Reservoir Monitoring by Tracer Test of a 2002 Dual Circulation Test at the Hijiori HDR Site, Yamagata, Japan

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Keywords

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ABSTRACT

A dual circulation test using two injection wells, SKG-2 and HDR-1, had been conducted from 23 December 2001 to 31 August 2002 at the Hijiori HDR site. This is a test after single circulation test using one injection well, HDR-1. During the test we carried out tracer tests every one or two months for monitoring the flow in the reservoir. First, tracer reagents including sodium fluorescein were pumped into the shallow reservoir at a depth of 1,800 m through injection well SKG-2. After two days, tracer pumped into the deep reservoir at a depth of 2,200 m through injection well HDR-1. Tracer response curves of production wells HDR-2a and HDR-3 were obtained continuously by a fiber-optic fluoremeter. For analysis flow regimes in reservoir, we compare the change of tracer response with the change of reservoir pressure and flow rate from every reservoir calculated from PTS surveys by NEDO. From tracer curves, the volume anisotropy in the shallow reservoir is smaller than that in the deep reservoir and the breakthrough volume became smaller with circulation progressing. Tracer curve changed with the injection rate to both HDR-1 and SKG-2. In shallow reservoir, the rate change reflects the peak concentration but this change reflects the breakthrough volume in the deep reservoir. The flow regime in shallow reservoir shows different response from deep reservoir with the injection change.

Introduction

A tracer test is a useful method for determining flow regimes in a geothermal reservoir. In Hot Dry Rock (HDR) test fields, tracer tests have been conducted to estimate reservoir volumes and their changes with circulation conditions (Robinson at al., 1987; Matsunaga et al., 1996). Since the spatial expansion of HDR reservoirs influences the efficiency of heat extraction, tracer response in production fluid gives important information for estimating the volume and lifetime of the HDR reservoir.

At the Hijiori HDR test field, several circulation tests had been carried out. In 1991, for determining the fluid flow of the shallow reservoir (the depth of 1,800m and the temperature up to 250°), a three-month circulation test was carried out. Then, progress by the New Energy and Industrial Technology Development Organization (NEDO) led to their R&D project to develop a deep reservoir (depth of 2,200m and temperatures up to 270°). The deep reservoir was successfully hydraulically fractured at the bottom of HDR-1, and the two production wells HDR-2a and HDR-3 were drilled into the deep reservoir. In 1995 and 1996, short-term (one-month) circulation tests and a reservoir survey were carried out on the deep reservoir. (Hyodo et al., 1996; Matsunaga and Tao, 1998; Miyairi and Sorimachi, 1996; Tenma et al. 1996, 1999)

Since the short-term circulation tests, a new injection pump, surface facility, micro-seismic monitoring system have been installed. The long-term circulation test (LTCT) was started on 27 November 2000.

The purpose of the LTCT is for the demonstration and evaluation of heat extraction with the multi-fracture reservoir with multiple wells. Besides the fundamental logging and monitoring performed by NEDO, we have conducted tracer tests. The LTCT has been separated in two stages. In the first stage of the LTCT, from 27 November 2000 to 15 November 2001, circulation fluid, which was pumped up from a nearby river, was injected into only the deep reservoir through the HDR-1. A Pressure, Temperature, Spinner (PTS) logging survey, well test with multi-flow rates, and tracer tests revealed the very complex flow regime and the severe interaction between the shallow and the deep reservoirs. Thermal breakthrough in the HDR-2a recognized in the middle of the first stage of the LTCT. (Oikawa et al., 2001;Kawasaki et al., 2002; Matsunaga et al., 2002; Tenma et al., 2002;Yanagisawa et al., 2002).

The second stage of the LTCT was began on 23 December 2001 and ended on 31 August 2002. At the stage, the dual circulation test and power generation test were carried out. During this stage, fluid was injected into both the shallow reservoir through SKG-2 and the deep reservoir through HDR-1.

This paper shows the result of the tracer tests, the estimation the volume change of the reservoir, and a discussion the reservoir

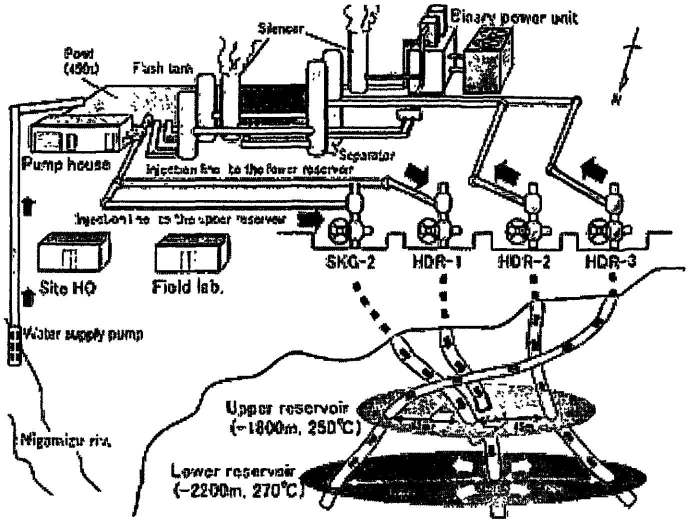

Figure 1. Schematic diagram of circulatiom system at the Hijiori test site.

Table 1. Flow program, the change of injection ratio, during the dual circulation.

Injection Program

Date	SKG-2	HDR-1	Ratio
2001.12.23-2002.4.7	8.33kg/s	8.33kg/s	1:1
2002.4.8-4.28	4.16kg/s	12.5kg/s	1:3
2002.4.29-5.31	0	0	0
2002.6.1-8.31	4.16kg/s	12.5kg/s	1:3

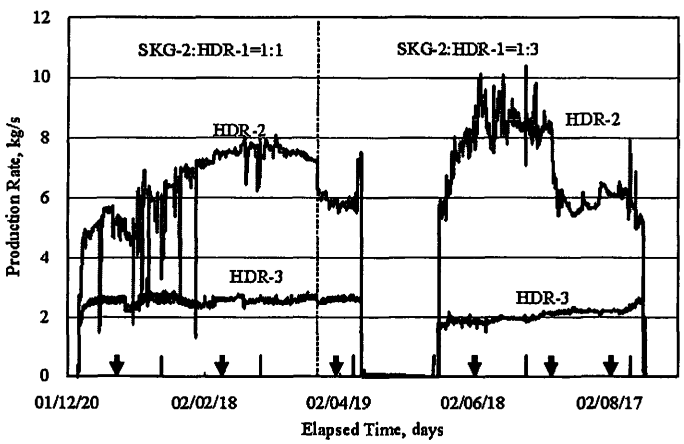

Figure 2. Production rate (HDR-2a and HDR-3) since the start of the dual circulation test. The arrows show the date of tracer tests.

related pressure and production rate obtained by the PTS survey during the dual circulation test.

Dual Circulation Test

The fluid circulation system at the Hijiori HDR site is schematically shown in Figure 1. A multi-stage centrifugal pump (ESP TJ9000) was used to inject the fluid at a constant flow rate of 16.66 kg/s. After being pressurized by the pump, the injection fluid was separated into two lines. One was connected HDR-1, which was

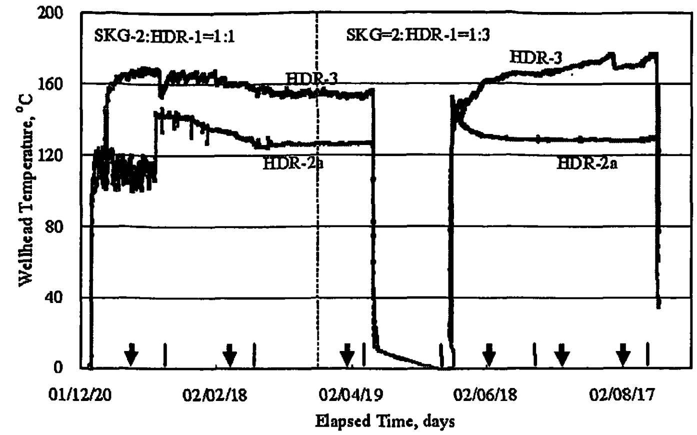

Figure 3. Temperature of production fluids (HDR-2a and HDR-3) since the start of the dual circulation test. The arrows show the date of tracer tests.

Table 2. The PTS survey date and contents during dual circulation test.

Date	Pressure				Production	
	SKG2	HDR1	HDR2	HDR3	HDR2	HDR3
2002.1.30			O	O		O
2002.3.14	O	O	O	O	O	O
2002.4.24	O	O	O	O	O	O
2002.5.28	O	O	O	O		
2002.7.11	O	O	O	O	O	O
2002.8.26	O	O	O	O	O	O

used as an injection well for the deep reservoir, and the other to SKG-2. The injection program is shown in Table 1. On 8 April 2002, the injection ratio of HDR-1 to SKG-2 changed from 1:1 to 3:1. From 29 April to 31 May, injection was stopped to prepare the power generation test. From 1 June to 31 August, the water injection ratio of HDR-1 to SKG-2 was kept 3:1. Total production rates and temperatures of production wells in the dual circulation test are shown in Figure 2 and Figure 3. In these figures, arrows show the date of tracer tests. During the circulation test, the PTS survey was also carried out. The survey date and contents were shown in Table 2.

Tracer Test

Tracer tests have been conducted 6 times during the dual circulation test listed in Table 3. In every tracer test, first, the tracer was pumped into the shallow reservoir at 1,800m depth through injection well SKG-2. The tracer returned in several hours. After observation of tracer response for two days, the tracer was pumped into the deep reservoir at a 2,200m depth through injection well HDR-1. In early two tests, the tracer was pumped into both reservoirs after pumped into each reservoir. For the tests tracers, including Na fluorescein (uranine), two naphthalene sulfonates (Rose et al, 1999) and potassium salts (KI and KBr) were selected and used. Around 200g of Na fluorescein and naphthalene sulfonate and 20kg of potassium salts were dissolved in 0.2m^3 of circulation fluid in a tank. The tracer solution was fed into HDR-1 and SKG-2 well though the feed pump. The flow rate of the feed pump was about 10 to 15 kg/min.

No.	Test date	Tracer fed into	Tracers				
			FL	ANS	NS	KBr	KI
1	1/9	SKG2	152.3g			20.0kg	
	1/11	HDR1	158.7g	196.1g			20.0kg
	1/13	SKG2+HDR1	315 1g		204.7g		
2	2/25	SKG2	153.8g				20.0kg
	2/27	HDR1	99 0g	300.2g			
	3/1	SKG2+HDR1	199.0g				
3	4/16	SKG2	50 6g		137.1g		4.3kg
	4/18	HDR1	401.7g	199.3g			
4	6/16	SKG2	101.0g		97.4g		10.0kg
	6/18	HDR1	100.3g	100.7g			
5	7/22	SKG2	25 0g				
	7/23	HDR1	50 0g				
6	8/17	SKG2	75 0g		150.0g		
	8/20	HDR1	50 0g		150.0g		

*1:FL=Na flourescein (uranin)
*2:NS=1naphtarendisulfonate acid
*3:ANS=7amino,1,3naphtarendisulfonate acid

Table 3. Tracer tests at the Hijiori site during the dual circulation test.

When the fluids produced from HDR-2a and HDR-3 reached the flow-through cell sampling line, the fluorescence of production fluid was continuously monitored using a portable fluoremeter with a fiber optic sensor at the flow-through cell (Matsunaga, et al. 2001). Production fluid was collected for fluorescein concentration analysis using fluorospectrometry and major chemical composition analysis, including potassium salts, at our laboratory. After we determined the relation of fluorescence with progressing time, the fluorescence was standardized with the original fluid in the tracer tank before injection and the progressing time was converted to production volume using production rate. We obtained tracer response curves with standardized concentrations versus production volumes.

Results and Discussion

The results of the tracer tests are summarized in the following sentences. Figure 4 shows the tracer response change of HDR-2a from SKG-2 via the shallow reservoir. Figure 5 shows the HDR-3 response change from SKG-2 via the shallow reservoir. Figure 6 shows HDR-2a response from HDR-1 via the deep reservoir. We tried to confirm the response curve of HDR-3 via HDR-1, but this curve was masked with tracer via HDR-2a and SKG-2.

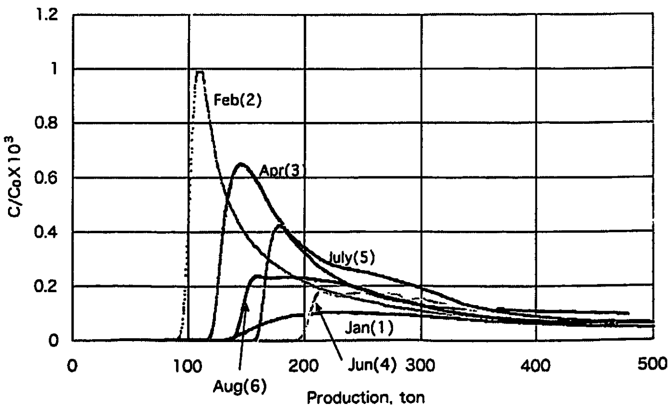

Figure 4. Comparison of tracer response curves in HDR-2a from SKG-2 during dual circulation test.

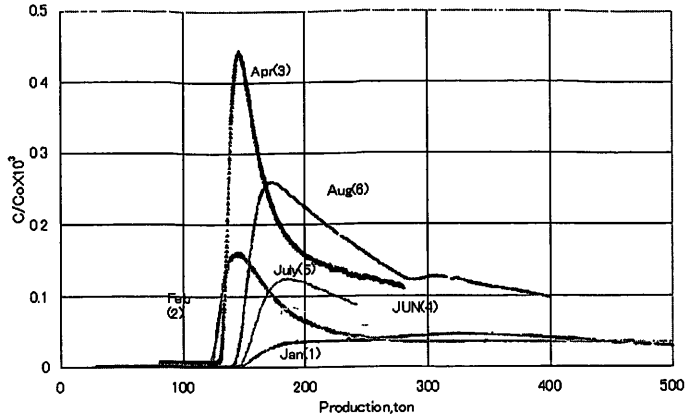

Figure 5. Comparison of tracer response curves in HDR-3 from SKG-2 during dual circulation test.

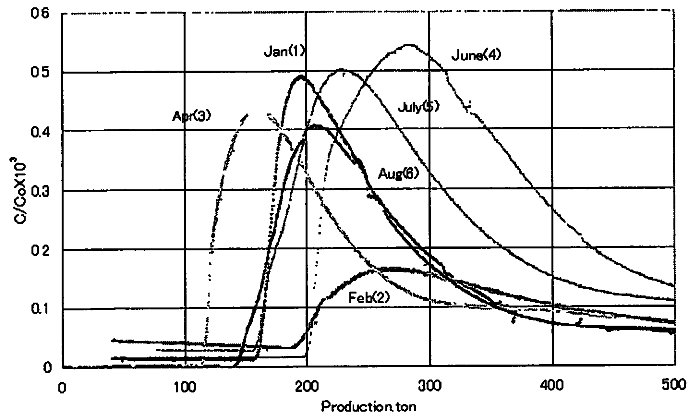

Figure 6. Comparison of tracer response curves in HDR-2a from HDR-1 during dual circulation test.

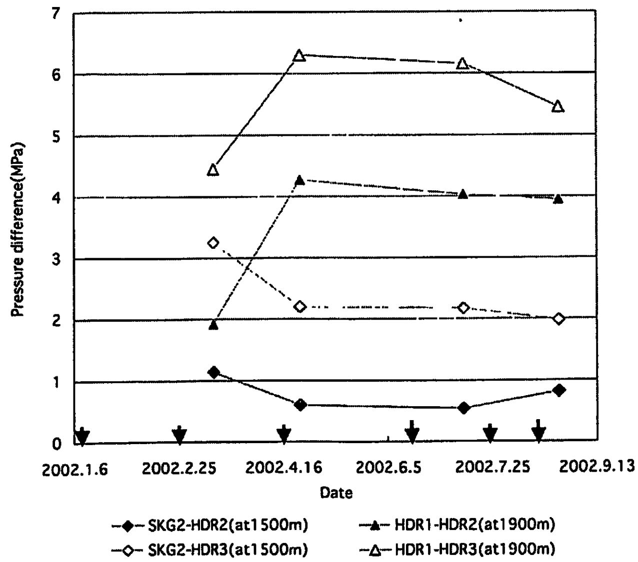

Figure 7. Pressure difference between injection and production well of shallow reservoir and deep reservoir. Closed diamond shows the difference pressure at depth 1,500m in shallow reservoir between HDR-2 and SKG-2. Open diamond shows that between HDR-3 and SKG-2. Closed diamond shows the difference pressure at depth 1,900m in deep reservoir between HDR-2 and HDR-1. Open diamond shows that between HDR-3 and HDR-1. The arrows show the date of tracer tests.

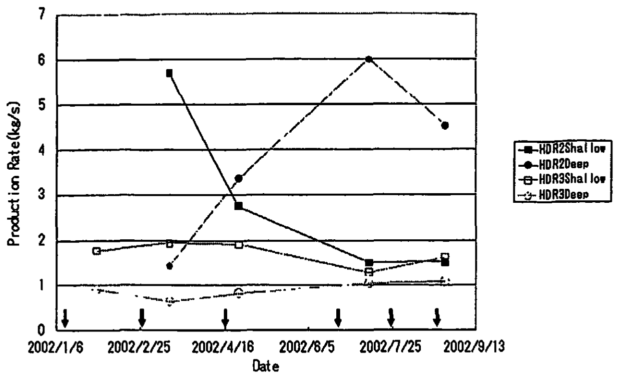

Figure 8. Production rates of the production wells, HDR-2a and HDR-3, from each reservoir. Closed square shows the shallow reservoir production of HDR-2a. Open square shows that of HDR-3. Closed circle shows the deep reservoir production of HDR-2a. Closed circle shows that of HDR-3. The arrows show the date of tracer tests.

Therefore we cannot separate the curve. From these figures, the change of tracer response of HDR-2a and HDR-3 were very complex because of the change of the injection water ratio and circulation interruption. But the change trend of the response curve of HDR-2a was same as that of HDR-3. This trend was in contrast to the deep reservoir and the response of HDR-2a was sharp, but that of HDR-3 became slower with progressing circulation (Matsunaga et al., 2002;Yanagisawa et al., 2002). We now discuss the change of tracer response in two stages, before and after change in the injection rate. Furthermore, we compare the tracer response with reservoir pressure and the production rate from each reservoir calculated from the PTS survey (NEDO, 2003). Figure 7 shows the pressure difference between production well and injection well for each reservoir. Figure 8 shows the production rate from each reservoir. In these figures, the arrows show the date of tracer tests.

Tracer Response When Injection Flow Ratio of SKG-2 and HDR-1 are Same

The tracer curves of HDR-2a and HDR-3 from SKG-2 of the first tracer test had a lower peak concentration and a larger mode

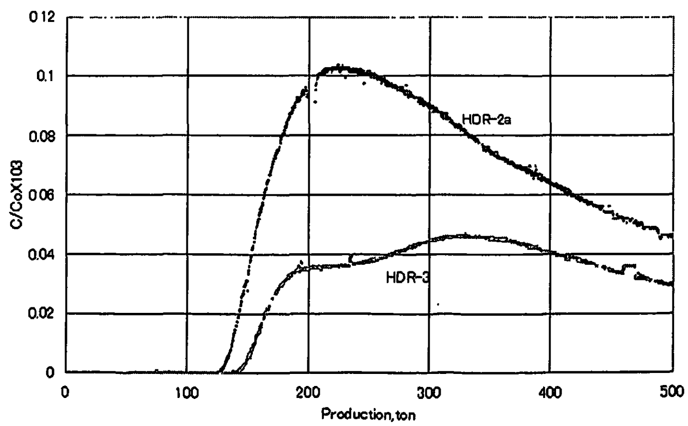

Figure 9. Tracer breakthrough curves of HDR-2a and HDR-3 from SKG-2 at the first test.

volume than those of the later tests. This fact suggests the shallow reservoir was large and wide spread because of the break of injection to the shallow reservoir from 1991. These tracer curves were enlarged in the Figure 9. The breakthrough volume of HDR-2a and HDR-3 are similar and the peak concentration of HDR-2a was about two times as that of HDR-3. The anisotropy of two wells of the shallow reservoir is less than that of the deep reservoir. Furthermore, two peaks existed in the response curve of HDR-3 suggests that multi-flow paths exist in HDR-3.

On the other hand, the tracer curve of HDR-2a from HDR-1 shows a similar curve as that of the 2001 test of a single injection to HDR-1, but the breakthrough volume is greater than double and the peak concentration is lower than that of the 2001 test. This suggests the mixing of non-tracer fluid from SKG-2 via the shallow reservoir to the fluid, including tracer from the deep reservoir.

We pumped tracer into SKG-2 and HDR-1 simultaneously after pumped into each reservoir. Before the test the tracer curve of the simultaneous test was estimated by adding that of SKG-2 to HDR-1. The result of measured value of the simultaneous test and estimated value are shown in Figure 10. From this figure, the measured value was almost same as the estimated value.

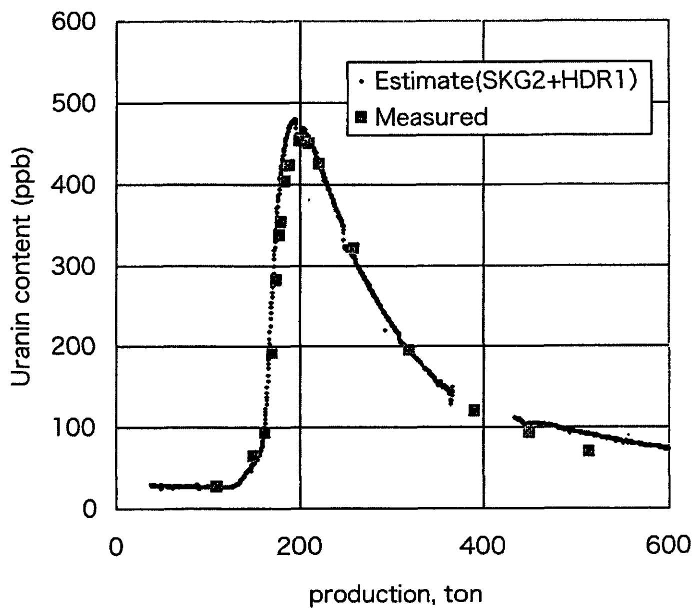

Figure 10. Measured value of simultaneous tracer injection test to HDR-1 and SKG-2 and estimated value from HDR-1 test and SKG-2 test.

This result suggests that the reservoir condition kept constant for several days.

On the second tracer test, the tracer response of HDR-2a and HDR-3 from SKG-2 became sharp from first test. This suggests that the volume of direct flow path became smaller by collecting flow path and production increasing. On the other hand, in the tracer curve of HDR-2a from HDR-1, the breakthrough volume became larger and peak concentration decreased more than that of HDR2 from SKG-2. That is reverse to the case via SKG-2. This phenomenon suggests that the fluid, including tracer from HDR-1, is diluted by non-tracer fluid from SKG-2 due to increasing production from SKG-2. The production rate from Figure 8 supports this phenomenon. Then, we pumped tracer into SKG-2 and HDR-1 simultaneously again and the tracer curve was corresponded to the total of each tracer test.

Tracer Response After the Injection Ratio of SKG-2 Was Decreased

The change of injection influenced the tracer response. In the third tracer test, the tracer response of HDR-2a from HDR-1 became sharper than that of the first test because of increasing production from deep reservoir shown in figure 8. On the other hand, the tracer response of HDR-2a from SKG-2 shows increasing volume and a decreasing peak concentration with decreasing of the production rate from the shallow reservoir. But, the tracer response of HDR-3 from SKG-2 shows an increasing peak concentration and the production rate did not change. Figure 7 shows the pressure difference between the injection well and the production well of the shallow reservoir decreasing and that of the deep reservoir increasing with injection rate change. This phenomenon suggests that the pressure sensitively changes with injection rate but that the change of production rate has a time lag between HDR-2a and HDR-3. Therefore, the change of tracer response corresponds with the production ratio.

After circulation interruption, the tracer response of the fourth tracer test shows an increasing breakthrough volume in every case. But the peak concentrations of both wells from SKG-2 decreased in spite of an increasing peak concentration from HDR-1. Figure 7 shows constant pressure during the same injection ratio. But figure 8 shows the change of the production rate during the same injection ratio. The production rate of HDR-2a and HDR-3 from the shallow reservoir decreased from third to the fourth tracer test and corresponds with the decreasing peak concentration. On the other hand, the reservoir volume of HDR-2a from SKG-2 increased with the production rate from deep reservoir.

After the fifth test, with the increasing production rate of HDR-3 from the shallow reservoir, the peak concentration of HDR-3 increased. The volume of the tracer curve of HDR-2a decreased with the production decreasing from the deep reservoir. In other words, the tracer response curve changed with the production rate. This rate change reflects the peak concentration of HDR-2a and HDR-3 from SKG-2. But in the case of HDR-2a from HDR-1, the change reflects the breakthrough volume.

Conclusion

A dual circulation test was carried out from 23 December 2001 to 31 August 2002 at the Hijiori test site. We have conducted a series of tracer tests for evaluating the flow regime in the reservoirs. The results are follows;

1) Tracer curves of HDR-2a and HDR3 from SKG-2 show smaller anisotropy than those from HDR-1. The change of tracer curves of HDR-2a and HDR-3 show similar response with injection condition change.

2) When the injection rates of SKG-2 and HDR-1 were both 8.33kg/s (injection ratio of SKG-2: HDR-1 = 1:1), tracer response of HDR-2a from SKG-2 became faster and sharp. This change was the reverse of the response from HDR-1 to HDR-2a. This suggests the change of the production ratio of the reservoirs. And when the tracer injection was implemented for two wells at same time, the tracer curve corresponded with the sum of each test.

3) After the injection rate of SKG-2 changed to 4.16kg/s from 8.33kg/s and that of HDR-1 change to 12.5kg/s from 8.33kg/s (injection ratio of SKG-2: HDR-1 changed to 1:3 from 1:1), tracer response curve changed with the production rate. This rate change reflects the peak concentration of HDR-2a and HDR-3 from SKG-2. But in the case of HDR-2a from HDR-1, this change reflects the breakthrough volume.

4) The flow regime in shallow reservoir shows different response from deep reservoir with the injection change.

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