PROCEEDINGS, 24th Annual PNOC-EDC Geothermal Conference
Hotel Inter-Continental, Makati City, Philippines, March 12-13, 2003

DEVELOPMENT OF A HOT DRY ROCK POWER GENERATION SYSTEM AT HIJIORI TEST SITE

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ABSTRACT

In a hot dry rock geothermal power generation system, two or more wells are drilled into hot dry rock located underground and an artificial fracture is formed by injecting high-pressure water through one of the wells. After the wells become connected by the artificial fracture, the injected water passes through the fracture and is recovered at ground level in the form of steam or hot water, which can then be used for power generation.

In 1985, NEDO started R&D of hot dry rock at Hijiori, Yamagata Prefecture. By 1994, two artificial reservoirs were formed by hydraulic fracturing at an each depth of about 1,800m and 2,200 m. The long-term circulation experiment was conducted for one year and seven months (from December 2000 to August 2002) to confirm the feasibility of hot dry rock power generation. For the first year, "Deep Circulation" was operated to evaluate the long-term performance of the lower reservoir. For the last seven months, "Dual Circulation" was operated to confirm the interaction and to evaluate the performance of injecting into both reservoirs. For the last three months of the Dual Circulation, "Generator Test" was also implemented to demonstrate the performance of reservoirs using a binary power unit (130KW). These circulations were successfully achieved over a period of approximately 550 days whereby valuable data was obtained towards the practical use of a Hot Dry Rock Power Generation System.

1.0 INTRODUCTION

Hot Dry Rock (HDR) is a generic team used to refer to the rock of which the temperature is higher (for example, over 250°C) but natural geothermal reservoirs are not much formed. It was gathered that HDR would exist abundantly in Japan, but HDR is not utilized as the energy at present. If an HDR power generation system was put to practical use, geothermal electrical capacities will be increased dramatically all over the world.

Utilization of HDR was invented in early 1970s by Los Alamos National Laboratory (U.S.A.). In 1975, HDR R&D was stared at Fenton hill, New Mexico U.S.A. In 1979, it was continued as the tripartite collaborative research in International Energy Association (IEA). NEDO Japan joined there with KFA Germany.

In 1985, NEDO started HDR R&D for the domestic development at Hijiori site (Yamagata Prefecture) after obtaining the outcomes at Fenton Hill. In November 2000, the final experiment, "The long-term circulation test" was started, and in August 2002, was finished. In March 2003, the project will be completely finalized. In this paper, the outline of results in Hijiori Project is compiled.

2.0 HDR POWER GENERATION SYSTEM

2.1 Basic Concept

The concept of HDR system is shown in Figure 1. The artificial reservoir is created in hot dry rock through the well using hydraulic fracturing technology, which is derived from petroleum engineering. The heat is extracted from the reservoir as a heat exchanger.

In an HDR system, an artificial reservoir and an injection pump should be added to the conventional geothermal facilities. However an HDR system is superior to it because:

- The miss of drilling is decreased more as the target is larger.
- The production rate can be controlled by adjustment of the injection rate.
- It has less effect on the environment (the closed cycle).

2.2 Creation of the Artificial Reservoir

An HDR generation system is produced roughly by four steps.

(i) The first well is drilled toward the target of hot dry rock.

(ii) Hydraulic fracturing is conducted by pressuring volumes of water through the drilled well. In fracturing, Acoustic Emission (AE) is surveyed in order to interpret the 3D location of the reservoir. The artificial reservoir is formed.

(iii) Second well is drilled based on the location of reservoir estimated by AE in order to form the rope connection between the surface and artificial reservoir.

(iv) The surface facilities (an injection pump, a generator and so on) are created.

After creating, the water is injected to the artificial reservoir through one well, and is heated in the reservoir. The hot water and the steam are produced through another well. In the design of an HDR system, it is most important to create a highly-efficient reservoir.

2.3 Hjiori System

The concept of Hijiori model is shown in Figure 2. The system consists of four wells and two-tier artificial reservoirs. Hijiori model had been improved since 1980 according to the underground condition to increase the production. At the present, it was said that this is the most advanced system in the world.

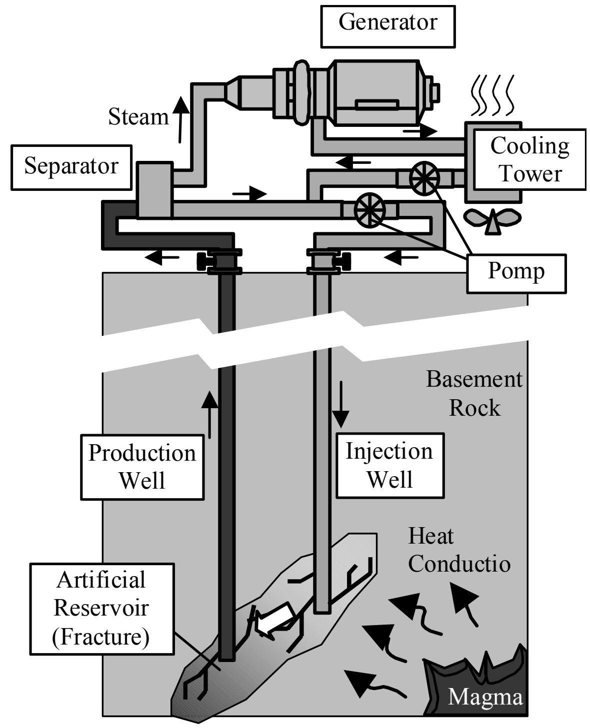

Figure 1. The general concept of HDR system.

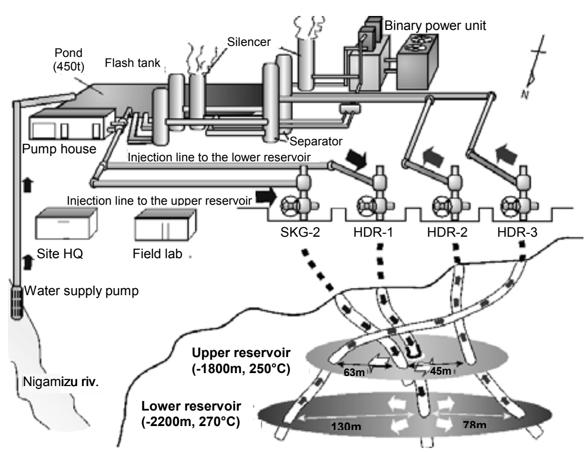

Figure 2. The concept of Hijiori model.

At Hijiori site, the water is collected from the river to the 450-ton pit. The water pressurized by the injection pump is delivered respectively to HDR-1 or SKG-2. The water in HDR-1 is passed through only the lower reservoir because of sealing the upper reservoir with casing and cementing. The heated water in each reservoir is derived to HDR-2 or HDR-3. The heated fluid is produced to the surface through both production wells. The fluid is separated between the hot water and the steam in the separator. The flow rate, temperature and pressure of each well are measured. The hot water is recovered to the pit and reused as the injection water mixed with the river water.

3.0 HISTORY OF PROJECT

3.1 Overview

Hijiori Project was started in 1980 at Hijiori site in Yamagata prefecture by NEDO. The test site is located in a small caldera with a diameter of about 2km (Figure 3). Hijiori spa town is located 1km from the test site. There were two reasons in choosing Hijiori as the test site. One was to confirm that HDR existed under a depth of 1,500m by exploratory wells to survey the conventional geothermal resources before the project. Another was to be possibly divert two exploratory wells (SKG-1 and SKG-2) for the project conveniently.

The most important object of this project is to reveal the feasibility of the practical application of the HDR power generation system improving some technologies, for example, “Drilling”, ”AE survey”, ”logging survey”. The goal of this project is to demonstrate that it is practically possible to create the artificial reservoirs in the domestic underground, and how much the performance of the reservoirs is.

Most time of the project duration was spent to form the circulation system of the underground. This project consists of two phases. In Phase 1, the upper reservoir was formed at a depth of 1,800 m drilling HDR-1 HDR-2 HDR-3 from 1980 to 1991. In Phase 2, the lower reservoir had been formed at a depth of 2,200m deepening their wells since 1992. The present system was achieved in 2000, and it was confirmed that it was possible technically to create the HDR system with dual reservoirs in the domestic field. At the last two years (2000-2002) of Hijiori Project, the long-term circulation test was conducted to evaluate the performance of it. This test was finished on 31 August 2002. In March 2003, Hijiori Project will be completed analyzing observed data.

3.2 Phase 1 (1980-1991)

The goal of the Phase 1 was to create the HDR system in the domestic underground. In Fenton

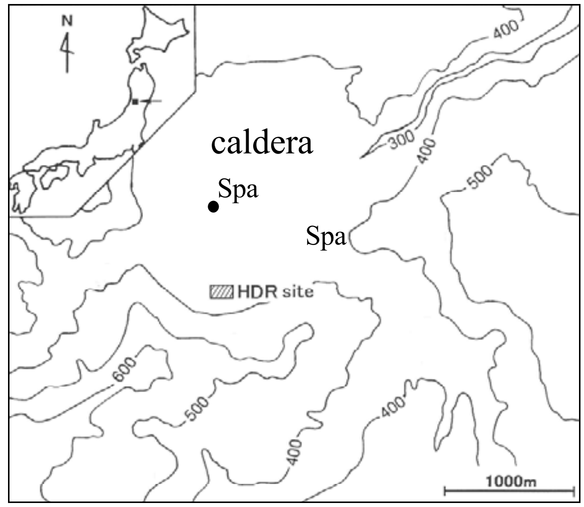

Figure 3. The location of Hijiori site.

Hill Project, the difficulty of connection between production well and injection well was already recognized because the hydraulic fracturing was conducted after drilling both wells. Therefore, in Hijiori Project, at first, the large hydraulic fracturing was implemented through SKG-2 at a depth of 1,800 m. After the artificial reservoir was formed, the second well (HDR-1) was drilled at the appropriate location, which was estimated by AE distribution. However, the recovery was only 40% and less than expected. In 1987 and 1988, two additional production wells (HDR-2, HDR-3) were drilled toward the east-west reservoir (Figure 2). Finally, in this phase, SKG-2 was used for the injection and the others for production in the upper reservoir. The size of the reservoir was about 100m to east-west direction.

After the connectivity among four wells was improved, the short-term circulation test was conducted for 90 days in 1991. It was successful to recover 70% volume (80% in the short term) and to extract 8.5MWt on the average from the small-scale reservoir.

In this phase, it was confirmed that it was possible to improve the recovery in an HDR system by applying the design consisting of one injection well and several production wells. In the world today, it is recognized that Hijiori model is the most beneficial method in order to improve the recovery. This result impacted to the later HDR project in the world.

3.3 Phase 2 (1992-2002)

The goal of Phase 2 is to enlarge the scale of the system and to estimate the performance of the reservoirs in the long term. The additional fracturing was conducted mostly from 1992 to 1994. The long-term circulation test was planed from 2000 to 2002 for the evaluation of the HDR system. The results will be described in the next chapter.

For the scale expansion, the lower reservoir was added at a depth of 2,200m, beneath the upper reservoir (Figure 2). In this phase, SKG-2 and HDR-1 were used for injection, and the other wells were used for production. SKG-2 was connected only to the upper reservoir. HDR-1 was connected only to the lower reservoir because all depths above were sealed with casing and cementing. Production wells were connected to both reservoirs at each depth.

In the hydraulic fracturing to create the lower reservoir, PBR (Polished Borehole Receptacle) was especially used to separate the target from the upper reservoir. PBR is the equipment combining the steel pipe and the packer-like O-ring. The packer works to seal the pressure under its location. It was successful to form the lower reservoir at a depth of 2,200m by hydraulic fracturing with PBR. After the fracturing was achieved, HDR-2 and HDR-3 were deepened toward the west and the east of the lower reservoir. The size of the lower reservoir was 200 m to east-west direction, which was twice as large as the upper reservoir.

4.0 THE LONG-TERM CIRCULATION TEST

4.1 Overview

Another goal of Phase 2 is to estimate the performance of the reservoirs in the long-term circulation. “The Long-term Circulation Test” was started on 27 December 2000 as the last experiment of Hijiori Project. The duration of this test consists of three parts. For the first year, “The Lower Circulation” was conducted to observe the heat extraction using only the lower reservoir. For the next four months, the "Dual Circulation” was implemented to observe the characterization between the upper and lower reservoirs by simultaneously injecting both reservoirs. For the last three months, “the Generator Test”, was conducted to demonstrate the performance of the HDR system with the 130KW binary unit continuing the dual circulation. The circulation test was finished on 31 August 2002.

4.2 The Lower Circulation (27 Nov. 2000 - 15 Nov. 2001)

(1) Actual Operation

“The Lower Circulation” was successfully conducted for 333 days using one injection well HDR-1 and two production wells HDR-2, HDR-3. The circulation was suspended for scale reaming in borehole HDR-2, and the predictive inspection of the facilities for 19 days (25 Sept. – 15 Oct. 2001). The main data of this circulation is shown in Table 1.

Table 1. Observed data in the lower circulation (27 Nov. 2000 - 15 Nov. 2001)

General Status (circulation time is for 333 days)				
	HDR-1	HDR-2a	HDR-3	HDR-2a +HDR-3
Injection volume (t)	478,389			
Production volume of hot water (t)		86,130	69,655	155,785
Production volume of steam (t)		27,946	22,485	50,431
Production volume (t)		114,076	92,140	206,216
Recovery (%)		24%	19%	43%
Net thermal output (MWh)		32,377	26,022	58,399
Mean thermal output (MW)		4.1	3.3	7.3

(2) Injection Status

The injection rate and the pressure of the wellhead are shown in Figure 4. In order to observe the change of the reservoir, the injection rate was set constant at 16.7kg/s (60 ton/hr) using a turbine pump (maximum discharge pressure: 10MPa). Five days were required to reach the planned rate. For the first two months of the circulation, it was difficult to control the injection rate owing to extremely high rock pressure. For the next three months, the injection rate was different owing to the disorder of the pressure indicator in the pump discharge. After adjustment, the injection rate was constant. The injection pressure decreased from 10 to 6MPa in one and a half months. The injection temperature fluctuated between 20 and 40°C according to seasons (Figure 5).

(3) Production Status

The wellhead pressures of both HDR-2 and HDR-3 were mostly constant at 1MPa (Figure 4). From July to August 2001, the wellhead pressure of HDR-3 was very low. After the adjustment of production valves, the pressure was stable.

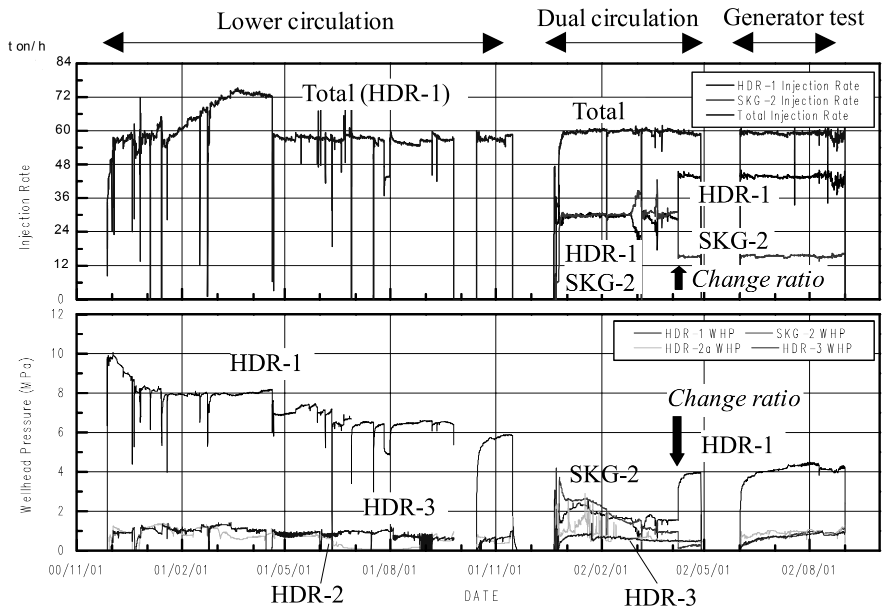

Figure 4. Injection rate (above) and wellhead pressure (below).

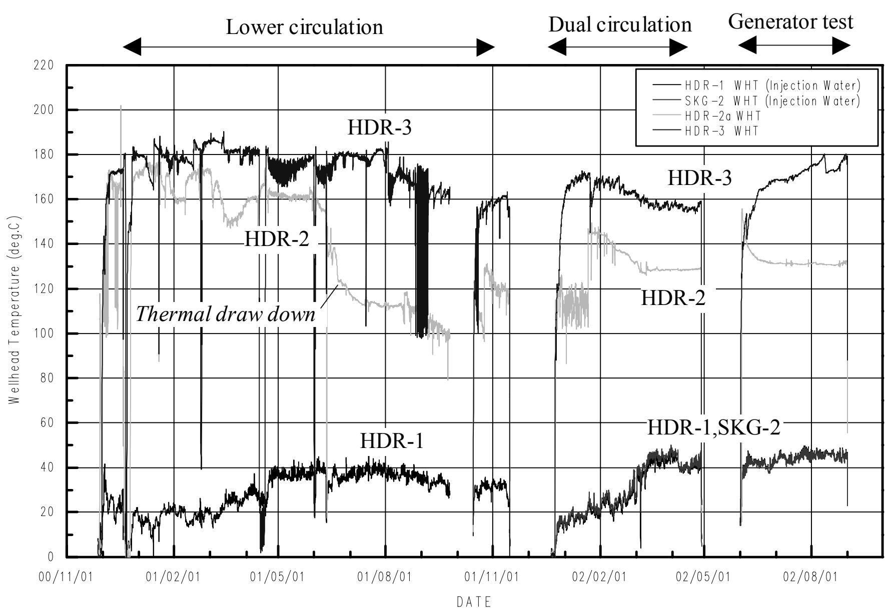

Figure 5. Temperature of the wellhead.

The wellhead temperature was very different between HDR-2 and HDR-3 (Figure 5). In HDR-3, the temperature was stable at 160-180°C. In HDR-2, the sharp drop from 160 to 110°C was found in the middle of June. This drop was expected before test. This thermal drawdown was also observed in the PTS logging survey of HDR-2. These data were very valuable to improve the numerical model of Hijiori underground.

The production rate of HDR-2 was stable before the thermal drawdown. After that, the steam rate of HDR-2 declined rapidly, and was finally stable at 2tons/hr. The hot water rate of HDR-2 was stable. After the middle of July, both the steam and hot water rates of HDR-3 declined gradually in spite of adjusting the production valves. The total recovery was about 43% (Table 1).

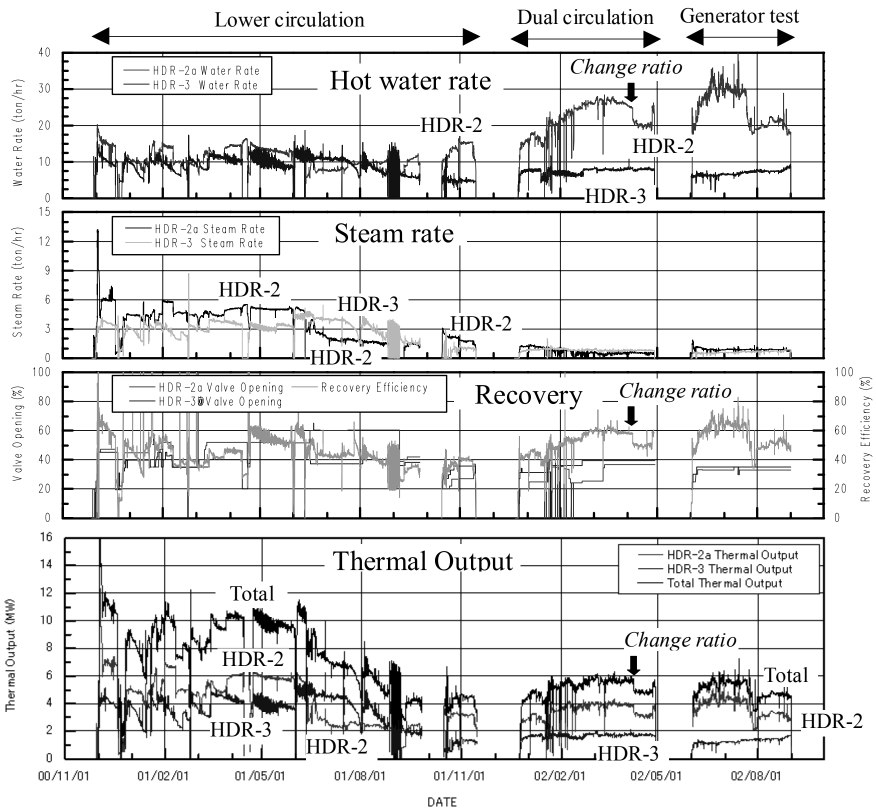

Figure 6. Production data (hot water rate, steam rate, recovery, thermal output, from the top).

The total thermal output declined rapidly from 10 to 7MWt after the thermal drawdown, and gradually from 7 to 4 MWt after the middle of July 2001 (Figure 6). The mean output was about 7MWt (Table 1).

(4) The Anhydrite Scale

The problem of anhydrite scale was clarified in the borehole. It had been unexpected before the circulation because it never occurred in the short circulation test for 90 days in 1991. The indication was found in the PTS logging of HDR-2. Since 13 April 2001, the tool could not go down below around 2,000m depth. Since 14 July 2001, the production water became white by the suspended anhydrate scale in the logging. In HDR-3, the tool failed to penetrate around 2,000m depth since 31 May 2001, but the production water never became white in the logging.

Basically, the anhydrite was characterized by dissolving easily at the lower temperature, and made up around 5% by weight of the rock of Hijiori underground. The process of the deposited scale is assumed as follows:

(i) The anhydrite was dissolved out of the basement rock in the injection water at lower temperature.

(ii) The anhydrite-saturated water was heated at the reservoir.

(iii) The anhydrite scale was deposited in the borehole at the higher temperature or at the flash point.

In a week of 20 days for the periodical inspection, the scale of HDR-2 borehole was reamed easily by the coil tubing method. The reaming in HDR-3 was not implemented over the budgets.

(5) Results

In the lower circulation for one year, the main findings were as follows:

- It was successful to operate the HDR system stable for 333 days.
- It was confirmed that 7MWt was extracted on the average from the lower reservoir at Hijiori site.
- Thermal drawdown was observed in the HDR-2 as expected. These data were very valuable to improve the numerical model of Hijiori underground considerably.
- It was clarified that the problem of the anhydrite scale might occur in the HDR borehole, similar to that in a conventional geothermal well. It was successful to remove the scale deposited by the coil tubing method in a week.

4.3 The Dual Circulation (24 Dec. 2001 - 28 Apr. 2002)

(1) Actual Operation

"The Dual Circulation" was continuously conducted for 125 days using two injection wells (SKG-2, HDR-1), and two production wells (HDR-2, HDR-3). The injection ratio was changed to confirm the optimal ratio for the generator test in the next step for the last 20 days (8 - 28 April 2002). The main data of this circulation are shown in Table 2.

Table 2. Observed data in the dual circulation (24 Dec. 2001 - 28 Apr. 2002)

General Status (circulation time is for 125 days)						
	SKG-2	HDR-1	SKG-2 +HDR-1	HDR-2	HDR-3	HDR-2 +HDR-3
Injection volume (ton)	85,329	96,210	181,539			
Production volume of hot water (ton)				65,859	23,770	89,629
Production volume of steam (ton)				3,510	3,793	7,303
Production volume (ton)				69,369	27,563	96,932
Recovery (%)				38%	15%	53%
Net thermal output (MWh)				8,447	5,026	13,473
Mean thermal output (MW)				2.8	1.7	4.5

(2) Injection Status

At the start of this circulation, the injection rate was shared equally about 8.3kg/s (30 ton/hr) to each injection well keeping the total injection rate constant at 16.7kg/s (Figure 4). For the last 20 days, the ratio of SKG-2 to HDR-1 was changed from one-to-one to one-to-three and at a constant total injection rate without shut down in order to confirm the optimal injection ratio for the generator test.

The wellhead pressure of HDR-1 was stable except for the higher status for the first one month (Figure 4). Otherwise, to stabilize the wellhead pressure of SKG-2, the four months was required. It is thought that the impedance of the reservoir was increased owing to closing the fracture for the long intermittence (ten years).

(3) Production Status

The wellhead pressure of HDR-3 was stable in spite of changing the injection pressure. HDR-2 wellhead pressure changed according to the injection pressure. It was implied that the impedance of reservoir was lower toward HDR-2 than HDR-3.

The wellhead temperature of HDR-3 was very stable at 160°C. That of HDR-2 was finally recovered to 130°C (Figure 5). It is implied that the upper reservoir contributed to increase the temperature of HDR-2.

The production rate of HDR-3 was stable through circulating (Figure 6). Otherwise the hot water rate of HDR-2 was increased gradually and finally twice as much as in the last of the lower circulation. The total thermal output was also increased to 6MWt.

The total recovery was increased to 53% according to the hot water rate of HDR-2 (Table 2).

(4) The Change of the Injection Ratio

A merit of an HDR system is that it is possible to control the production by adjusting the injection rate. For the last 20 days in this circulation, the change of the injection ratio was implemented to confirm whether production would be controlled as expected.

At first, the prediction curves in rough three types of the injection ratio were calculated by the reservoir simulator for Hijiori model, assuming that the wellhead pressure of HDR-2 and HDR-3 would be 1 and 0.7MPa. Those curves are shown as the sum of HDR-2 and HDR-3 production rate at Figure 7. In Type 1, the ratio of SKG-2 to HDR-1 was set to three-to-one (45 to 15ton/hr) at constant total injection rate. In Type 2, the ratio was set to one-to-one (30 to 30ton/hr) at the same condition. In Type 3, the ratio was done to one-to-three (15 to 45ton/hr). In Types 1 and 2, the prediction curves of the

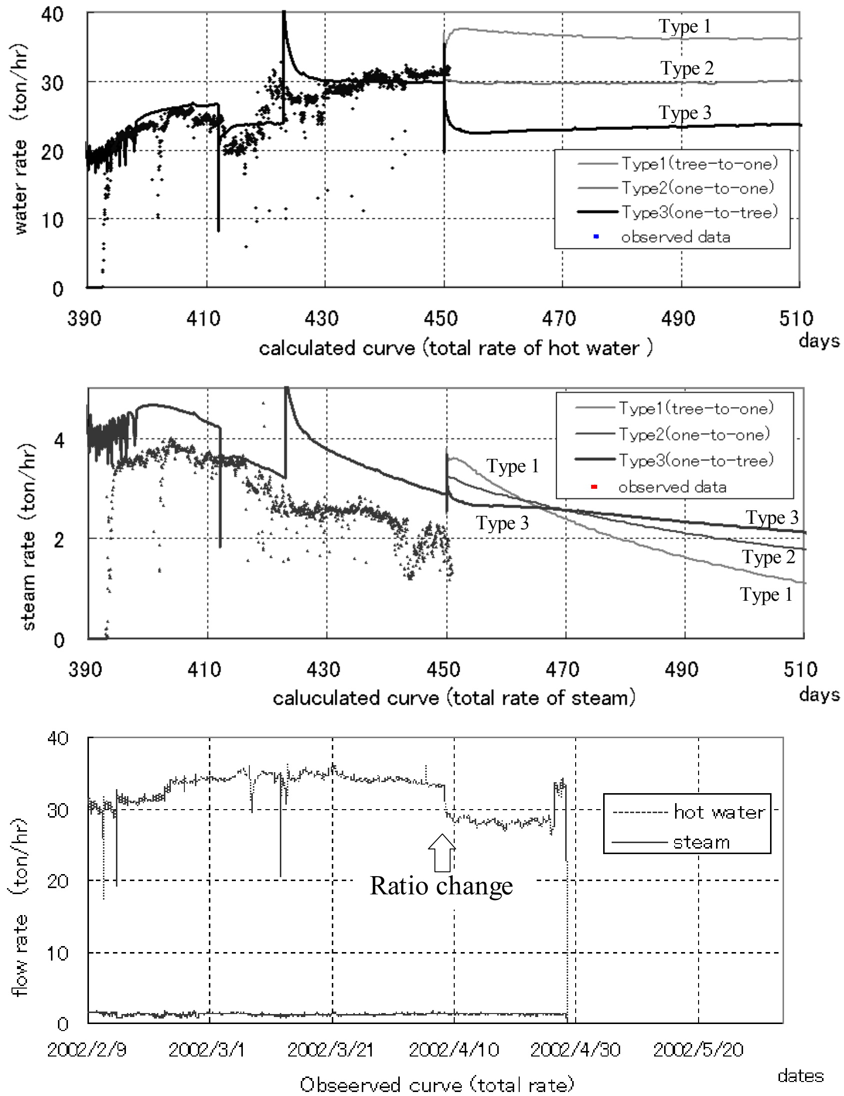

Figure 7. Calculated curve (above, middle) and observed data (below)

steam rate were less than Type 3 in 20 days since the ratio was changed. Type 3 was the best for producing the steam stably in three types. Secondly, the injection ratio of SKG-2 to HDR-1 was practically changed and kept to one-to-three for 20 days to confirm the validation of the prediction. The result was that the observed curve matched roughly the predicted curve in Type 3 (Figure 7). Therefore, in the generator test, one-to-three was chosen for the injection ratio of SKG-2 to HDR-1.

(5) Result

In the lower circulation for around one year, the main findings were as follows:

- It was successful to operate the dual circulation system of HDR for 125 days continuously.
- It was successful to increase the thermal output by adding the upper reservoir.
- It was confirmed that in the HDR system, it was possible to control the projection (as expected) by adjusting the injection. It is very difficult in the conventional system.

4.4 The Generator Test (01 Jun 2002 - 31 Aug. 2002)

(1) Actual Operation

"The generator test" was conducted for 58 of 92 days, continuing the dual circulation. The injection rate of SKG-2 to HDR-1 was kept constant at 4.2kg/s (15ton/hr) to 12.5kg/s (45ton/hr). The main data of this circulation is shown in Table 3.

Table 3. Observed data in the generator test (1 Jun. 2002 - .31 Aug. 2002)

General status of the dual circulation (circulation time: 92 days)						
	SKG-2	HDR-1	SKG-2 +HDR-1	HDR-2	HDR-3	HDR-2 +HDR-3
Injection volume (ton)	33,868	95,389	129,257			
Production volume of hot water (ton)				53,593	15,176	68,769
Production volume of steam (ton)				1,931	1,353	3,284
Production volume (ton)				55,524	16,529	72,053
Recovery (%)				43%	13%	56%
Net thermal output (MWh)				8,078	2,834	10,912
(output of the steam (MWh))				(1403)	(996)	(2399)
Mean thermal output (MW)				3.7	1.3	4.9
(output of the steam (MWh))				0.6	0.5	1.1

General status of the generating test	
Operating dates (days)	58
Operating time (hours)	1,168
Net output (KWh)	53,296
Mean output (KW)	45.6
Generating efficiency (%)	4.20%

(2) Circulation Status

The injection status was stable continuously after the ratio change in the dual circulation (Figure 4). The temperature of wellhead in HDR-3 was increasing to around 18°C in the latter (Figure 5).

The total steam rate was produced constantly at 0.42kg/s (1.5ton/hr). Otherwise the hot water rate of HDR-2 declined in the last one month (Figure 6). It is thought that the diameter of the pipeline became smaller by the scale deposited inside it. The total recovery was 56% (Table 3). The thermal output of the steam was estimated at 1MWt of total 4.5MWt.

(3) The Binary-Unit

130KW binary-unit for the generator test is shown in Figure 8. Basically, it had been developed by NEDO since 1991, and recently modified a little by a private company. HCFC-123 was used as the energy medium. The medium vaporized in the evaporator rotates the screw turbine and generates the electricity. Only steam was used for generating not to deposit the scale in the evaporator. The steam condition of 0.75kg/s (2.7ton/hr) and 120°C was required to the rating output 130KW.

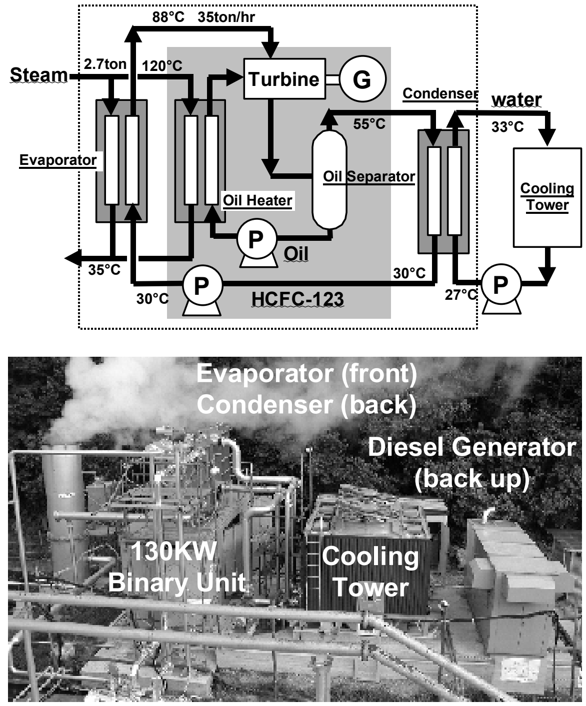

Figure 8. 130KW binary unit (above: system distribution, below: external view).

(4) Generator Status

The output and the steam status of the generator are shown in Figure 9. In the first week, only steam of HDR-2 was supplied to the unit to warm it up, and the output was about 20KW. After supplying the steam of both wells, the output was stable at around 50KW. The inlet steam of the evaporator was also stable at 105°C and 0.42 kg/s (1.5ton/hr). The generating efficiency was about 4% as required to the steam condition (Table 3). However two troubles happened. One was the unit trip caused by the hard rain. It is thought that in the steel pipe, which was not covered with insulation, the steam was cooled rapidly in the driving rain and did not supply the adequate amount for the turbine. Another was the lubrication oil leak from the rotator. It was thought that the mechanical seal breakdown caused it. The detail of the blight will be clarified after the overhaul. The continuous run was given up to protect the generator for the last month.

(5) Result

In the generator test, the main findings were as follows:

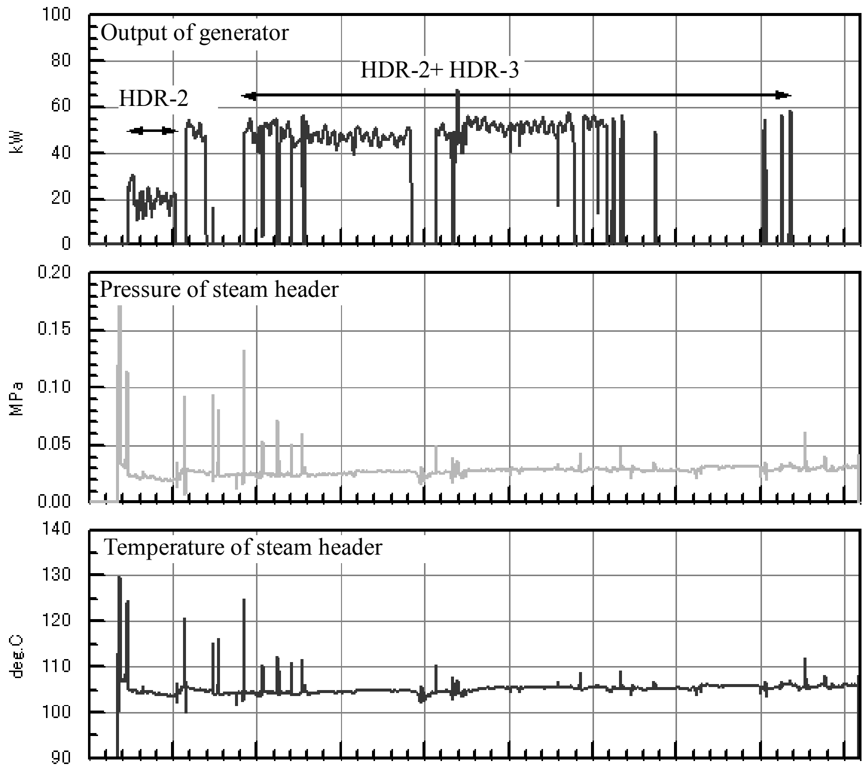

Figure 9. Output and steam status in the generator facilities.

- It was successful to operate the power generation system of HDR for 58 of 92 days continuing the dual circulation.

- It was clarified that the plant design has to been considered to protect the pipeline with the insulation as the small generator like 100KW was sensitive to the hard rain.

5.0 CONCLUSION

“Long-term circulation test” for 550 days was unprecedented in the past and the very valuable results were brought in the world by it. The HDR technology was advanced toward the commercial development by demonstrating that it is technically possible to develop HDR, and specifying the performance of the small-scale HDR system in Hijiori Project. However, in order to commercialize the HDR power generation system, some solutions to problems (the anhydrite scale, the cost-cutting for commercial development, and the technical problem in forming the larger-scale HDR system), have to been cleared. It is expected that the problems can be solved by the technological innovation in the near future and the HDR technology will be applied to not only the geothermal field but also different technical area.

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