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Tracer Tests for Evaluation of Flow in a Multi-Well and Dual Fracture System at the Hijiori HDR Test Site

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ABSTRACT

A long-term circulation test was conducted for around two years from 27 November 2000 at the hot dry rock (HDR) test site in Hijiori, Japan. During the test we carried out tracer tests every two or three months to monitor the flow regime in the reservoir. Tracer reagents including potassium salts, sodium fluorescein, and naphthalene sulfonates were injected into injection well HDR-1 in a single well injection stage and into HDR-1 and SKG-2 during a dual injection stage. Fluids from two production wells HDR-2a and HDR-3 were sampled and analyzed to obtain tracer response curves. A fiber-optic fluorimeter was installed in the sampling lines at surface to obtain real time data of fluorescein concentration. Comparison of the tracer response curves suggests that the flow regime in the reservoir was affected severely by pressure difference between injection and production wells.

1. INTRODUCTION

At the hot dry rock (HDR) test site in Hijiori, a long-term circulation test (LTCT) was conducted from 27 November 2000 to 31 August 2002. Purpose of LTCT was evaluation of heat extraction from a multiwell and multifracture reservoir and demonstration of the HDR system performance at Hijiori. During the test, the New Energy and Industrial Technology Development Organization (NEDO) carried out pressure-temperature-flow (PTS) logging, geochemical monitoring of circulation fluid, and microseismic monitoring to characterize the reservoir. Besides these logging and monitoring activities, since the tracer response in production fluid is important information to estimate the volume and then the lifetime of the HDR reservoir, we conducted tracer tests to determine the flow regime in the reservoir and its changes with circulation. Although results of these tests have been reported previously (Matsunaga et al., 2001, 2002; Yanagisawa et al., 2003), additional work was needed to obtain precise reservoir volume by subtracting wellbore volumes and the mixing effect between the two reservoirs at the dual injection stage. Calibrated tracer response curves were used to evaluate the flow regime during the dual injection stage of the LTCT.

2. LONG-TERM CIRCULATION TEST (LTCT)

An outline of the LTCT at Hijiori test site was described previously by Oikawa et al. (2001) and Kawasaki et al. (2002), hence we explain the circulation system and flow data briefly because these data are very important to evaluate the tracer tests.

A schematic view of the fluid circulation system at the Hijiori HDR site is shown in Figure 1. A multistage centrifugal pump of ESP TJ9000 was used to inject fluid at a flow rate of 16kg/s.

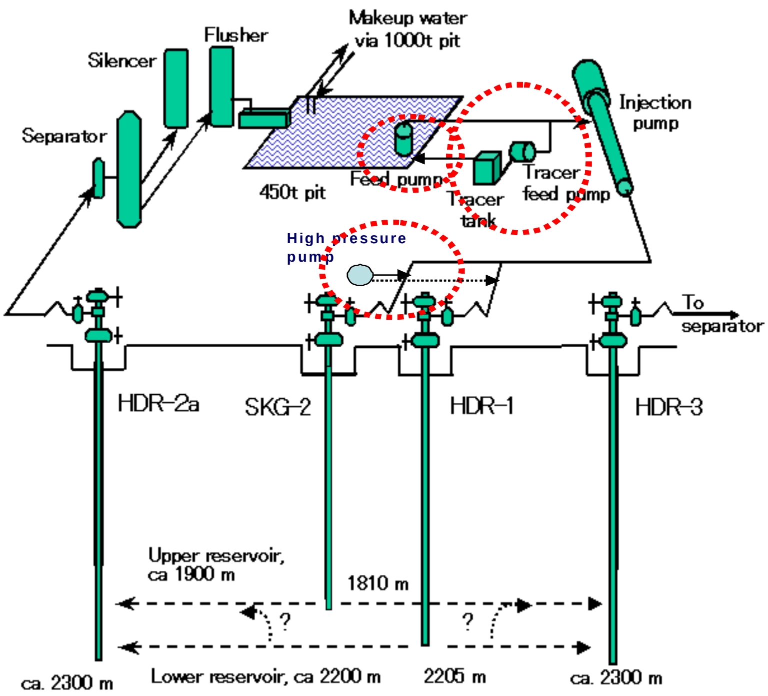

Figure 1: Schematic view of the HDR system at Hijiori. Red dotted circles indicate facilities for tracer injection.

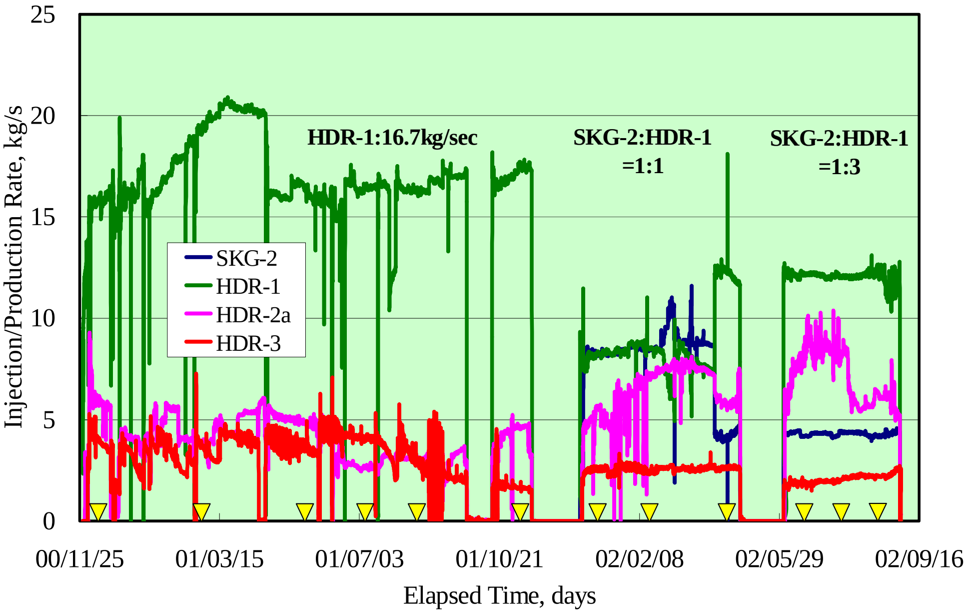

Figure 2: Injection and production flow rates during LTCT.

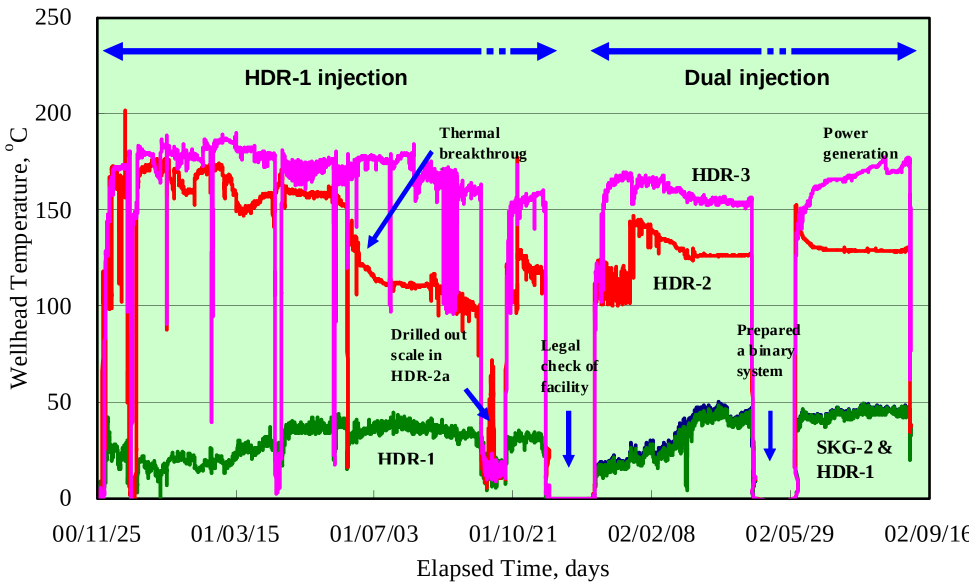

Figure 3: Injection and production temperature during LTCT

Flow rate measurements during the LTCT are shown in Figure 2. In the first stage of the LTCT from 27 November 2000 to 15 November 2001, fluid was injected to the lower reservoir through HDR-1. After setting up an injection line to SKG-2, the second stage of LTCT was started on 23 December 2001. During the second stage, fluid was injected into the upper reservoir through SKG-2 and the lower reservoir through HDR-1. Injection flow rate to both SKG-2 and HDR-1 was kept constant at around 8.3 kg/s at the beginning half of the dual injection. During the latter half of the dual injection, injection flow rate was decreased from 8.3 kg/s to 4.2 kg/s at SKG-2 and increased from 8.3 kg/s to 12.5 kg/s at HDR-1 to improve recovery rate. HDR-2a and HDR-3 were used as production wells during the LTCT.

3. TRACER TEST

During the LTCT, 12 tracer tests were conducted as listed in Table 1 and also indicated by triangles in Figure 2. Except for the last two tests, two or three kinds of tracer, including potassium salts (KI and KBr), Na fluorescein (Uranine), and two naphthalene sulfonates (Rose et al., 1999) were selected and used. During the single well injection stage, around 15 kg of potassium salts and 200 g of Uranine and a naphthalene sulfonate were dissolved in circulation fluid in a 1 m^3 tank. Then tracer solution was fed into the main suction line to the injection pump by a feed pump as shown in Figure 1. The flow rate of the feed pump was about 100 l/min. In the seventh tracer test, which was carried out in the second stage, we injected tracers individually to the high-pressure lines from the injection pump to SKG-2 or to HDR-1 in order to assess flow paths in the upper and lower reservoirs. Hence we used a small high-pressure pump to inject tracer fluid with a flow rate around 15 l/min. from a 200 l tank into the injection lines to SKG-2 or to HDR-1.

Table 1: Tracer tests during LTCT

Test	Injection Date	Injection Well	Tracers
1	2000/12/06	HDR-1	KI, KBr, Fl
2	2001/03/07	HDR-1	KBr, NS, Fl
	2001/03/08	HDR-1	KI, NS, Fl
3	2001/05/23	HDR-1	KBr, ANS, Fl
4	2001/06/28	HDR-1	ANS, Fl
5	2001/08/15	HDR-1	KI, ANS, Fl
6	2001/11/02	HDR-1	KBr, Fl
	2001/11/06	HDR-1	NS, Fl
7	2002/01/09	SKG-2	KBr, Fl
	2002/01/11	HDR-1	KI, ANS, Fl
	2002/01/13	SKG-2+HDR-1	KI, NS, Fl
8	2002/02/25	SKG-2	KI, Fl
	2002/02/27	HDR-1	ANS, Fl
	2002/03/01	SKG-2+HDR-1	Fl
9	2002/04/16	SKG-2	KI, NS, Fl
	2002/04/18	HDR-1	Fl
10	2002/06/16	SKG-2	KI, NS, Fl
	2002/06/18	HDR-1	ANS, Fl
11	2002/07/22	SKG-2	Fl
	2002/07/23	HDR-1	Fl
12	2002/08/17	SKG-2	Fl
	2002/08/20	HDR-1	Fl

NS: 1naphtaren disulfonated acid
ANS: 7amino 1,3 naphtarendisulfonate acid
Fl: Fluorescein Na (Uranine)

Produced fluids from HDR-2a and HDR-3 were collected using an automatic sampler at sampling lines from the weirs. Fluid samples were collected in a 250 ml bottle at each scheduled time. Electrical conductivity and pH of filtered samples were measured at the site. The fluorescence of production fluid was monitored continuously by a portable fluorimeter with a fiber optic sensor (Benischke and Leitner, 1992) at a flow-through cell in the sampling line (Matsunaga, et al., 2001). Tracer and major dissolved species were analyzed at the laboratory using ion chromatography, ICP-ES, and fluorospectrometry.

4. RESULT OF TRACER TESTS

Since tracer tests during the stage of single well injection to the deep reservoir were already reported (Matsunaga et al., 2002), tracer tests during the dual injection stage were evaluated.

Figures 4 and 5 show the normalized response curves in the shallow reservoir from SKG-2 to HDR-2a and to HDR-3, respectively.

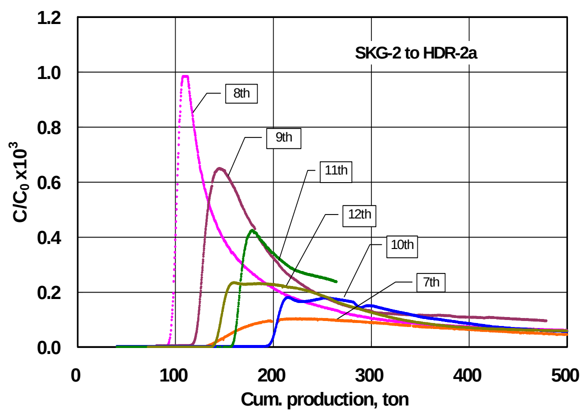

Figure 4: Tracer response curves from SKG-2 to HDR-2a during the dual injection stage of LTCT.

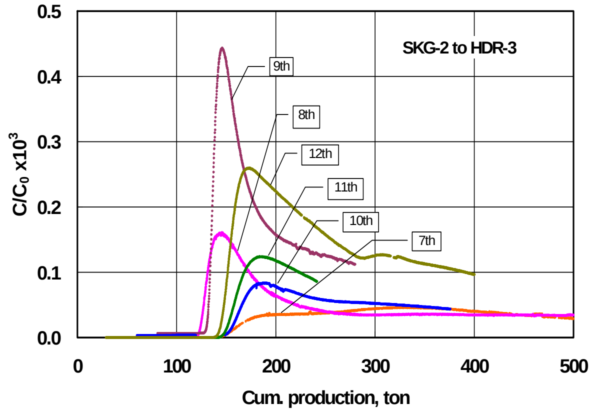

Figure 5: Tracer response curves from SKG-2 to HDR-3 during the dual injection stage of LTCT.

Tracer response was different in each test. In the first tracer test of the dual injection, weak responses were obtained in the shallow reservoir toward both sides of injection well SKG-2. As shown in Figure 6, no such response is recognized in the deep reservoir. Anhydrite coagulations periodically came out from HDR-2a during the seventh test. Recently Yanagisawa et al. (2004) concluded that anhydrite scale precipitated in the high temperature zones in HDR-2a and HDR-3 by reverse solubility with temperature. Anhydrite may have precipitated and tended to plug flow paths in the upper reservoir during the interruption of circulation between the single well injection stage and the dual injection stage.

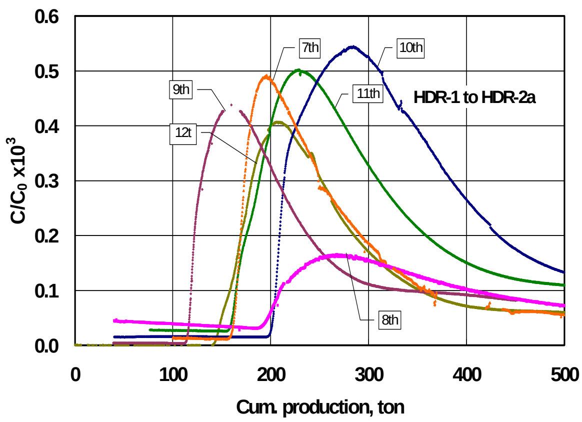

Figure 6: Tracer response curves from HDR-1 to HDR-2a during the dual injection stage of LTCT.

No remarkable tendency is observed by comparing the three figures. If we assume that the density of fluid is 1000 kg/m^3, breakthrough and modal volumes between HDR-1 and HDR-2a are estimated from the seventh test as 158 m^3 and 195 m^3, respectively. Since the wellbore volume of HDR-2a is roughly 79 m^3, an apparent volume of the main flow path from HDR-1 to HDR-2a can be estimated as 116 m^3.

However there was inlet flow from the shallow reservoir, so we need production data to obtain the true volume of the main flow. Since the tracer response was obtained at surface, calibration for wellbore volume, tracer dispersion in an injection well, and dilution in a production well are needed to obtain the precise response at each feed point in the reservoirs. Production flow rates from the shallow and deep reservoir are also required to calibrate dilution. The

PTS log was restricted by anhydrite scales in HDR-2a and no flow data in the deep reservoir were obtained. Hence the recovery flow rate estimated by numerical simulation (Tenma et al., 2004) was used for calibration. Calibrated curves in HDR-2a for the shallow and deep reservoirs are shown in Figures 7 and 8, respectively.

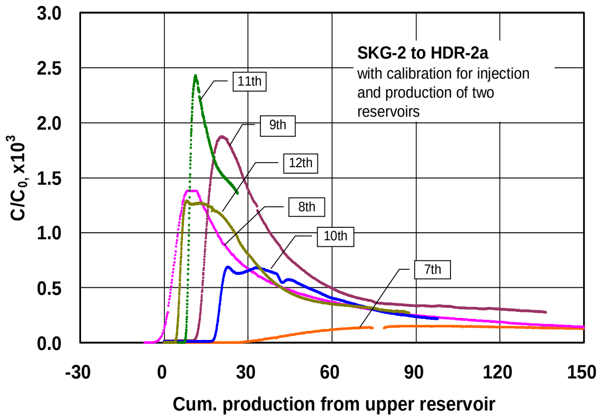

Figure 7: Calibrated response curves in the shallow reservoir during the dual injection stage.

In the shallow reservoir (from SKG-2 to HDR-2a), injected fluid tended to flow directly to HDR-2a after divergent flow stage in the seventh tracer test at the beginning of the dual injection. Higher return was obtained after decreasing flow rate after the eighth test. After interrupting injection to prepare for binary power generation, injection flow seemed to change slightly but not remarkably.

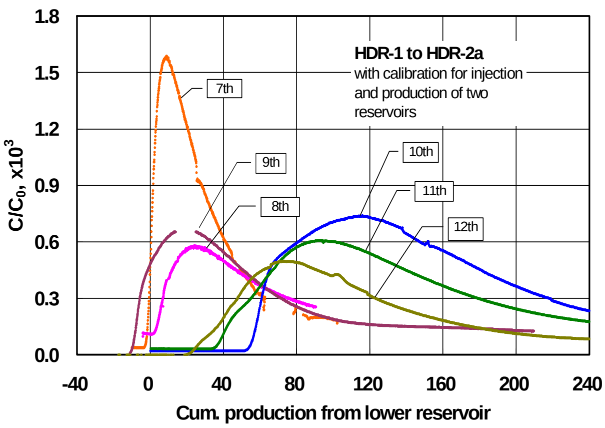

Figure 8: Calibrated response curves in the deep reservoir during the dual injection stage.

By comparing Figures 6 and 8, it is evident that tracer responses at the reservoir depth are remarkably different from those at surface. Decreases of peak concentration between the seventh and eighth tests were initiated by decreasing fluid recovery. Although the change of injection flow rate was associated with clear pressure change, as shown in Figure 9, no remarkable change was recognized in the tracer response. The interruption of pumping for the binary power generation made clear the increase of breakthrough volume in the deep reservoir. Then tracer tended to come out faster with progressing circulation. The shape of tracer curves of the 11th and 12th tests suggest that there are several flow paths with different contributions.

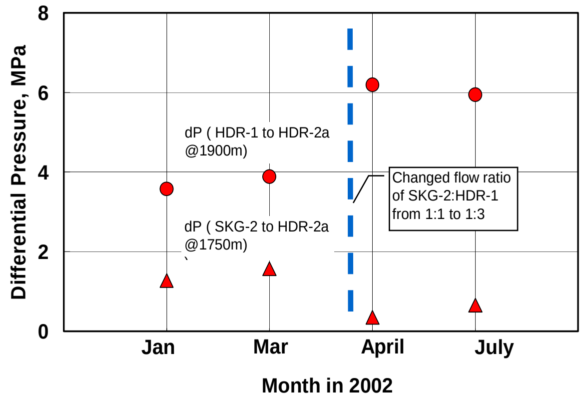

Figure 9: Differential pressures obtained from PTS logs.

5. SUMMARY

Twelve tracer tests were conducted during the LTCT at Hijiori. As we were restricted by a lack of flow data in the feed zones, tracer response curves were calibrated using recovery rates obtained from numerical simulation and used to evaluate the flow regime and its changes during the dual injection stage. Comparison of the tracer response curves suggests the complexity of the flow regime in the multiwell, multifracture system. Flow in the reservoir changed with the progress of the circulation. The flow regime in the reservoir was also affected by injection flow rates and temperature changes in the reservoir. Interruption of pumping for a certain duration affected the reservoir response remarkably.

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