Proceedings World Geothermal Congress 2005
Antalya, Turkey, 24-29 April 2005

Scale Precipitation During Circulation at the Hijiori HDR Test Field, Yamagata, Japan

Norio Yanagisawa 1, Isao Matsunaga 1, Hajime Sugita 1, Masatake Sato 2 and Takashi Okabe 2

1. National Institute of Advanced Industrial Science and Technology, 16-1 onogawa Tsukuba, 305-8569,Japan

2. Geothermal Energy Research and Development, Tokyo, Japan

n-yanagisawa@aist.go.jp

Keywords: Scale, calcite, anhydrite, amorphous silica, HDR

ABSTRACT

Several kinds of scale precipitated in the pipeline and production well during two years long circulation test in the HDR geothermal system of Hijiori, Yamagata, Japan.

The ratio of silica and calcium carbonate depends on fluid temperature and chemical composition. In the case of HDR-2 nearer to the injection well, wellhead temperature is about 120℃ after thermal breakthrough and the major scale is calcium carbonate, calcite and aragonite, changed from amorphous silica. And the lower reaches of the pipeline, calcite became dominant instead of aragonite.

In the case of HDR-3 further from the injection well, wellhead temperature is kept about 160℃ during the circulation test and amorphous silica scale precipitated slightly.

At the deep zone of the production well, anhydrite scale precipitated at the reverse temperature zone shown by PTS survey. Injection of cool water dissolved the anhydrite in the reservoir rock and anhydrite precipitated at the higher temperature zone because of the reverse solubility curve of anhydrite.

This anhydrite dissolve and precipitation influence scaling in the pipeline. In the pipeline of HDR-2, high content Ca reacted with CO2. High content Ca came from dissolved anhydrite in the reservoir and kept during the lower temperature of production well. However in HDR-3, further from the injection well and higher in temperature, slight amounts of amorphous silica precipitated. Ca content was too low for scaling and SiO2 was high enough to precipitate slightly.

1. INTRODUCTION

From November 2000 to August 2002, a long term circulation test (LTCT) was conducted at Hijiori Hot Dry Rock (HDR) test fields in Yamagata, Japan.

Figure 1 shows the location of test field. This site is near from Hijiori Spa and Nigamizu river. The river water was pumped up and used for injection water of HDR system.

As the LTCT of HDR system is the first in the world, several kinds of logging and tests were carried out. For example, Pressure, Temperature, Spinner (PTS) logging surveys, geochemical measurements, acoustic Emission (AE) and micro earthquake measurements and tracer tests. (Oikawa et al., 2001;Kawasaki et al., 2002; Matsunaga et al., 2002; Tenma et al., 2002;Yanagisawa et al., 2002)

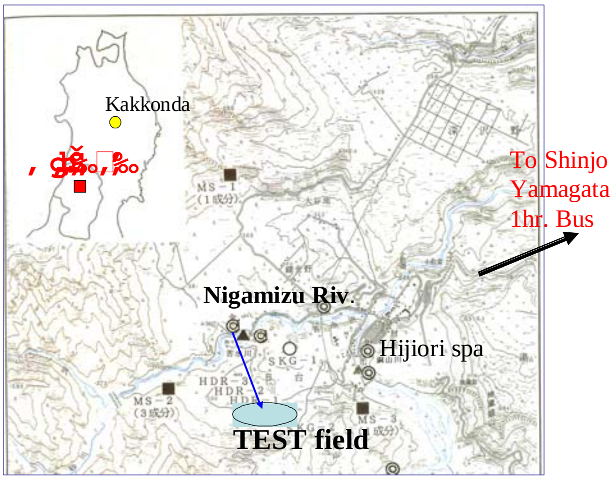


Figure 1: The location of Hijiori HDR test field in Japan

The purpose of the LTCT is the demonstration and evaluation of heat extraction with a multi-fracture reservoir with multiple wells and was performed by NEDO. The LTCT was separated into 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. The second stage of the LTCT began on 23 December 2001 and ended on 31 August 2002. During this 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 and several kinds of surveys, including a tracer test, were carried out (Yanagisawa et al. 2003)

Before the LTCT, several short circulation tests had been carried out. In 1991, for determining the fluid flow of the shallow reservoir (depth of 1,800m and temperature up to 250℃), a three-month circulation test was carried out. After development of a deep reservoir (depth of 2,200m and temperatures up to 270℃), short-term (one-month) circulation tests and a reservoir survey were carried out on the deep reservoir in 1995 and 1996. (Hyodo et al., 1996; Matsunaga and Tao, 1998; Miyairi and Sorimachi, 1996; Tenma et al. 1996, 1999)

During short circulation tests, scale precipitation on pipelines was not a problem because the fluid volume was smaller and silica content was lower than usual in a geothermal field. In the case of a usual deep geothermal field, production fluid is high in silica composition because of high temperatures of the reservoir and long times for water-rock interaction. As the temperature and time of this HDR are smaller than the usual geothermal field, the problem of scaling in HDR was not thought to be serious even for the LTCT.

However, after the LTCT, scaling on pipelines and in the production well was recognized and influenced the PTS survey and production.

This paper shows the results of mineral and chemical analysis of the scale in the pipeline and production well during the LTCT and discusses the mechanism of scaling in the HDR system.

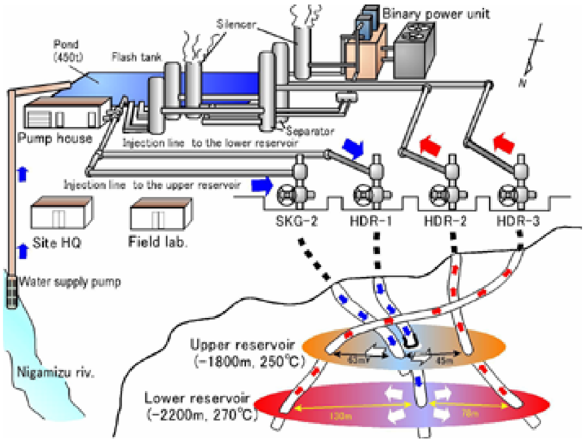


Figure 2: Schematic diagram of a circulation system at the Hijiori test site

2. LONG TERM CIRCULATION TEST

The fluid circulation system at the Hijiori HDR site is schematically shown in Figure 2. A multi-stage centrifugal pump (ESP TJ9000) was used to inject the fluid at a constant flow rate of 16.66 kg/s.

In the first stage of the LTCT, this fluid was directly injected into HDR-1. In the second stage, the injection fluid was separated into two lines after being pressurized by the pump. One was connected HDR-1, which was used as an injection well for the deep reservoir, and the other to SKG-2. 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 for the power generation test. From 1 June to 31 August, the water injection ratio of HDR-1 to SKG-2 was kept 3:1.

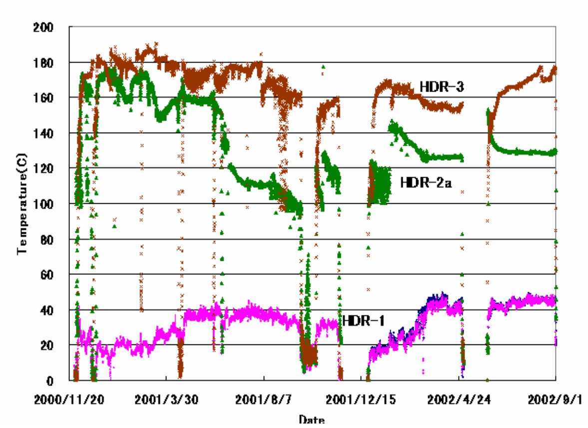
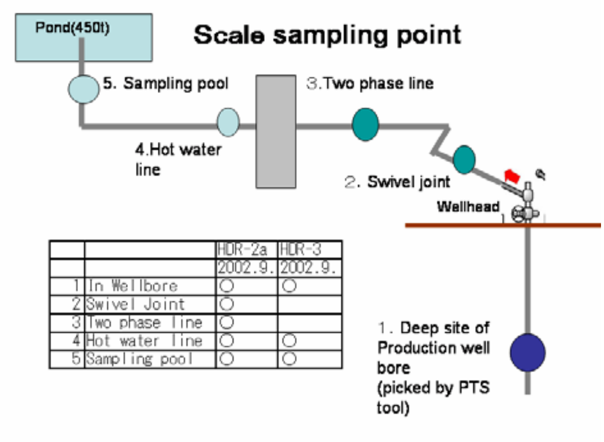


Figure 3: Temperature of production (HDR-2a and HDR-3) during Long time Circulation test.

The change of temperatures of production in the LTCT is shown in Figure 3. On June 2001, temperature of HDR-2 rapidly decreased because of thermal breakthrough (Kawasaki aet al., 2002, Yanagisawa et al.,2002).

3. SCALE SAMPLING AND ANALYSIS

Scale sampling points are shown in figure 4. Scale in the production well was collected by PTS survey tools and scales in the pipeline were collected after the circulation test on September 2002. But scales at the sampling pool shown in figure 5 after the hot water line were collected several times during the LTCT.



		HDR-2a	HDR-3
		2002.9.	2002.9.
1	In Wellbore	○	○
2	Swivel Joint	○	
3	Two phase line	○	
4	Hot water line	○	○
5	Sampling pool	○	○

Figure 4: Scale sampling point in production well and pipeline of HDR-2a and HDR-3

Figure 5: The photo of the sampling pool after the pipeline

The bulk sample was powdered for X-ray diffraction and chemical analysis. The methods of the chemical analysis are as follows:

1) Major metal elements were analyzed by Inductively Coupled Plasma Emission Spectrometry (ICP-ES) method.

2) Na, K in the solution made by above method was analyzed by an ion chromatography.

3) S and C were analyzed by High-frequency burning infrared absorption method.

And the electrical conductivity and pH of the fluid were determined on site. Major dissolved species were analyzed using ion chromatography (Cl^-,SO_4^{2-},Na^+,K^+,Ca^{2+}), the titration with H_2SO_4 (HCO_3^-) .

4. RESULTS

4.1 Change of scale with sampling site

Figure 6 shows several photos of the pipeline on September 2002 after the LTCT. The photos arranged from left to right are at the swivel joint, the two phase line and the hot water line. Scales at HDR-2 are white and thick. But scales at HDR-3 are black and thin.

These pipelines were cleaned on May 2002 for preparation of power generation test and these scales precipitated during the three month power generation test. The thickness of scale at HDR-2 was about 40mm after 3 months and the precipitation rate is 13mm/month.

On the other hand, scales in the production well picked up by the PTS tool are a white to slightly grey powder.

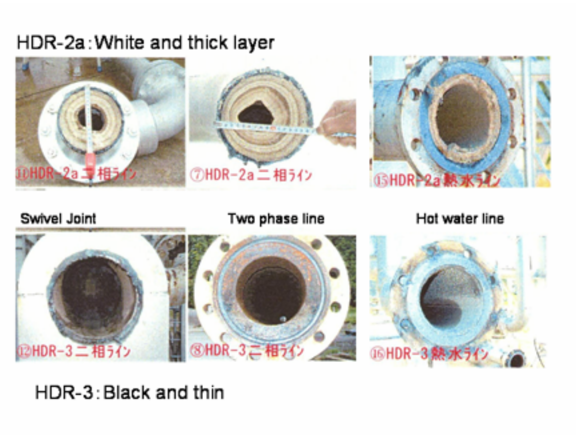


Figure 6: The photo of cross section of pipeline at swivel joint, two phase line and hot water line in HDR-2 and HDR-3

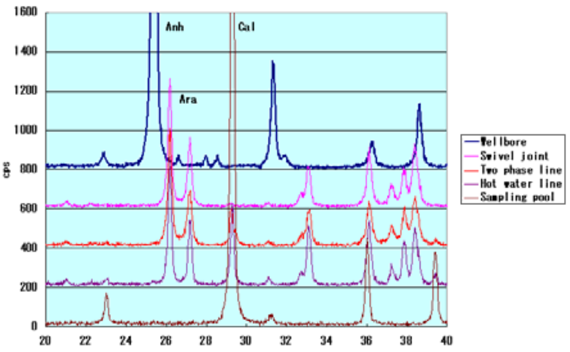


Figure 7: X-ray diffraction pattern of scale sample at several points in HDR-2 on September 2002

	SiO_2	Al_2O_3	FeO	CaO	SO_4	CO_2
Wellbore	1.5	0.4	0.2	40.6	53.8	4.0
Swivel Joint	0.18	0.08	0.33	54.94	1.25	42.30
Two phase line	0.18	0.07	0.16	55.25	1.38	42.50
Hot water line	1.29	0.29	0.33	52.99	2.75	40.30
Sampling pool	3.5	0.2	0.8	51.2	3.7	38.6

Table 1:Chemical composition of scale sample at several points in HDR-2 on September 2002

Figure 7 shows the chart of X-ray powder diffraction of samples from the deep site in the production well, the swivel joint near wellhead, the two phase line, the hot water line and the fluid sampling pool on September 2002 at HDR-2. This figure shows the strong anhydrite peak from the production well sample. But anhydrite disappeared after the swivel joint. Instead of anhydrite, calcium carbonate minerals appeared. Near the swivel joint, aragonite, a calcium carbonate mineral, was the major part of the scale. At lower reaches of the pipeline, calcite became dominant instead of aragonite. At the fluid sampling pool, most of the scale is calcite with small part amorphous silica. Table 1 shows the results of chemical analysis. The main composition is calcium and carbonate with slight silica.

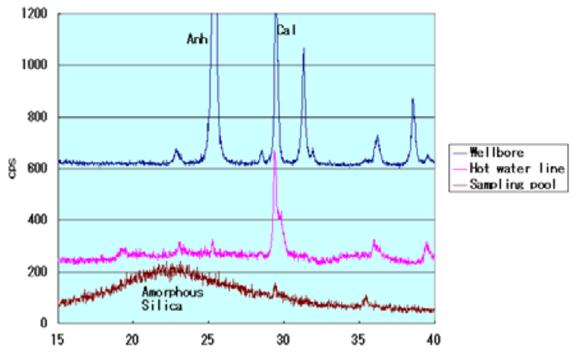


Figure 8: X-ray diffraction pattern of scale sample at several points in HDR-3 on September 2002

	SiO_2	Al_2O_3	FeO	CaO	SO_3	CO_2
Wellbore	2.0	0.7	1.0	42.5	30.9	17.8
Hot water line	39.6	6.8	4.5	13.6	1.7	7.8
Sampling pool	74.7	2.9	5.6	1.4	0.2	1.8

Table 2: Chemical composition of scale sample at several points in HDR-3 on September 2002

Figure 8 and Table 2 show the chart of X-ray powder diffraction and chemical composition of samples from the deep site in production well, water flow line and fluid sampling pool on September 2002 at HDR-3. At the swivel joint near wellhead and the two-phase flow line, samples cannot be collected because the scale is very thin. This figure shows the strong anhydrite and calcite peak of scale from the production well. But anhydrite disappeared at the hot water line, where calcite and amorphous silica were the major part of scale. This scale contained about 40% more silica than that of HDR-2. At the fluid sampling pool, most of the scale is amorphous silica with a small amount of calcite.

4.2 Change of scale with circulation progressing

Figure 9 shows the change of the X-ray powder diffraction of scale samples with circulation progress at the fluid sampling pool of HDR-2. These scales were collected May 2001 and October 2001 during the single well injection test and February 2002 and August 2002 during the dual injection test. Table 3 shows the chemical composition of these samples. The first two samples contain amorphous silica and calcite. During the single injection test, silica content decreased and calcium increased. The last two samples contain mainly calcium carbonate. Samples collected in February contain calcite and aragonite but those from August contain mostly calcite.

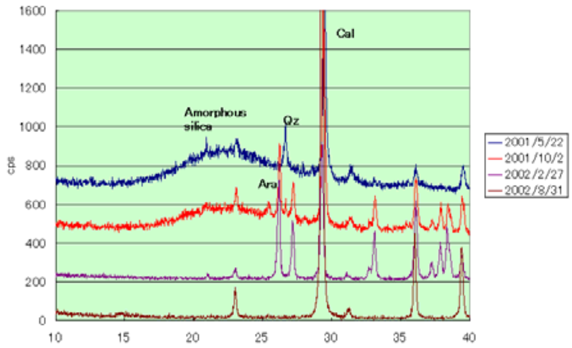


Figure 9: Change of X-ray diffraction pattern of scale sample at fluid sampling pool in HDR-2 at several times during Long time Circulation test

	SiO_2	Al_2O_3	FeO	CaO	SO_4	CO_2
2001/5/22	68.2	1.9	3.2	10.4	1.6	9.1
2001/10/2	47.1	1.6	2.5	22.4	2.6	17.7
2002/2/27	0.8	0.2	0.0	53.8	2.1	42.1
2002/8/31	3.5	0.2	0.8	51.2	3.7	38.6

Table 3: Chemical composition of scale sample at fluid sampling pool in HDR-2 at several times during Long time Circulation test

Figure 10 shows the change in the X-ray powder diffraction of scale with the time at the fluid sampling pool of HDR-3. These scales were collected at the same time as HDR-2. Table 4 shows the chemical composition of these samples. All samples contain mainly amorphous silica with a small percentage of iron.

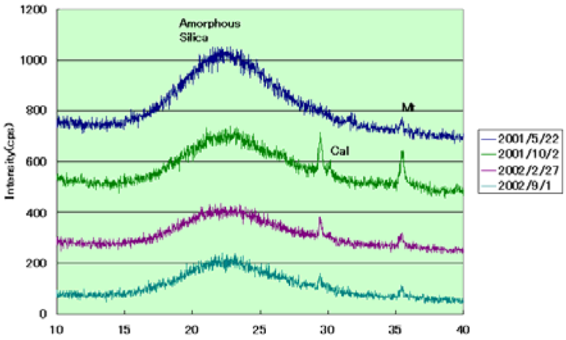


Figure 10: Change of X-ray diffraction pattern of scale sample at fluid sampling pool in HDR-3 at several times during Long time Circulation test

	SiO_2	Al_2O_3	FeO	CaO	SO_4	CO_2
2001/5/22	84.7	1.3	2.0	0.6	0.0	0.6
2001/10/2	74.7	1.5	4.8	1.5	0.3	2.3
2002/2/27	78.5	2.4	1.4	1.4	0.2	1.6
2002/9/1	74.7	2.9	5.6	1.4	0.2	1.8

Table 4: Chemical composition of scale sample at fluid sampling pool in HDR-3 at several times during Long time Circulation test

5. DISCUSSION

The scales precipitated at the deep site in the production well consisted mainly of anhydrite. Because the solubility of anhydrite decreases with higher temperature the reverse of usual scale compositions such as silica, anhydrite precipitates at higher temperature zones in the flow path. In the case of HDR, injection water is about 70C when the water reached the reservoir. At the injection point, water dissolves anhydrite veins in the granite rock of the reservoir.

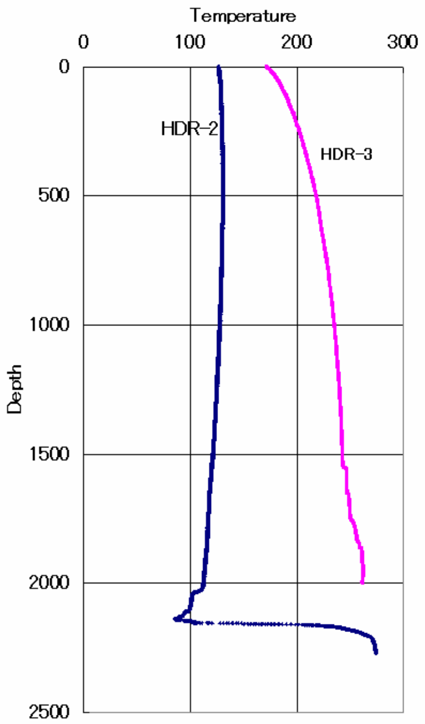


Figure 11: Temperature depth profile of HDR-2 and HDR-3 obtained by PTS survey.

Dissolved anhydrite was transported with fluid flow in the reservoir to the production well and the water was heated by granite rock around the reservoir, and the heated fluid became supersaturated with anhydrite. As shown in the temperature curve in figure 11, a temperature high exists at 500m depth, and a step change is seen at 2,000m. Anhydrite precipitated around this temperature high and step change zone and was picked from there by the PTS logging tool. The HDR-3 temperature is higher than HDR-2 and gradually increases with depth until 1,950m where there is a slight decrease at the deeper zone. The PTS logging tool did not go down beyond 2,000m depth due to anhydrite scale at the high temperature zone. Anhydrite scaling at high temperature zones in production wells is found in other geothermal fields, for example, at Sumikawa geothermal field (Kato et al., 2002).

The temperature in the production well and wellhead reflects the scale species in the pipeline. In HDR-2, the lower temperature well, calcium carbonate is the major scale component. Ca and SO4 content of the HDR-2 fluid were higher than HDR-3 due to higher anhydrite solubility at lower temperature. The high content of Ca reacted with CO2 on ground to deposit calcium carbonate. On the other hand, in HDR-3, the higher temperature well, there was slight amorphous silica deposition. The Ca and SO4 content of HDR-3 were too small for precipitation of calcium carbonate. The SiO2 content was higher than HDR-2 but lower than other geothermal fields and silica precipitated slightly.

With circulation progress, scale species changed from amorphous silica to calcium carbonate at HDR-2. This change was related with the temperature decreasing and Ca and SO4 increasing as shown in figure 12. At HDR-2, thermal breakthrough occurred on June 2001 and temperature decreased as shown in figure 2, fluid composition changed and tracer response changed to quick and sharp (Yanagisawa et al., 2002) as shown in Figure 13. The scale change corresponds with decreasing temperature.

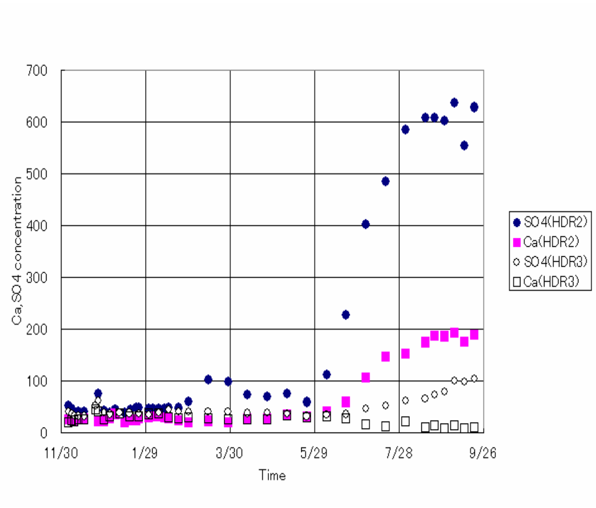


Figure 12: Change of Ca and SO4 concentration of HDR-2 and HDR-3 during LTCT

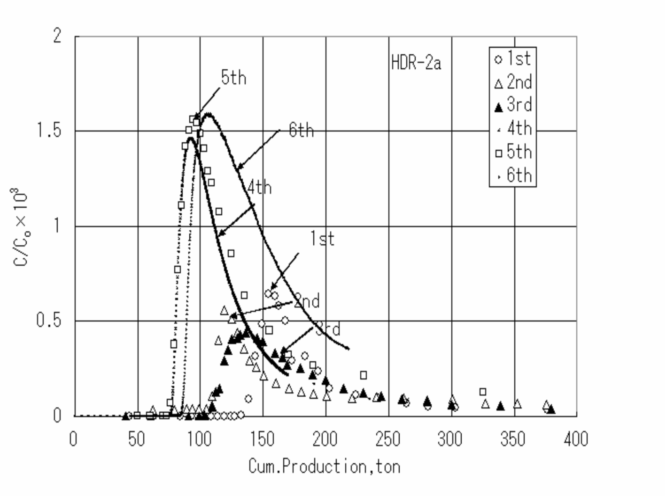


Figure 13: Comparison of tracer response curves in HDR-2 in 2001. The third test was carried out in May 2001 before thermal breakthrough and fourth test after thermal breakthrough.

In the case of HDR-3 production well, anhydrite scale precipitate at the feed point. But the temperature is higher than 200℃ and anhydrite seem to precipitate in reservoir with temperature increasing in flow path and cause to sealing the flow path. In order to reach production well, injection water round other path. Then, as shown in figure 14, the tracer response became later with circulation.

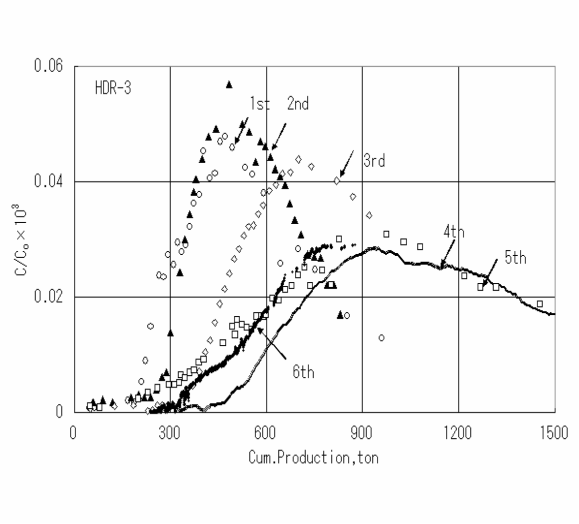


Figure 14: Comparison of tracer response curves in HDR-3in 2001. Tracer response became later with circulation progress.

6. CONCLUSION

Several kinds of scale precipitated in the pipeline and production well during two long term circulation test in the Hijiori HDR geothermal system.

(1) At the deep zone of the production well, anhydrite scale precipitated at the reverse temperature zone shown by PTS survey. Injection of cool water dissolved the anhydrite in the reservoir rock and anhydrite precipitated at the higher temperature zone because of the reverse solubility curve of anhydrite.

(2) At HDR-2, closer to the injection well and lower in temperature, calcium carbonate scales such as calcite and aragonite precipitated at a 13mm/month rate. In the pipeline, high content Ca reacted with CO2. High content Ca came from dissolved anhydrite in the reservoir and kept during the lower temperature of production well.

(3) At HDR-3, further from the injection well and higher in temperature, slight amounts of amorphous silica precipitated. Ca content was too low for scaling and SiO2 was high enough to precipitate slightly.

(4) With circulation progress, scale species changed from amorphous silica to calcium carbonate at HDR-2 with the temperature decreasing.

ACKNOWLEDGEMENTS

The research described in this paper has been supported by the Ministry of Economy, Trade and Industry. The authors would like to thanks NEDO and its contract companies, GERD, Mitsui M&S Co., JAPEX, and CRIEPI for helping our tests and providing sample and data.

REFERENCES

Kato, H., Kamei, J. and Kitao, K.:Fluid Flow-Precipitation Model of Anhydrite Scale in Wellbore-Case Study of the Sumikawa Production Well,SC-1. *Journal of the geothermal research society of Japan*, **22**, (2000) 171-185 (In Japanese with English abstract).

Kawasaki, K, Oikawa, Y., Sato, Y., Tenma, N., and Tosha T.:Heat Extraction Experiment at Hijiori Test Site (First Year). *Proceedings*,27th Stanford Workshop on Geothermal Reservoir Engineering,(2002) 89-94.

Hyodo, M., Shinohara, N., Takasugi, S., Write, R.A., and Conant, R.A.: HDR System Hydraulics Model and Analysis of the 1995 Preliminary Circulation Test at the Hijiori HDR Site of the NEDO Project, Japan. *Proceedings*,3rd International HDR Forum, (1996) 23-24.

Matsunaga, I., Tao, H and Kimura A.: Preliminary Characterization of the Hijiori HDR Deeper System by Fluid Geochemistry and Tracer Experiments of a One-Month Circulation Test, *Proceedings*,3rd International HDR Forum,(1996),25-26.

Matsunaga I. and Tao, H., 1998. "Geochemical Evaluation of a 1996 Circulation Test in the Hijiori HDR Reservoir. *Proceedings*, 4th International HDR Forum, (1998), 28-30.

Matsunaga, I., Yanagisawa, N., Sugita. H., and Tao, H., : Reservoir Monitoring by a Tracer testing During a Long-Term Circulation Test at the Hijiori HDR Site. *Proceedings* 27th Stanford Workshop on Geothermal Reservoir Engineering,(2002),101-104.

Miyairi M. and Sorimachi, M., : Characterization of Effective Fractures by Downhole Measurements at Hijiori HDR Test Site. *Proceedings*, 3rd International HDR Forum, Santa (1996)

NEDO :Summary of Hot Dry Rock Geothermal Power Project, FY2002 (2003).

Oikawa, Y., Tenma, N., Yamaguchi, T., Karasawa, H., Egawa, Y. and Yamauchi, T.: Heat Extraction Experiment at Hijiori Test Site. *Proceedings,* 26th Stanford Workshop on Geothermal Reservoir Engineering, (2001), 255-258.

Tenma N. Yamaguchi, T., Matsunaga, I., Kuriyagawa, M. and Sato, Y.: Interference of Production between Two Wells during a One Month Circulation Test at the Hijiori Hot Dry Rock Test Site. *Proceedings*, 2lst Stanford Workshop on Geothermal Reservoir Engineering, (1996), 295-298.

Tenma, N., Yamaguchi, T., and Karasawa, H. : A Study of the Pressure-Flow Response of the Shallow Reservoir at the Hijiori HDR Test Site., *Proceedings*, 24th Stanford Workshop on Geothermal Reservoir Engineering, (1999), 340-343.

Tenma, N., Yamaguchi, T., Tezuka, K., Kawasaki, K. and G. Zyvolosky.: Productivity Change in the Multi-Reservoir System at the Hijiori HDR Test Site during the long-Term Circulation Test, *Geothermal Resources Council Transactions*, **26**,(2002),261-266

Yanagisawa, N., Matsunaga, I., Sugita, H. and Tao, H.:Reservoir Monitoring by Tracer Test of a 2001 Long Term Circulation Test at the Hijiori HDR site, Yamagata, Japan, *Geothermal Resources Council Transactions*, **26**,(2002), 267-271

Yanagisawa, N., Matsunaga, I., Sugita, H. and Tao, H.: Reservoir Monitoring by Tracer Test of a 2002 Dual Circulation Test at the Hijiori HDR site, Yamagata, Japan, *Geothermal Resources Council Transactions*, **27**, (2003),785-790