AN EXPERIMENT TO PROVE THE CONCEPT OF THE DOWNHOLE COAXIAL HEAT EXCHANGER (DCHE) IN HAWAII

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ABSTRACT

The first experiment for the Downhole Coaxial Heat Exchanger (DCHE, see Fig. 1) was carried out successfully at the HGP-A well on the island of Hawaii using an interval from the surface down to a depth of 876.5m. The temperature at the bottom of the DCHE before the onset of the experiment was 110°C. The observed highest hot water temperature during the experiment was 98°C, and the maximum gross and net thermal outputs were 540 kW and 370 kW, respectively. The experiment proceeded smoothly and excellent agreement between measured values and computed values was obtained in the analysis (Morita *et al.*, 1992). Thus, the concept of the DCHE was proved to be sound.

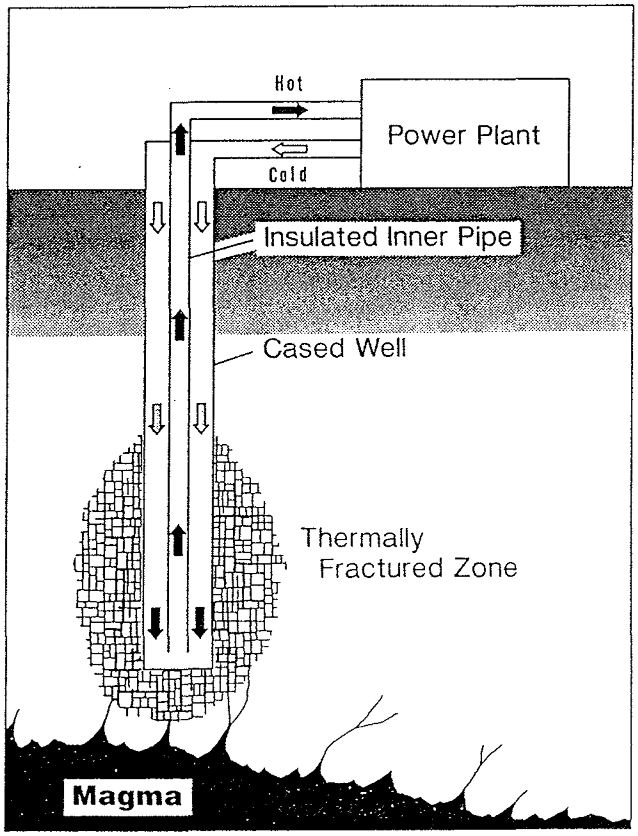

Fig. 1 Concept of the Downhole Coaxial Heat Exchanger.

INTRODUCTION

The DCHE has been proposed as a heat extraction method to exploit such undeveloped geothermal resources as low productive geothermal reservoirs (i.e., Hot Wet Rock), super hot rock adjacent to magma bodies and solidified magma bodies etc. (Morita *et al.*, 1985, Morita, 1991). Major features of this concept include the utilization of a highly-insulated inner pipe, reverse circulation (i.e. cold water down the annulus and hot water up the inner pipe), and a completely closed system creating a heat exchanger with which very clean geothermal energy could be efficiently extracted.

From February 22 to March 1, 1991, the experiment was carried out as a joint project between the Pacific International Center for High Technology Research (PICHTR) and the Engineering Advancement Association (ENAA) of Japan. The main purpose of this experiment was to prove the concept using an actual geothermal well. Additional objectives included performance evaluation of the insulated inner pipe in DCHE application and the investigation of the *in situ* heat transfer characteristics in the formation.

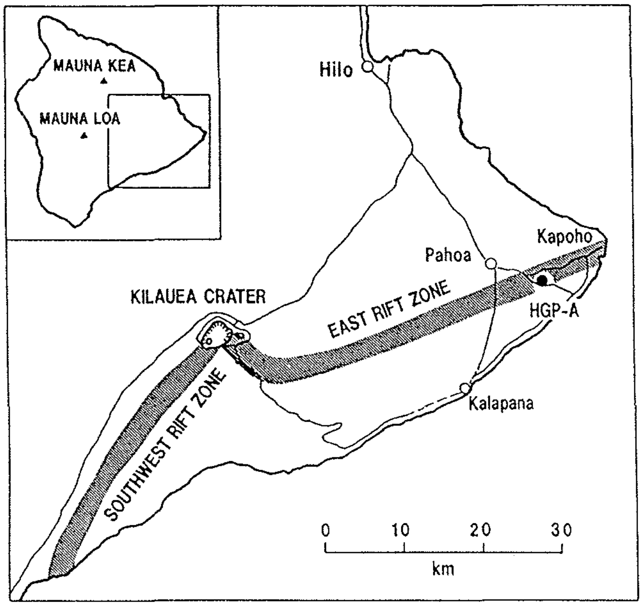

Fig. 2 The location of the HGP-A well.

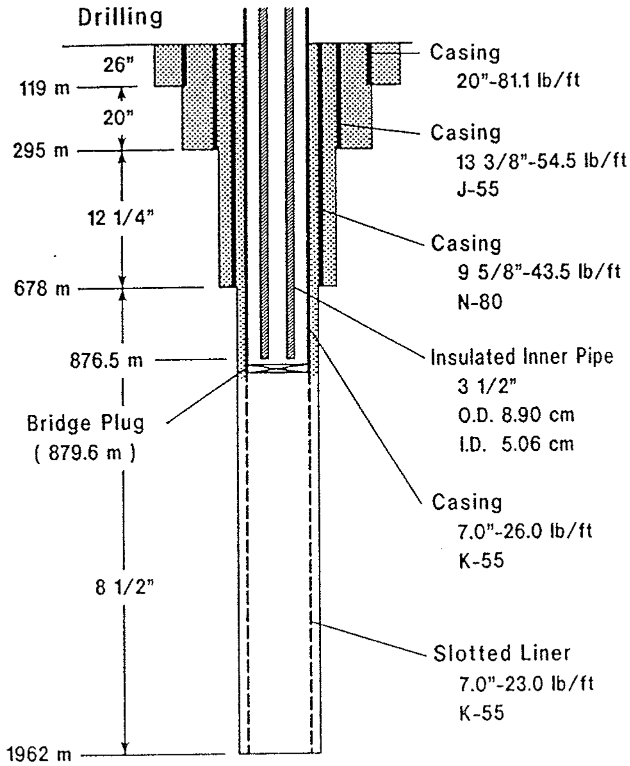

Fig. 3 The drilling and casing profile of HGP-A well.

TEST SITE, WELL AND DCHE

The experiment was conducted using HGP-A well located in the Kapoho area in Puna (see Fig. 2) in the Kilauea East Rift Zone which extends from Kilauea to the east. The distances from the Kilauea Crater and Hilo to the well site are 42 km and 35 km, respectively. The altitude of the site is about 180m. The drilling of the well was initiated in December 1975 and completed in April 1976 with the funding provided by the US Department of Energy, the State of Hawaii and others. The observed bottom hole temperature was 358°C, making HGP-A one of the hottest geothermal wells in the world at that time. The well was used as the only production well of the Puna Geothermal Facility until December 1989. After that time, the well was shut-in until well preparation work for this project began in January 1991.

The casing profile of the well is shown in Fig. 3. The figure also shows the DCHE configuration in the well. However, the 1m deep cellar and 30" conductor casing down to 2.4m in depth are not shown in this figure. The depth of the well from the ground surface is 1,962m. The well was completed setting 9 5/8" casing to a depth of 676m and 7.0" slotted liner to the bottom. During the well workover that was performed in September, 1979, the top section of the liner was removed and 7.0"-26.0 lb/ft K-55 casing was inserted from the surface down to 890m. The experiment was carried out within the 7.0" casing interval.

A retrievable bridge plug was set to separate the test section and to avoid the in-flow of geothermal brine into the DCHE. The top of the plug was at 879.6m. A total of 74 pieces of 3 1/2" vacuum type double tube insulated pipes produced by Sumitomo Metal Industries, Ltd., Kawasaki Thermal Systems Inc., and Kubota, Ltd. were used as the insulated inner pipe of the DCHE. The bottom end of the insulated inner pipe was 876.5m in depth. Taking into account the depth of the cellar, the total length of the DCHE was 875.5m. Nineteen pieces of centralizer were fitted to the pipe to centralize and avoid vibration. Thus a completely closed system DCHE was configured in the well.

The formation is basaltic along the entire length of the well. The formation from the surface to 450m in depth consists of derivatives of surface eruption such as a'a and pahoehoe lava, cinder and clinker. The interval from 450m to 700m is a transition zone consisting of derivatives from the surface eruptions and the sea floor eruptions. Below 700m is a sea floor eruption zone consisting of pillow lava. The ground water level at the site is about 186m in depth.

WORK SCOPE

PICHTR functioned as the U.S.-side partner and manager. U.S. funding was provided by the State of Hawaii via the Energy Division of the Department of Business, Economic Development and Tourism. Other organizations participating in the project included the Hawaii Natural Energy Institute (HNEI), the Hawaii Institute of Geophysics (HIG), the Natural Energy Laboratory of Hawaii Authority (NELHA), Sandia National Laboratories (SNL), the United States Geological Survey (USGS), and the International Consulting & Marketing Group, Inc. (ICMG).

The U.S.-side project responsibilities included the following:

(1) Securing and preparing the well and site for the experiment,

(2) Preparation of the surface heat exchanger and cooling system for the surface facility,

(3) Installation of the whole surface facility and the DCHE,

(4) System operation and data acquisition,

(5) Safety management, environment monitoring and environmental hazard prevention, and

(6) Analysis of results.

ENAA functioned as the Japan-side partner. A committee for the project was established to assist ENAA. The chairman of the committee was Dr. Sei-ichi Hirakawa and the committee consisted of members of Kyushu University, Akita University, ENAA, the National Institute for Resources and Environment (NIRE), the Geological Survey of Japan (GSJ), the Government

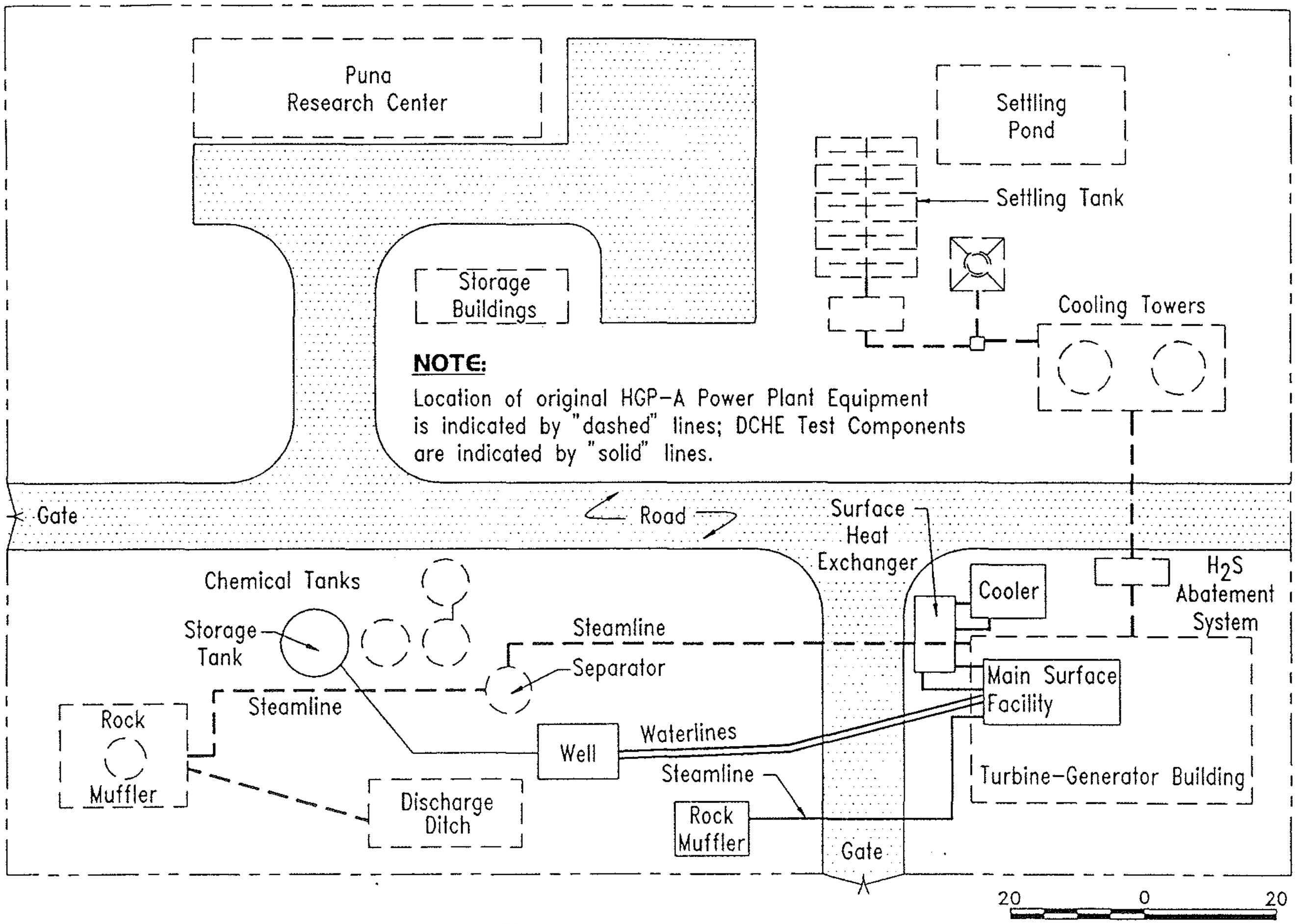

Fig. 4 Test site schematic.

Industrial Institute Tohoku, the Japan Metals & Chemicals Co. Ltd., Sumitomo Metal Industries, Ltd., Kawasaki Steel Corp., Kubota Ltd., and Mitsui Shipbuilding & Engineering Ltd. The last four companies formed the DCHE-Japan Study Group which was responsible to ENAA for the performance of the Japan-side responsibilities, which included the following:

(1) Preparation of the DCHE System design,

(2) Fabrication of the main surface facility,

(3) Supply of the insulated inner pipe for the DCHE,

(4) Assistance in the installation, checkout and operation of surface facility and the DCHE at the test site, and

(5) Analysis of the results.

PREPARATION FOR THE TEST

In December, 1990, the main surface facility components were installed at the site and checked out (see Figs. 4 to 7). The main surface facility was positioned inside the HGP-A turbine-generator building, the surface heat exchanger and the cooling system just

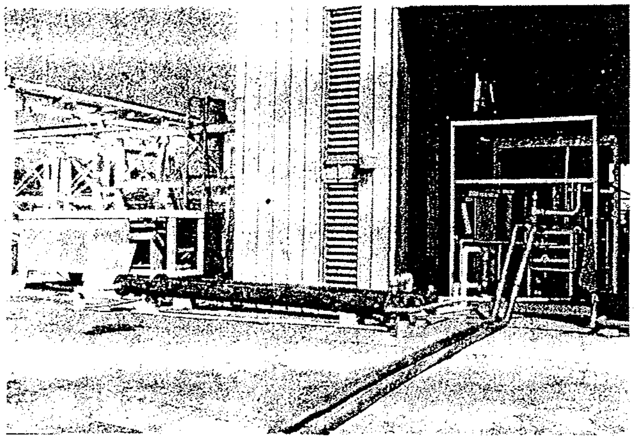

Fig. 5 Main surface facility (in the turbine-generator building), surface heat exchanger and cooling system.

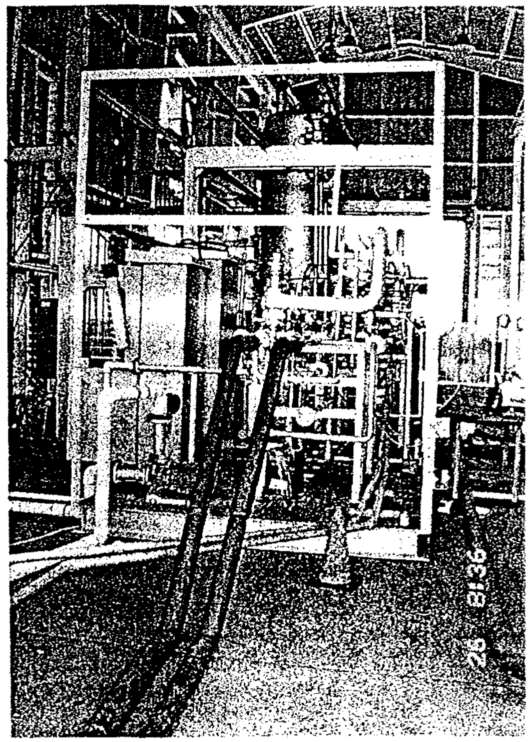

Fig. 6 Main surface facility.

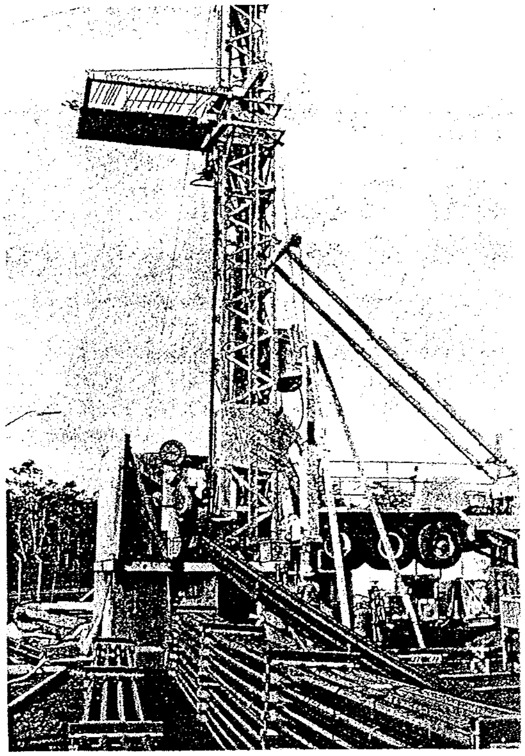

Fig. 7 Drilling rig and insulated inner pipes before the installation.

outside. The interconnection and assembly of the entire surface facility was completed and a successful test operation was carried out on January 23, 1991.

A trailer-mounted Universal 5000 drilling-rig which was used on the Scientific Observation Hole (SOH) Program (Olson *et al.*,1990) was used for well preparation work and installation of the DCHE. The rig was transported to the test site in early January, 1991. A well rework was performed by NELHA, including the drilling, scraping out of silica scale from the wellbore, setting the bridge plug, cement squeezing to repair leaks in the 7.0" casing, and the drilling, scraping out of cement in the wellbore.

After installation of the insulated inner pipe, flushing of the DCHE was carried out twice for two hours, respectively, employing reverse circulation. On January 25, the first flushing was carried out using one of the drilling rig's pumps. This flushing unintentionally became the first operation of the DCHE since this circulation method was the same as that of the DCHE concept. The flow rate and injected water temperature at the flushing were 189 l/min and 24°C. Observed peak hot water temperature was 71°C. The maximum gross and net thermal outputs were calculated to be 940 kW and 620 kW, respectively. The rig was released after this flushing. The second flushing was performed on January 28 using the main surface facility's circulation pump at 80 l/min of flow rate which was the same flow rate as in the experiment. The peak hot water temperature was 94°C. A 1.7 kgf/cm^2 higher outlet hot water pressure than the inlet pressure was observed at a temporary shut-in 30 minutes after the peak temperature. This indicates that, if the valves in the injection and production lines were opened, flow in the DCHE would initiate and continue without a pump.

On January 30, test operation of the entire experimental system including the DCHE was carried out for two hours. Flow rate, temperature and pressure of the injected water were set to the same values as those of the experiment. During the test, all the equipment including the control systems of the main surface facility worked properly. With this test, it was confirmed that there were no essential problems with the whole experimental system. After the test, the well was shut-in until February 22 to allow for the recovery of the formation temperature.

On February 15 and 21, temperature logs of the well were performed using a Kuster tool. The latter temperature log was performed the day before the onset of the experiment to obtain the initial temperature distribution in the wellbore. The temperature at the bottom of the DCHE was 110.3°C. The results of these logs are shown in Fig. 8.

EXPERIMENTAL SYSTEM AND CONDITIONS

a. Experimental System

A flow diagram of the experimental system is shown in Fig. 9. The capacity of the circulation pump was

83.3l/min at 30m lifting head. Pressure ranges of the pressure control or measurement system were designed to be -0.5 to 3.5 and -0.5 to 5.0 kgf/cm^2 (gage) for the injection and production line, respectively. In this system, the flow rate, pressure and temperature of the injected water were maintained at set values automatically. The length of the injection or production lines between the main surface facility and well head were 28m, respectively, and they were thermally insulated.

b. Data Acquisition

Flow rate, pressure and temperature in both injection and production lines, hot water temperature at the bottom of the DCHE and ambient temperature were measured. The data were recorded on a Campbell Scientific CR-21X data logger. Analog sensor inputs were sampled at a rate of 1/sec. These samples were then preaveraged into 1 minute averaged values, stored temporarily on cassette tape, and then periodically transferred onto floppy disc using a personal computer at the site. Also pressure drops and temperatures in the injection and production lines were measured manually.

Two techniques were used to measure the downhole temperature during circulation, one using a sheathed thermocouple attached to the insulated inner pipe and one using the Kuster tool. However, the data acquired by the shealthed thermocouple seem to be suspect since there was a short circuit in the thermocouple.

c. Test Conditions

Tap water was used as the working fluid. The test conditions were as follows:

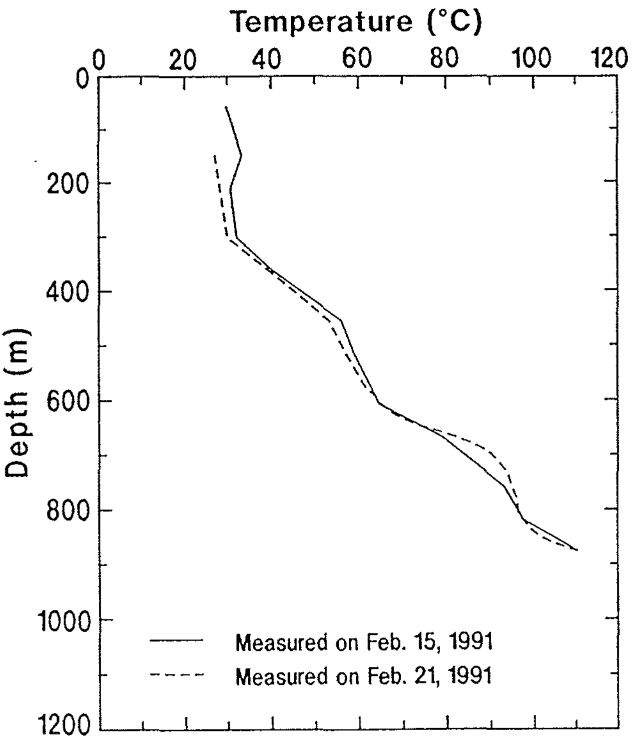

Fig. 8 The results of the temperature logs.

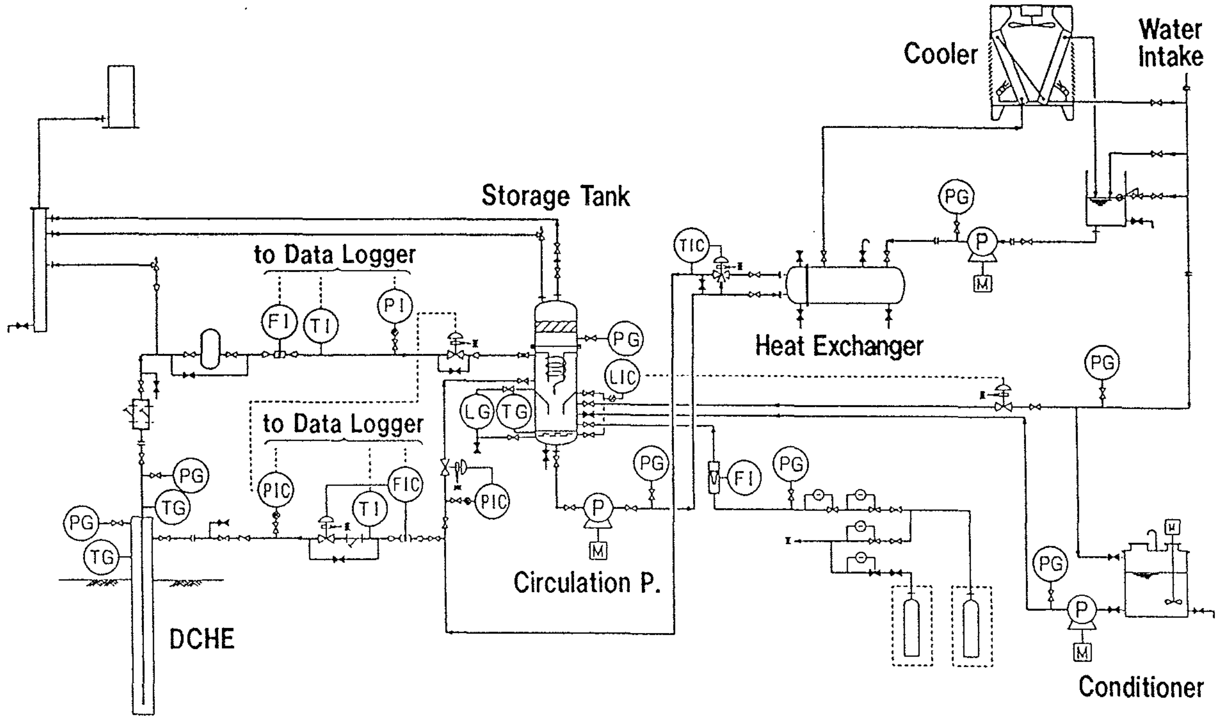

Fig. 9 Flow diagram of the experimental system.

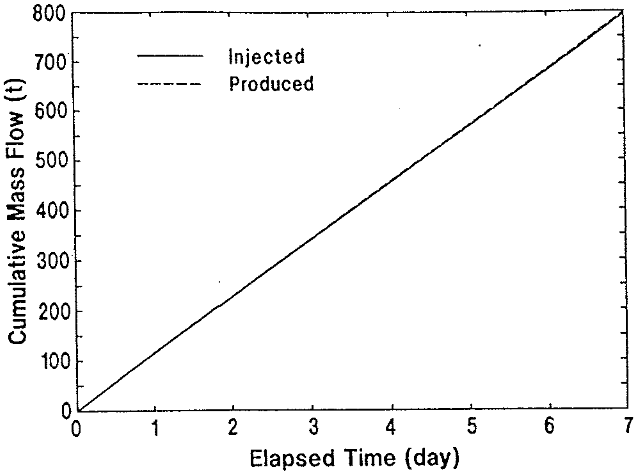

Fig. 10 Changes in injected and produced cumulative mass flows.

- Flow rate: 80 l/min
- Injection water temperature: 30 °C
- Injection water pressure: 1.5kgf/cm^2 (gage)

Above values were kept constant during the experiment.

OUTLINE OF EXPERIMENT

The experiment was initiated at 1447 on February 22, 1991. Particles, including scale and cement, flowed out in early stages of the experiment. Therefore, it was necessary to flush two filters installed in the production lines frequently on the first day. However, the amount of particles decreased with time and it became unnecessary to flush the filters after several days.

A 30 minute power failure occurred from 1020 to 1050 on February 24. Outlet and inlet valves at the well head were closed instantaneously to cease the circulation during the power failure. This was the only unexpected occurrence during the experiment.

A temperature log in the insulated inner pipe during circulation was carried out on February 26 using a Kuster tool. Circulation was stopped for 25 seconds to install a valve for the lubricator at 0727. Logging was initiated at 1040 and completed at 1247.

The experiment was finished at 1450 on March 1, the entire test duration being just 7 days. During that time, all the control systems worked as designed, and the flow rate, temperature and pressure of the injected water were controlled properly. Temperature and pressure of hot water changed in a similar manner as predicted before the experiment.

As shown in Fig. 10, injected and produced cumulative mass flows were almost the same throughout the experiment. The difference between injected and produced cumulative mass flow was within the range of the nominal error of the flow meter. This indicates that there was no detectable in-flow or out-flow from the DCHE during the experiment.

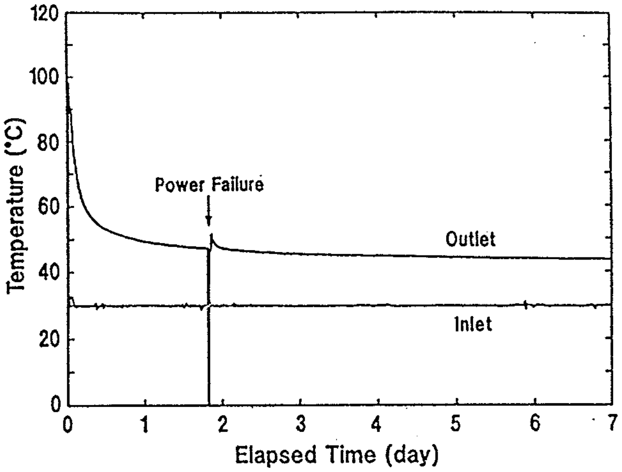

Fig. 11 Changes in injected and produced water temperatures at the surface.

RESULTS OF EXPERIMENT

a. Hot Water Temperature

Changes in injected cold water and produced hot water temperatures during the experiment are shown in Fig. 11. It can be seen that the temperature of injected water was controlled very well during the experiment. The hot water temperature reached its peak of 98.2°C 33 minutes after onset. And it became 43.6°C at the end of the experiment.

In the analysis of the experimental results (Morita *et al.*,1992), the heat transfer characteristics in the formation were investigated using these temperature data. Analysis indicated that the heat transfer mechanism in the formation during the experiment was almost pure conduction and the thermal conductivity of the formation was estimated to be 1.6 W/m·K. The fact that the heat transfer mechanism in the formation was pure conduction indicates that heat was mainly extracted in a low permeability conduction zone of the HGP-A reservoir.

b. Temperature Distribution in the Insulated Inner Pipe

Fig. 12 shows the results of the temperature log in the inner pipe during circulation. This temperature log was carried out using a Kuster tool on February 26 and it took about 2 hours as described previously. The change in produced hot water temperature during the log was 0.02°C. Therefore the temperature distribution in the DCHE can be regarded as unchanged during the log.

Temperatures measured with the Kuster tool or sensors installed in the main surface facility are indicated by unshaded circles or shaded circle, respectively, in the figure. At the surface, the hot water temperature measured by the Kuster tool was slightly lower than that measured at the surface facility. This was probably due to insufficient time to equilibrate the temperature of the Kuster tool to the hot water temperature. The thermal capacity of the tool is rather great, therefore, it took a longer time to equilibrate its temperature to the measurement environment.

If the hot water temperature measured at the main surface facility is assumed to be the water temperature at the outlet of the DCHE, the temperature drop in the interval between the bottom end of the inner pipe and the outlet of the DCHE is 1.2°C. This temperature drop is very slight and the equivalent thermal conductivity of the insulated inner pipe was estimated to be 0.06 W/m·K from this temperature drop (Morita *et al.*,1992). This indicates that the performance of the insulated pipes used as the inner pipe in this experiment is sufficient for DCHE application.

c. Hot Water Pressure

Fig. 13 shows the changes in injected cold water and produced hot water pressures at the wellhead during the experiment. It can be seen that also the pressure of injected water was controlled very well during the experiment. After the onset, an outlet pressure higher than the inlet pressure was observed for 5 hours. This indicates that the pressure which had arisen in the DCHE due to the density difference between the colder water in the annulus and the hotter water in the inner pipe was greater than the friction loss in the DCHE. This indicates that it was possible to circulate water in the DCHE without a pump during this period. This phenomenon occurred as it bad been predicted beforehand by simulation.

A period of significant and irregular change in the hot water pressure was observed beginning at from 20 to 30 minutes after the onset and ending at 82 minutes after onset. During that time, a significant amount of cement and scale particles flowed out. Therefore, this change in pressure was probably caused by increased hot water density and/or changes in the concentrations of particles in the up-flowing water in the inner pipe. Changes in the concentrations of particles in the water change the hot water density which results in a change in pressure.

d. Net Thermal Output

The change in net thermal output during the experiment is shown in Fig. 14. In this paper, the gross

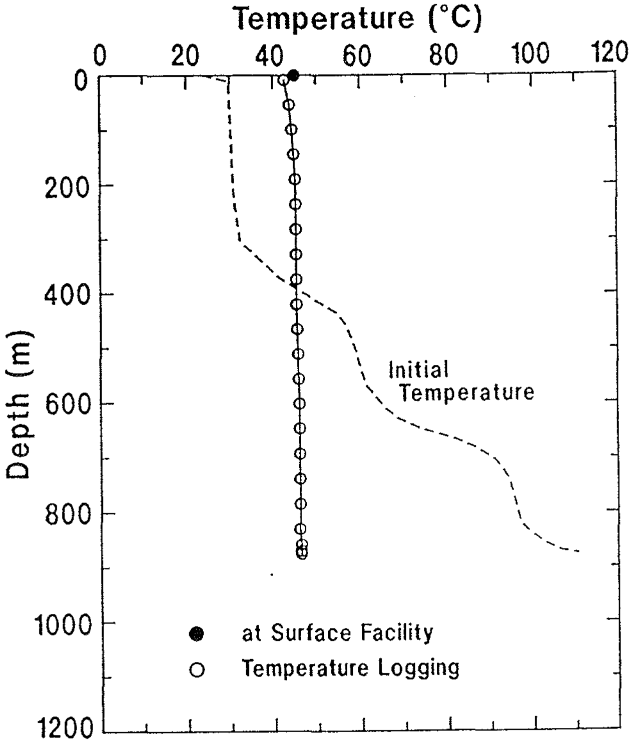

Fig. 12 Temperature distribution in the inner pipe during the circulation, about 93 hours after the onset of the experiment.

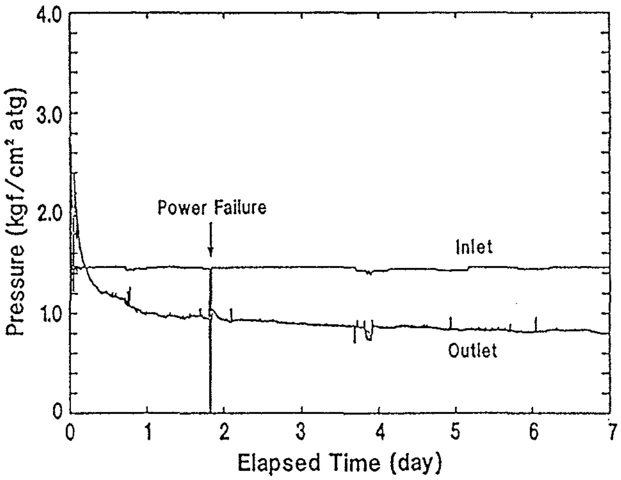

Fig. 13 Changes in injected and produced water pressures at the wellhead.

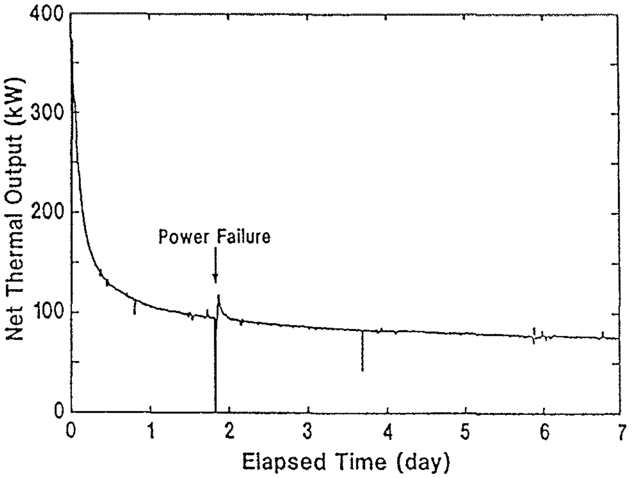

Fig. 14 Change in net thermal output.

thermal output was calculated multiplying specific enthalpy of produced hot water by mass flow rate, and the net thermal output was calculated multiplying the difference between the specific enthalpy of produced and injected water by mass flow rate.

The net thermal output changed in similar manner as that of the hot water temperature. The observed maximum gross and net thermal outputs were 542 kW and 373 kW, respectively. At the end of the experiment, they became 241 kW and 76 kW, respectively.

CONCLUSIONS

The specifications of the experimental system and test conditions were determined beforehand carrying out simulations using the simulator which had been used in the previous studies on the DCHE. The test results indicate that these were appropriate. And the insulation performance of the pipes used as the inner pipe for the DCHE in the experiment was proved to be sufficient in DCHE application. Also excellent agreement between measured values and computed values using the same simulator was obtained in the analysis (Morita *et al.*, 1992). Thus, the following were proven by this experiment:

(1) It is possible to configure the DCHE in an actual geothermal well using current technology.

(2) DCHE works as it had been predicted in previous papers (ex. Morita and Matsubayashi, 1986, Morita and Matsubayashi,1988).

Therefore, it can be concluded that the concept of the DCHE was proved to be sound and shows good potential for near-term, prototypical testing for direct use applications.

This experiment was carried out in a rather low temperature formation as shown in Fig. 15 and the analysis (Morita *et al.*,1992) indicates that the main heat extraction interval was in a low permeability conduction zone of the HGP-A reservoir. In order to evaluate the possibility of DCHE for generation of electricity, it is necessary to acquire more data concerning *in situ* heat transfer characteristics for different temperature distributions or formations by carrying out field experiments. Opportunities are now being sought for carrying out a field experiment at a much higher formation temperature.

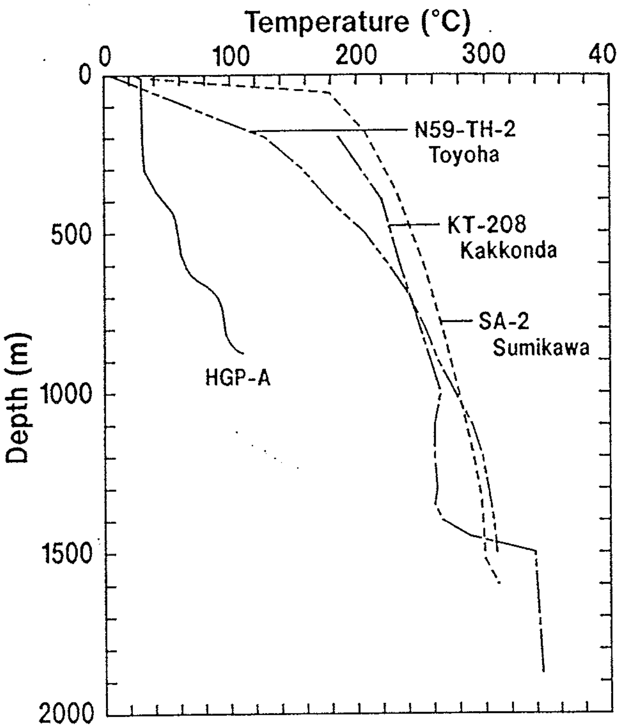

Fig. 15 Temperature distribution at the HGP-A well within the test interval and examples of the temperature distributions at several Japanese geothermal areas.

REFERENCES

Morita, K., Matsubayashi, O. and Kusunoki, K. (1985): Down-Hole Coaxial Heat Exchanger Using Insulated Inner Pipe for Maximum Heat Extraction, Geothermal Resources Council, Trans. Vol.9, Part 1, 45-50.

Morita, K. and Matsubayashi, O. (1986): The Effect of Major Design Parameters on the Performance of a Downhole Coaxial Heat Exchanger - Studies on the Downhole Coaxial Heat Exchanger (1st Report), J. of Geothermal Research Soc. of Japan, Vol.8, No.3, 301-322.

Morita, K. and Matsubayashi, O. (1988): A Study on the Thermal Output Characteristics of a Downhole Coaxial Heat Exchanger - Studies on the Downhole Coaxial Heat Exchanger (2nd Report), J. of Geothermal Research Soc. of Japan, Vol.10, No.2, 109-129.

Morita, K. (1991): New Heat Extraction Technology for New Sources of Geothermal Energy - A Downhole Coaxial Heat Exchanger System, J. of Geothermal Energy Association, Vol.28, No.1, 61-78.

Morita,K., Bollmeier, W.S. and Mizogami, F. (1992): Analysis of the Results from the Downhole Coaxial Heat Exchanger (DCHE) Experiment in Hawaii, Prepared for 1992 GRC Annual Meeting.

Olson, H.J., Seki, A., Deymonaz, J. and Thomas, D. (1990): The Hawaii Scientific Observation Hole (SOH) Program, Geothermal Resources Council, Trans. Vol.14, Part 1. 791-798.