of the deep reservoir.

As noted in Figure 6a - 6c, the model closely matches the measured pressure, temperature and flow rate throughout the Exp.9102. As shown in Figure 6b, temperature of HDR-2 is the best match. In this results, calculated temperature increase during single production tests. Also, temperature of HDR-3 is not the best match after the single production test. As the flow rate of each production well was zero during the single production test, hot water flow other production well that was kept open the wellhead valve through the shallow reservoir. Thus, we assume that flow path of HDR-3 is changed by the influence of the single production well test.

As noted in Table 2, parameters α, β and a are different in the Exp.9102 and LTCT. From the equation (4), n of exp.9102 and LTCT are similar before injection. But variation of n is different in Exp.9102 and LTCT as shown in Figure 7. We think that the exponent of the distribution of nail's heights n recovery because of no injection from end of Exp.9102 to LTCT. And variation of n in the Exp.9102 and LTCT are different by the effect of circulation. Also, a of LTCT is smaller than that of Exp.9102 by the effect of circulation.

6. CONCLUSIONS

Using the conceptual model of the Hijiori reservoir and the results of the LTCT and Exp.9102, a numerical model of the Hijiori reservoir was developed using FEHM. We obtained a reasonable match to the injection pressure, flow rate and temperature of the two production wells during these tests. Also, we compared with model parameters of the shallow reservoir. In the future, we investigate the model parameters of the deep reservoir

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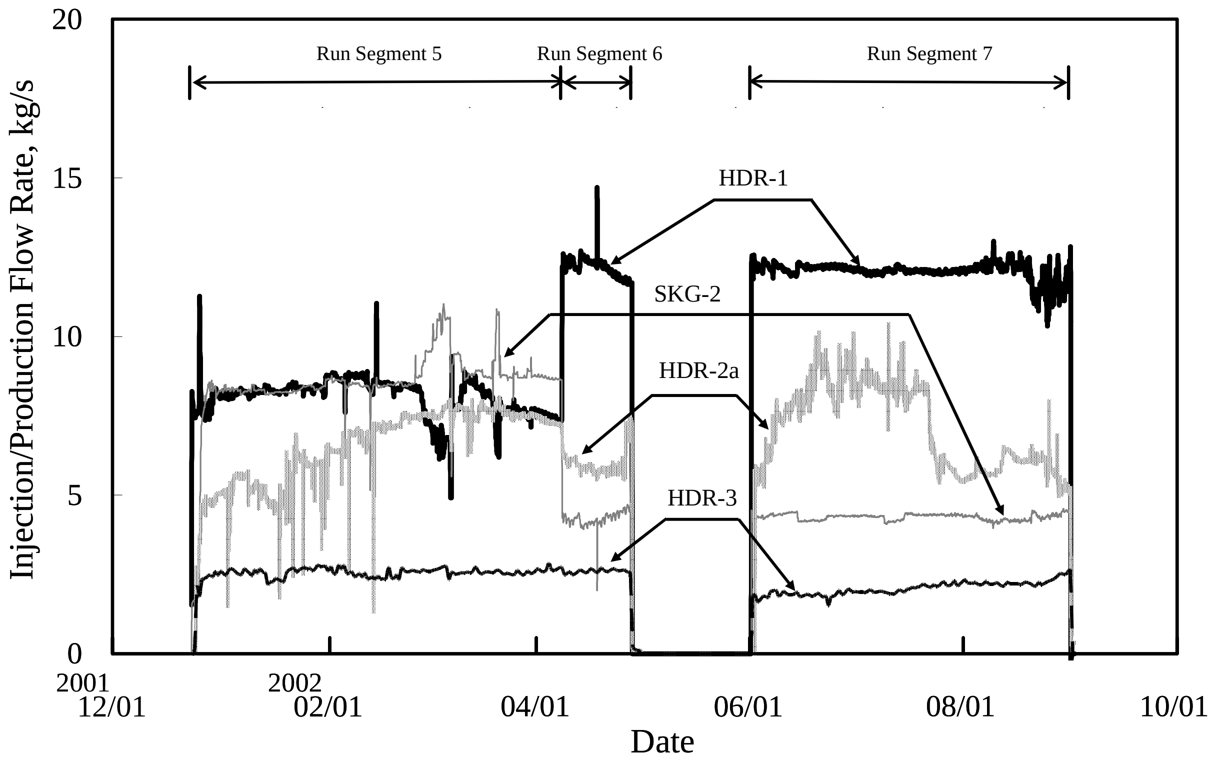

Figure 1a History of Injection (HDR-1 and SKG-2)/Production (HDR2-a and HDR-3) rate during the LTCT, Term 2 and Term 3.

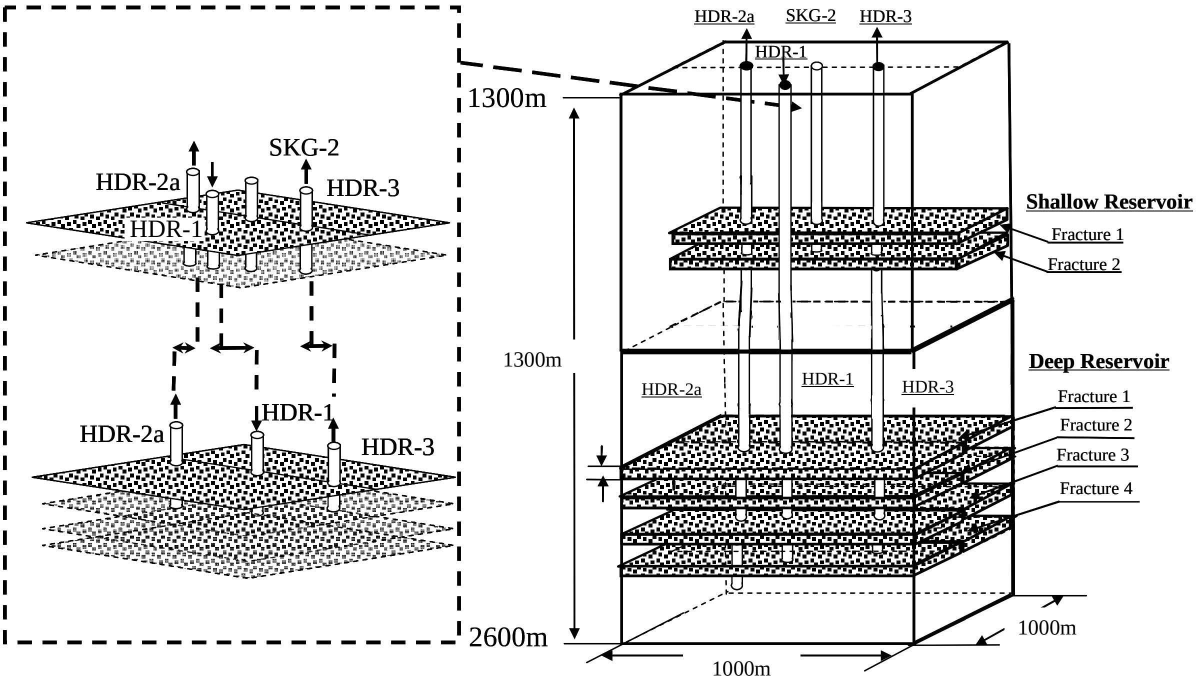

Figure 2 FEHM simulation model of the Hijiori HDR multi-reservoir

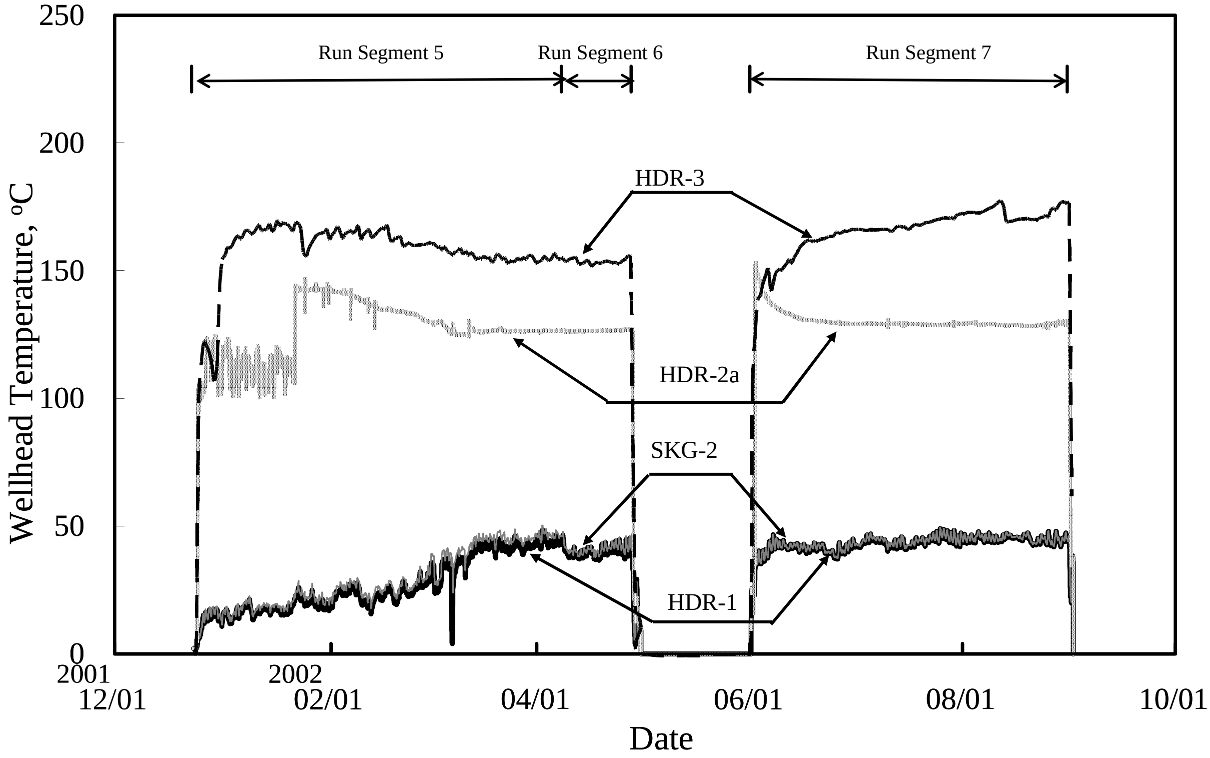

Figure 2b History of Wellhead temperature for Injection (HDR-1 and SKG-2)/Production(HDR2-a and HDR-3) during the LTCT, Term 2 and Term 3.

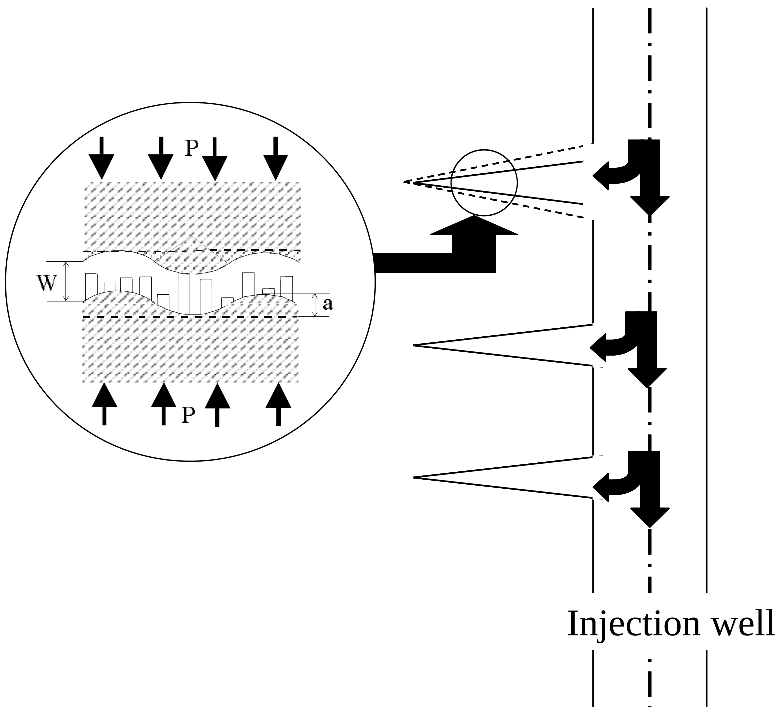

Figure 3 Schematic view of Gangi's Bed-of-Nails model

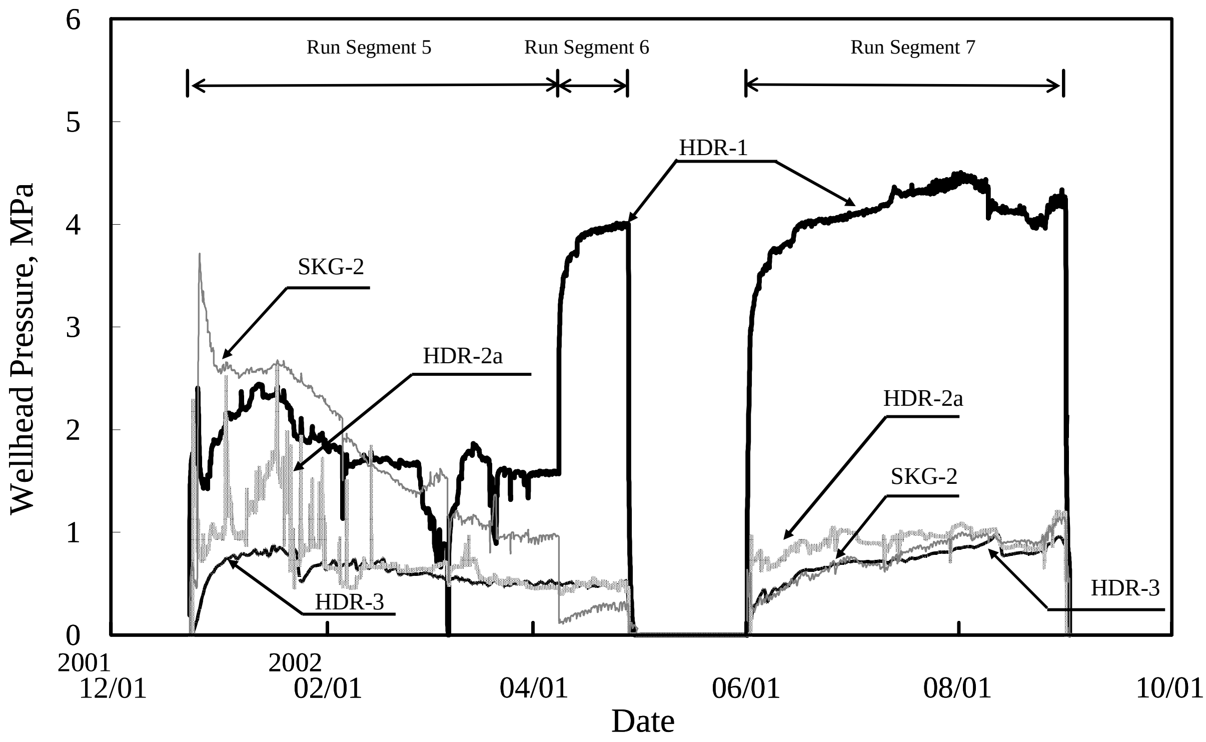

Figure 3c History of Wellhead pressure for Injection (HDR-1 and SKG-2)/Production (HDR2-a and HDR-3) during the LTCT, Term 2 and Term 3.

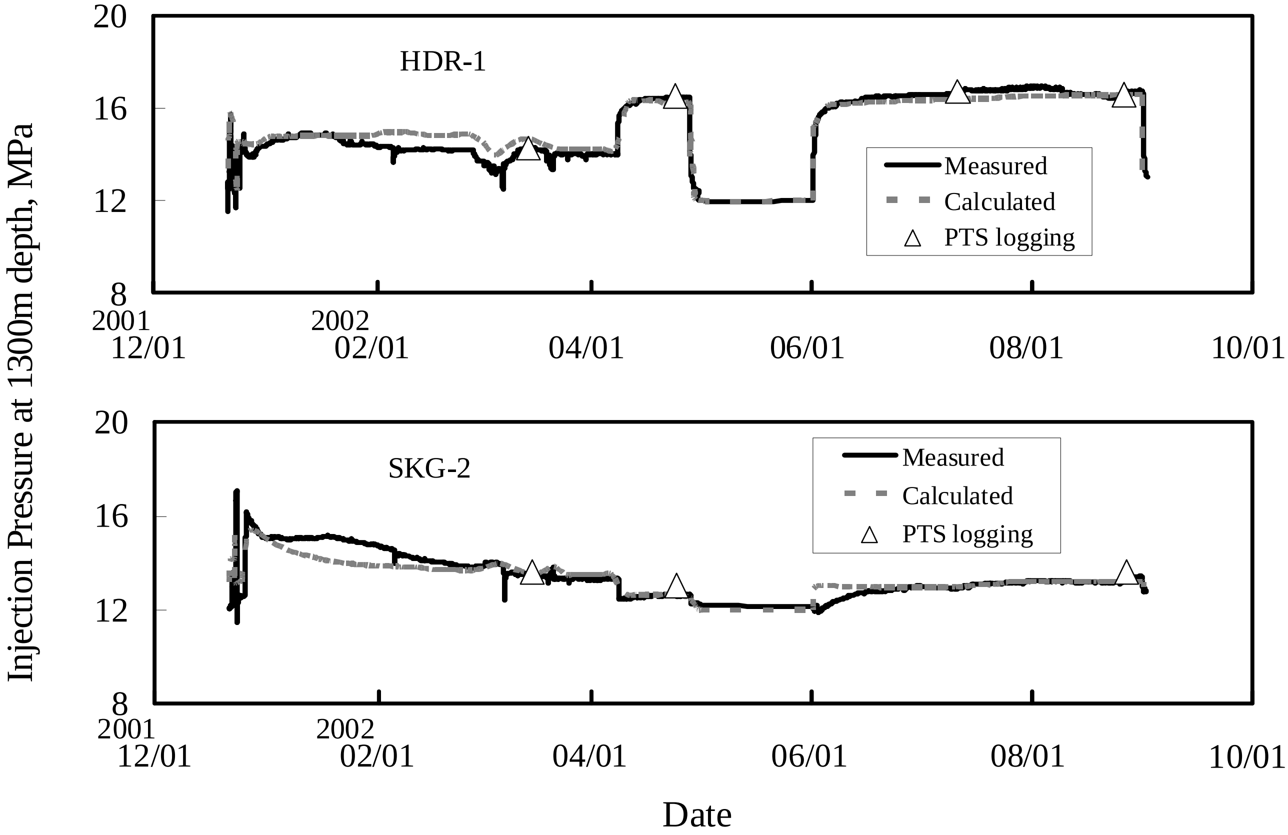

Figure 4a Calculated injection pressure at the depth of 1300m by FEHM during the LTCT, Term 2 and Term 3.

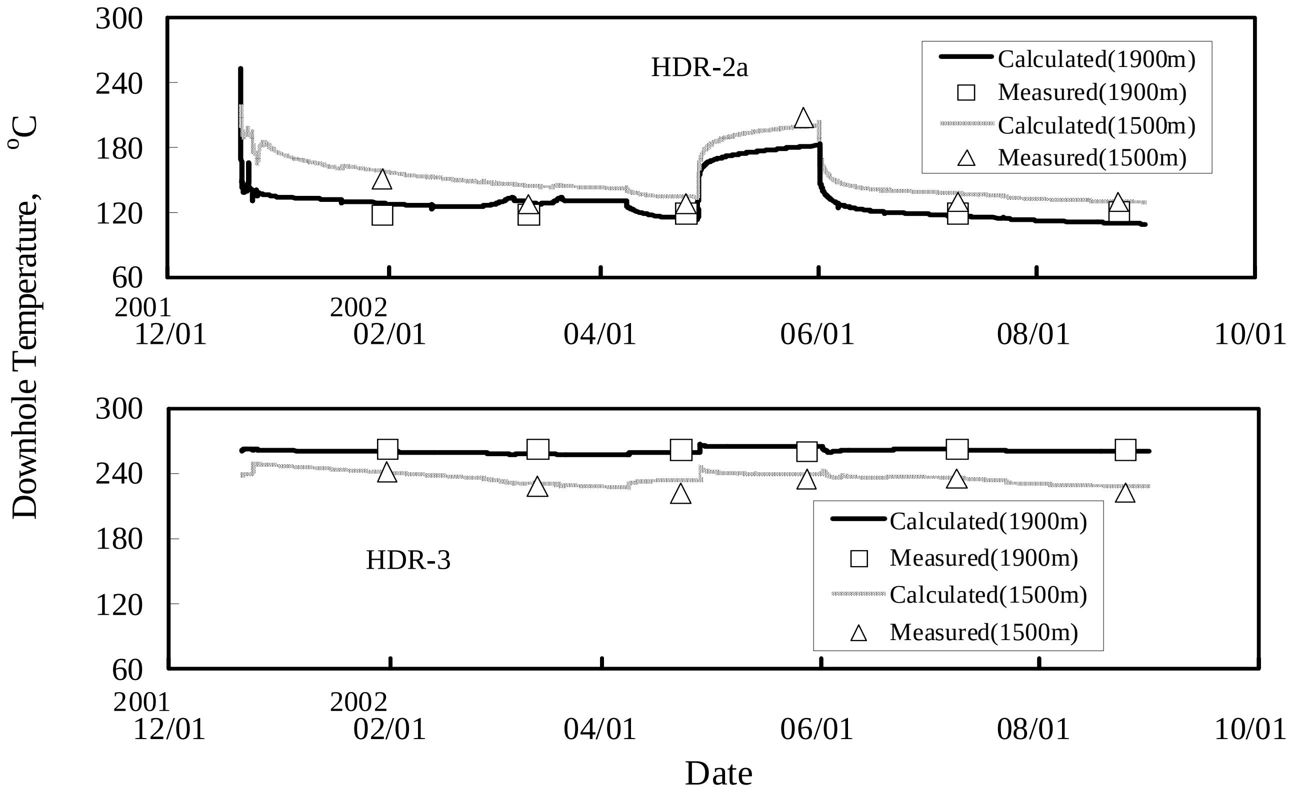

Figure 4b Calculated temperature at the depths of 1500m, 1900m and PTS logging data during the LTCT, Term 2 and Term 3.

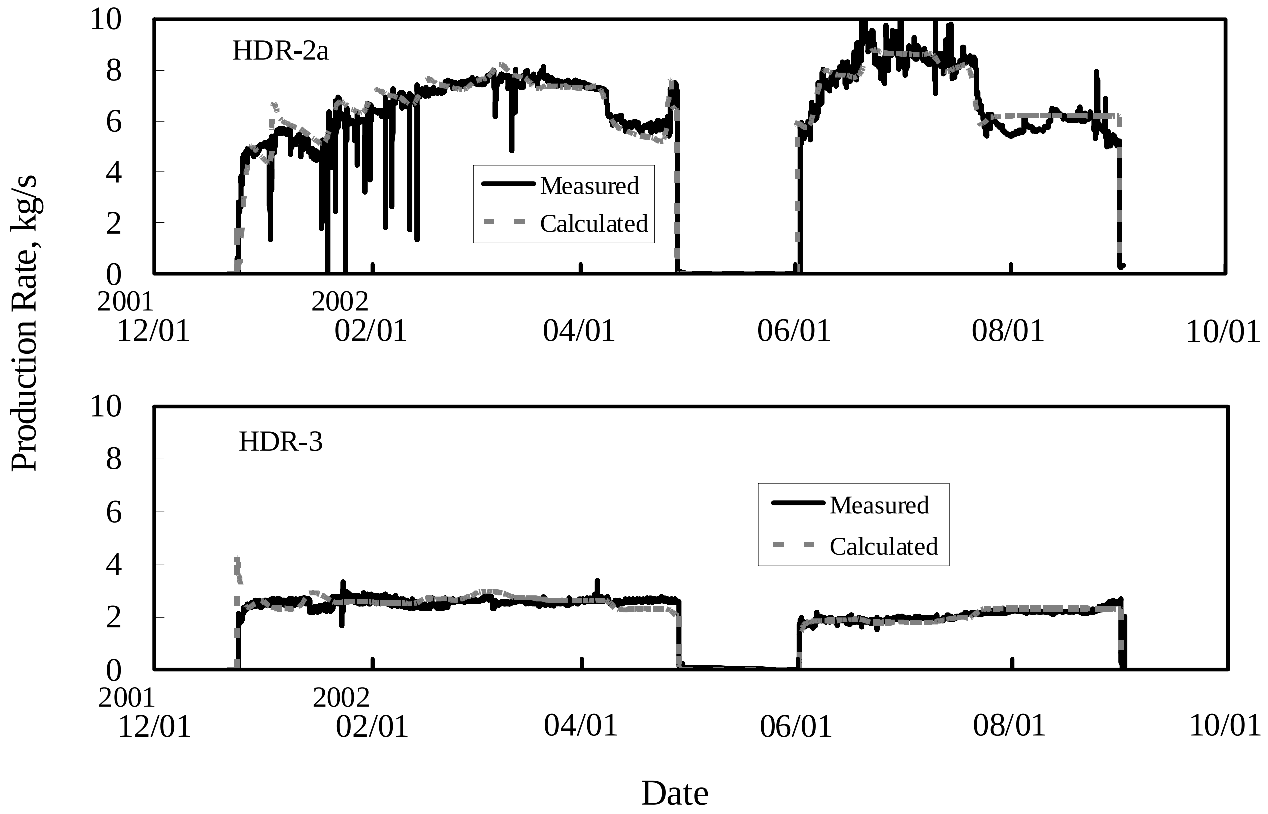

Figure 4c Calculated production rate of wells by FEHM during the LTCT, Term 2 and Term 3.

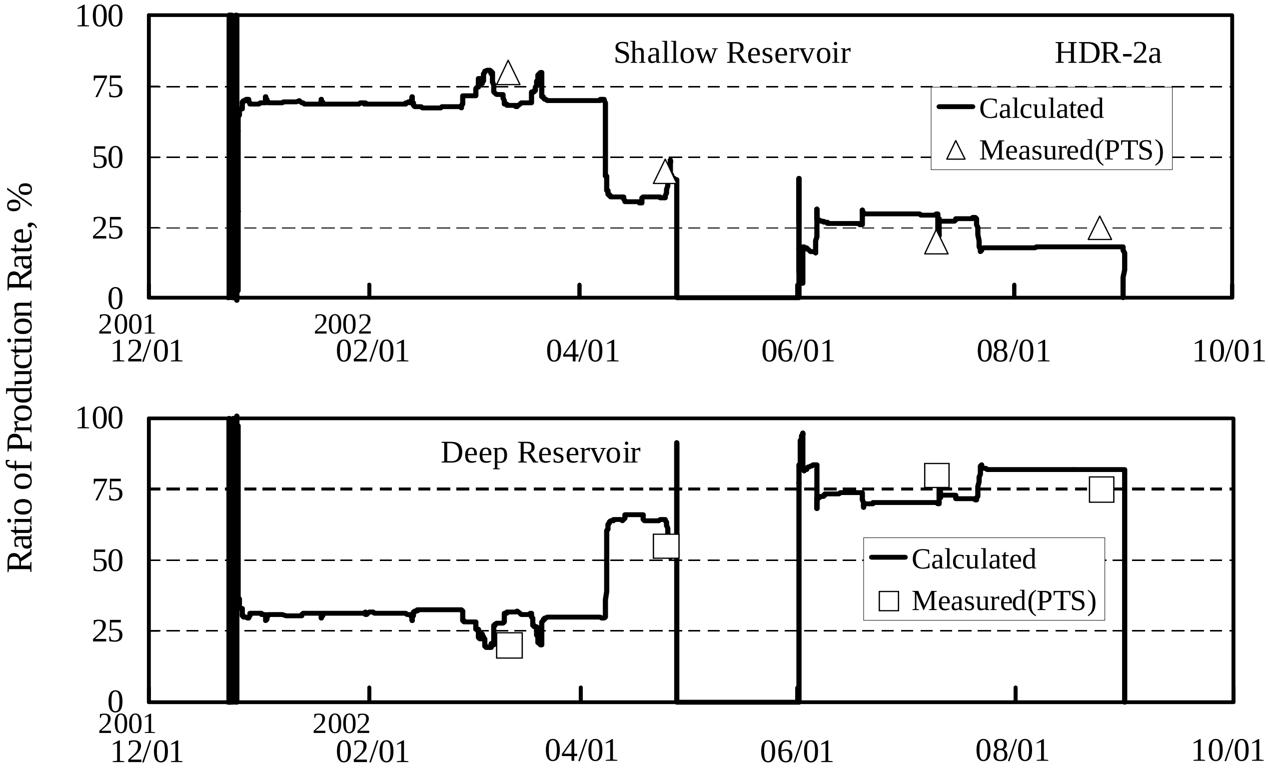

Figure 5a The ratio of production rate on HDR-2a and measured value by the PTS logging data during the LTCT, Term 2 and Term 3.

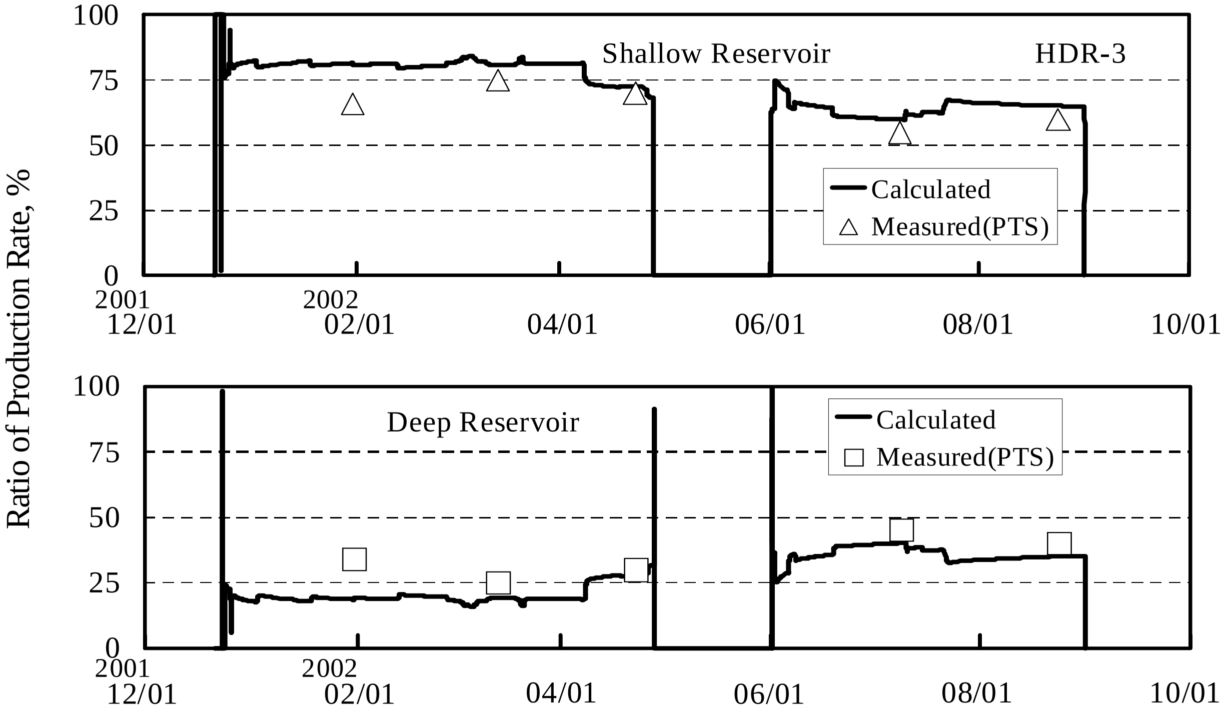

Figure 5b The ratio of production rate on HDR-3 and measured value by the PTS logging data during the LTCT, Term 2 and Term 3.

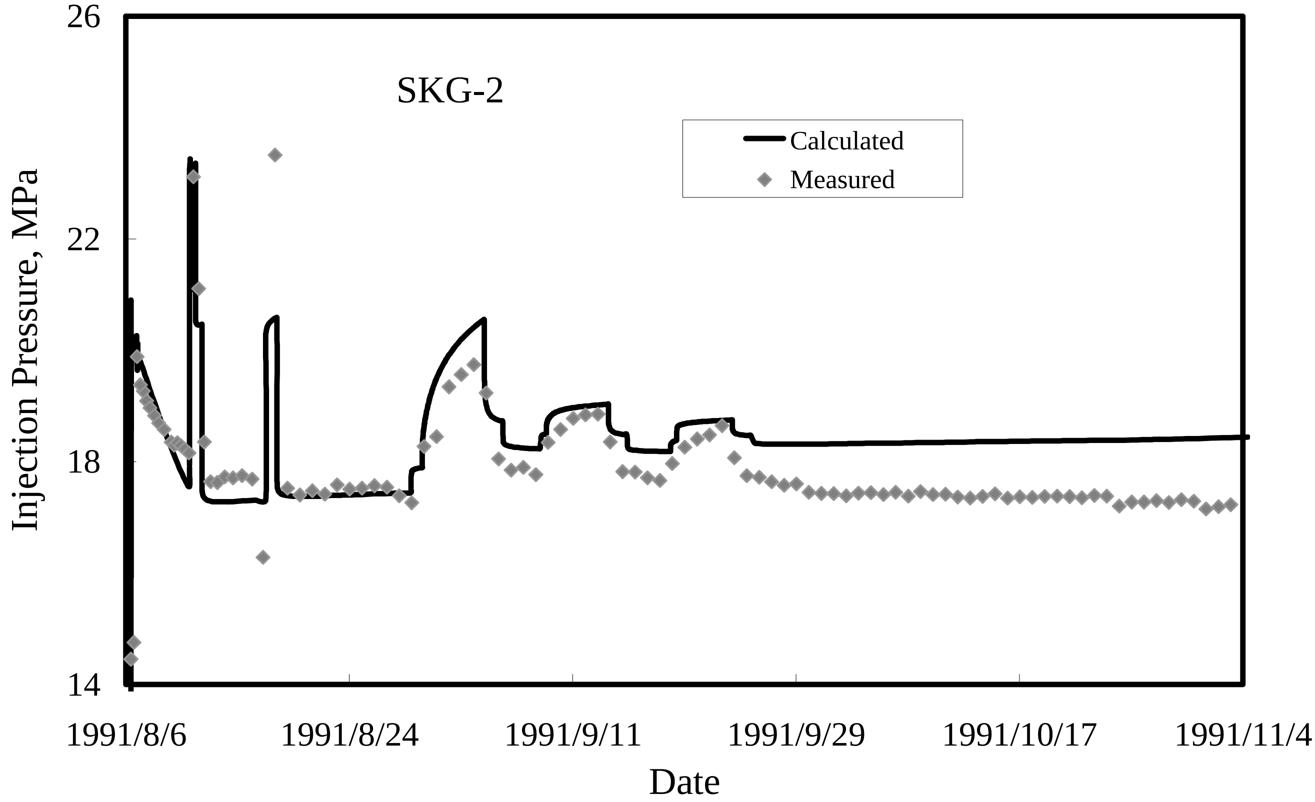

Figure 6a Calculated injection pressure at the depth of 1300m by FEHM during the Exp.9102.

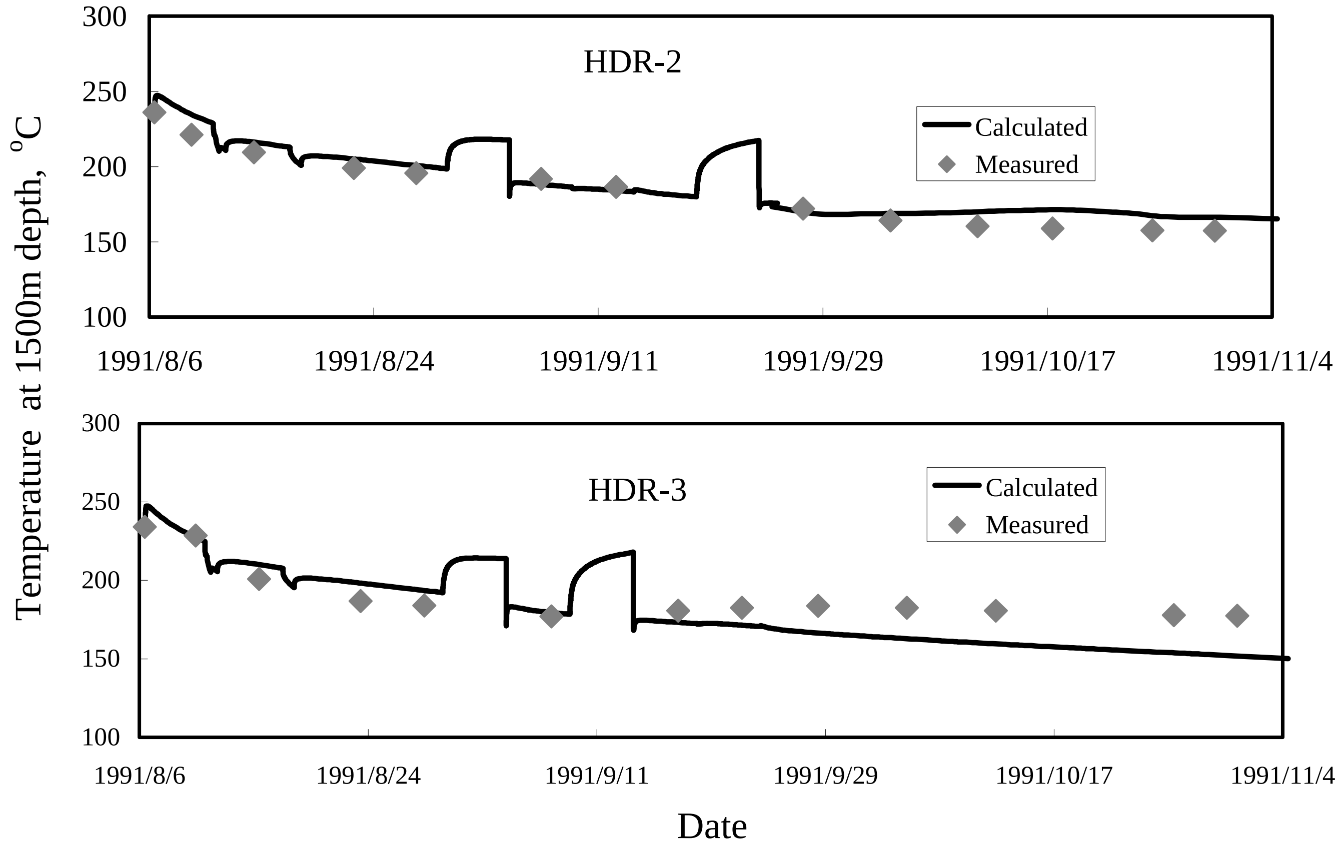

Figure 6b Calculated temperature at the depths of 1500m and PTS logging data during the Exp.9102.

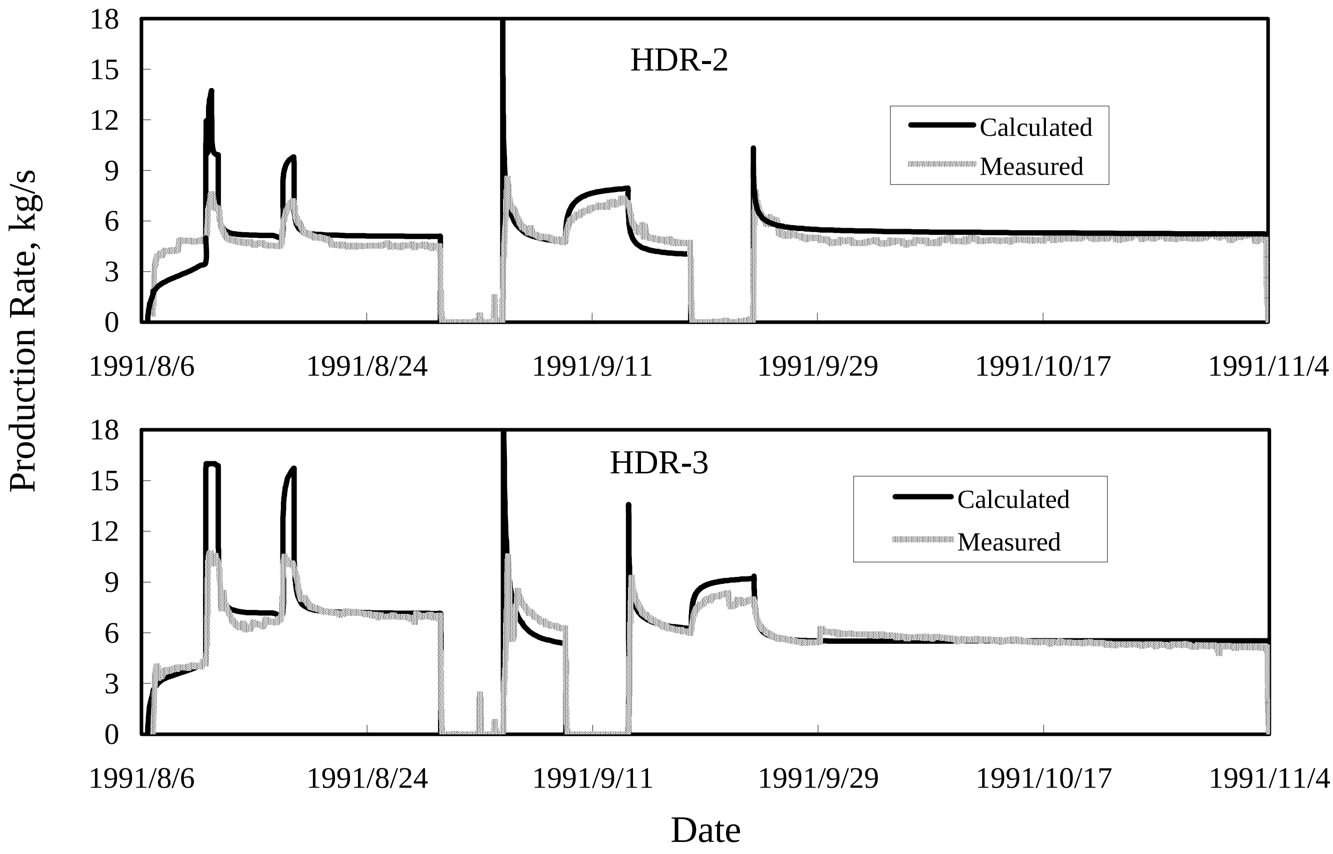

Figure 6c Calculated production rate of wells by FEHM during the Exp.9102.

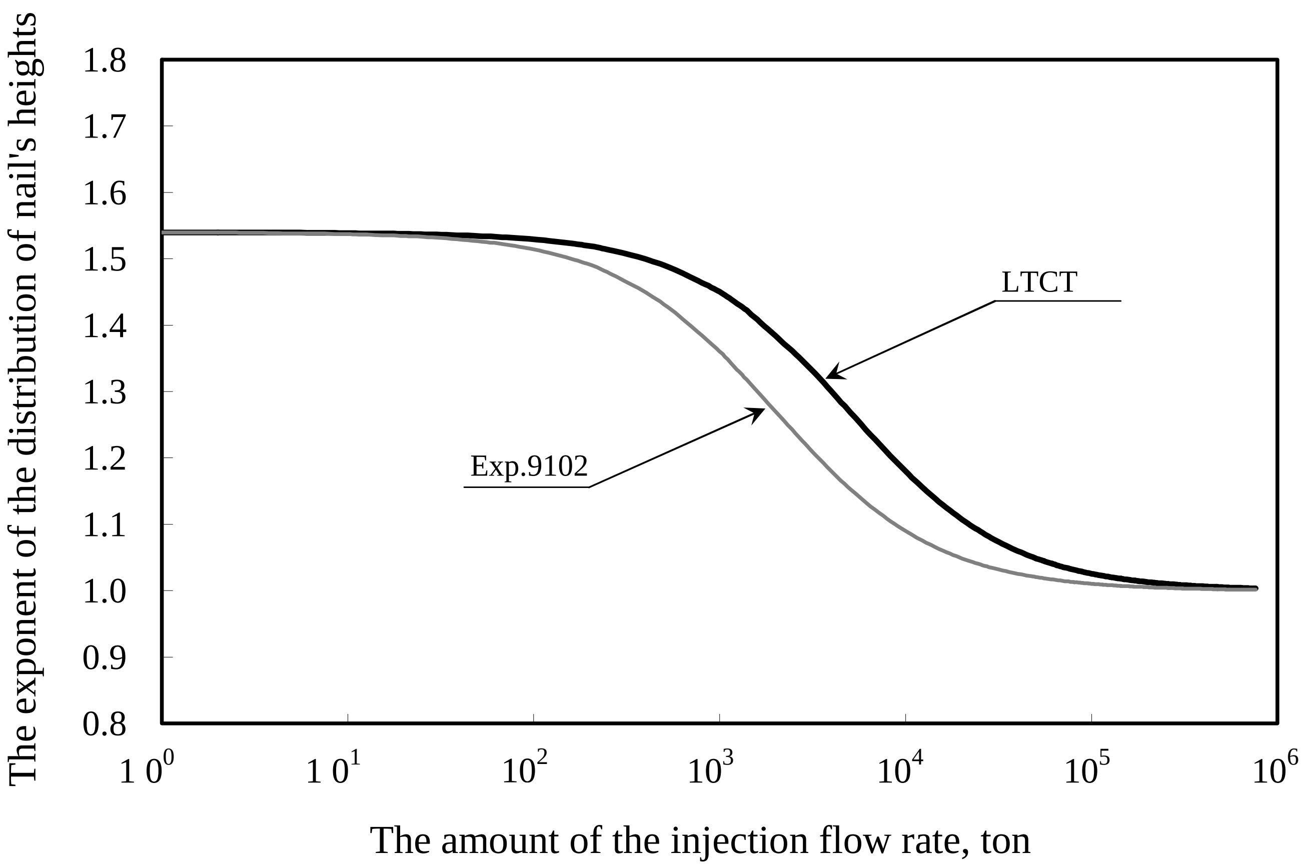

Figure 7 Relation between the exponent of the distribution of nail's heights and the amount of the injection flow.

Table 1 Outline of the Long-Term Circulation Test (LTCT)

Term	Run Segment	Period of segment	Remark	
			Injection Well(s)	Injection Rate(s) , kg/s
Term 2 **(126 day)**	Run Segment 1	2001/12/23□2002/04/08	HDR-1	8.35
			SKG-2	8.35
	Run Segment 2	2002/04/08□2002/04/28	HDR-1	12.53
			SKG-2	4.17
Term 3 **(92day)**	Run Segment 3	2002/06/01□2002/08/31	HDR-1	12.53
			SKG-2	4.17

Table 2 Comparison with model parameters of LTCT and Exp.9102 for the shallow reservoir

Parameter		Area		Value	
				LTCT	Exp.9102
The effective modulus of the asperities (P_α)		HDR-2a - SKG-2	Fracture 1	38.0 MPa	38.0 MPa
			Fracture 2	38.0 MPa	38.0 MPa
		HDR-3 - SKG-2	Fracture 1	38.0 MPa	38.0 MPa
			Fracture 2	38.0 MPa	38.0 MPa
The exponent of the distribution of nail's heights (n)	The control value (β)	HDR-2a - SKG-2	Fracture 1	4620 ton	1848 ton
			Fracture 2	3080 ton	1232 ton
		HDR-3 - SKG-2	Fracture 1	4620 ton	1848 ton
			Fracture 2	3080 ton	1232 ton
	The control value (α)	HDR-2a - SKG-2	Fracture 1	3000 ton	1200 ton
			Fracture 2	2000 ton	800 ton
		HDR-3 - SKG-2	Fracture 1	3000 ton	1200 ton
			Fracture 2	2000 ton	800 ton
The representative height of asperity (a)		HDR-2a - SKG-2	Fracture 1	0.60 cm	1.10 cm
			Fracture 2	0.60 cm	1.10 cm
		HDR-3 - SKG-2	Fracture 1	0.85 cm	1.10 cm
			Fracture 2	0.85 cm	1.10 cm
The initial aperture (W_o)		HDR-2a - SKG-2	Fracture 1	1.57 mm	1.57 mm
			Fracture 2	1.67 mm	1.67 mm
		HDR-3 – SKG-2	Fracture 1	2.07 mm	2.07 mm
			Fracture 2	1.65 mm	1.65 mm