CURRENT STATUS OF THE EGS PROJECT FOR WATER INJECTION IN THE SUPERHEATED REGION AT OKUAIZU GEOTHERMAL FIELD IN JAPAN

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ABSTRACT

An R&D project funded by Japan Oil, Gas and Metals National Corporation (hereafter referred to JOGMEC) on technology development for geothermal reservoir evaluation and management is under way. The purpose of the project is to propose guidelines for a technical manual, based on numerical simulation and model verification, for better understanding of artificial water recharge effects to geothermal reservoirs and/or hot spring aquifers.

Relevant examples include steam shortages resulting from the imbalance between the steam production rates and the natural water recharge; corrosion of surface facilities by superheated steam; and production of highly acidic fluid generated by superheating within the geothermal reservoir. These problems are widespread, and occur not only in existing geothermal power plants, but also in new geothermal developments and in newly developing areas. Our aim is to develop new and general countermeasures to such problems, which are both technically effective and cost effective. We will then collate these comprehensive measures into a new set of guidelines to ensure a stable supply of geothermal energy. Artificial water recharge is one of the EGS (Enhanced Geothermal Systems) technologies which has been successfully applied and shown to increase steam supply in the Geysers and Larderello geothermal fields. We will develop and verify an artificial water recharge technology through R&D set in the Okuaizu geothermal field in Fukushima prefecture, with an installed capacity of 65MW which has been running since 1995. The utilization factor of this power plant has reduced to 27.7% today, mainly due to the depletion of steam, the superheating effect, acidification and a decline of productivity and injectivity. The R&D project consists of project planning, design & management, survey and modeling, design and construction of a test facility, drilling of a recharge well, well testing and logging, a recharge test, numerical reservoir simulation, monitoring, and the preparation of a technical operation manual.

There are very few examples of reservoir simulation of a superheated reservoir in the world. The location of the recharge well in the field was decided by the comprehensive analysis of simulations, risk evaluations from past field injection tests and tracer analysis. Drilling of the recharge well and, recharge testing started in the beginning of June 2015. Approximately 170,000t of river water was injected through to the end of December until a cyclic phenomenon at an adjacent well (Well-8) caused by the recharge operation was observed. Despite this cyclic behavior, an increase of steam flow at Well-8 of 3-5t/h and a reduction of non condensable gas (NCG) concentrations were benefits of the recharge operation. Effects at Well-5 and 6 located in the same fault of the recharge well were also observed suggesting it is possible to maintain and/or increase steam production and control NCG by suitable recharge operation.

1. INTRODUCTION

Research on artificial water recharge projects is important since geothermal power plants sometimes require artificial recharge to support power production. One of the geothermal power plants with problems such as reservoir superheating and acidification is the Okuaizu geothermal field in Fukushima prefecture. The utilization factor of the facilities (actual power output/permitted capacity × power generation hours × 100%) has fallen below half of that at the start. Commercial operation of the Yanaizu-Nishiyama power plant started in 1995 by Okuaizu Geothermal Co., Ltd (geothermal developer and steam supplier) and Tohoku Electric Power Co., Inc. (power generation), but the amount of steam has decreased every year along with superheating problems. Fluid acidification phenomenon followed by superheating occurred requiring the discontinuation of production in some of the wells. Therefore, it is important to establish technology for water recharge and its know-how by using the Okuaizu geothermal field as an EGS R&D project in Japan.

This type of project has been seen overseas, e.g., municipal effluent water from Clear Lake and Santa Rosa has been injected in wells in the Geysers geothermal field from 1997 improving levels of power generation as well as reducing concentrations of non-condensable gas (Sanyal and Enedy, 2011). In the Larderello geothermal field in Italy, artificial water recharge was carried out from the 1970's after the steam production rate went down and the reservoir was superheated. As a result of the injection, steam production increased and non-condensable gas concentration was also reduced (Capetti, 1995). However, it is believed that these artificial water recharge projects were not based on detailed simulation, an operations manual and/or a detailed plan. The geothermal structure in Japan is smaller and rather complicated compared with these overseas examples and technology development is required to pay attention to environmental factors such as hot spring monitoring, pressure/temperature maintenance in a borehole and reservoir sustainability.

Until now, a comprehensive R&D project including evaluation of a recharge well location in a superheated reservoir by extensive simulation, drilling the recharge well, injection testing and evaluation of the injection test results has not yet been carried out. This five year project started in 2013 and the purpose is to develop a guideline for an artificial water recharge technology and to develop a technical manual through a verification test and numerical simulation of the effect of artificial water recharge on the geothermal reservoir and hot spring aquifer.

This paper reports on a brief history of the project and presents progress including an explanation and evaluation of monitoring data gathered since recharge operation started in June 2015 in the Okuaizu superheated geothermal reservoir.

2. PROJECT OVERVIEW

2.1 Okuaizu Geothermal Field in Fukushima

The Okuaizu geothermal field is located in northeastern Japan (Figure 1). Exploration of the Okuaizu geothermal field commenced with a reconnaissance survey by Mitsui Mining and Smelting Co., Ltd. (MMSC) in 1974. Subsequently, the first-phase geological, geophysical and geochemical surveys were conducted by the New Energy Development Organization (NEDO) from 1976 to 1977. After a geophysical and geochemical survey by MMSC in 1981, second phase geological, geochemical and geophysical surveys were conducted by NEDO from 1982 to 1983 (NEDO, 1985). In 1983, Okuaizu Geothermal Co., Ltd (OAG) was established to carry out further exploration and assessment, and to undertake development. From 1984 to 1985, OAG carried out geological, geophysical and geochemical surveys, and drilled five cored wells and four other wells. Production tests of 18 to 119 days for each production wells were also conducted. From 1986 to 1989, 13 more wells were drilled, with 30 to 109 day production tests conducted for each production well (Nitta et al., 1987). A total of 509 t/h of dry steam at about 165 °C from nine wells was confirmed during a three month simultaneous production test, from December, 1989, to February, 1990 (Nitta et al., 1990). Three additional production wells were drilled after that initial reservoir evaluation and the commercial operation started with a capacity of 65MW in 1995. Presently, the utilization factor of this power plant has reduced today to 27.7%, mainly because of depletion of steam, the superheating effect, acidification and decline of productivity and injectivity. The areas in the Chinoikezawa footwall fault and Chinoikezawa southeast fault have been gradually superheated from the decrease of the pressure and production some of the wells in the Chinoikezawa southeast fault was suspended due acidification caused by the superheating effect (Figure 2).

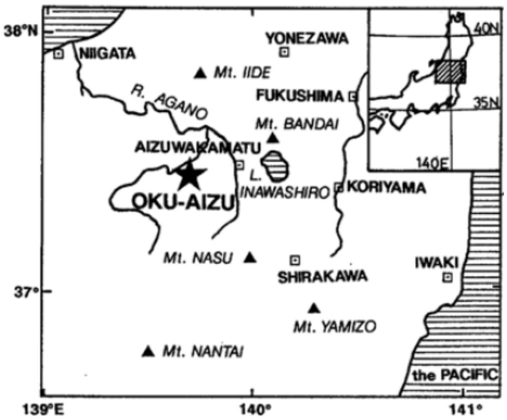

Figure 1: Location map of the Okuaizu geothermal field after Seki(1991).

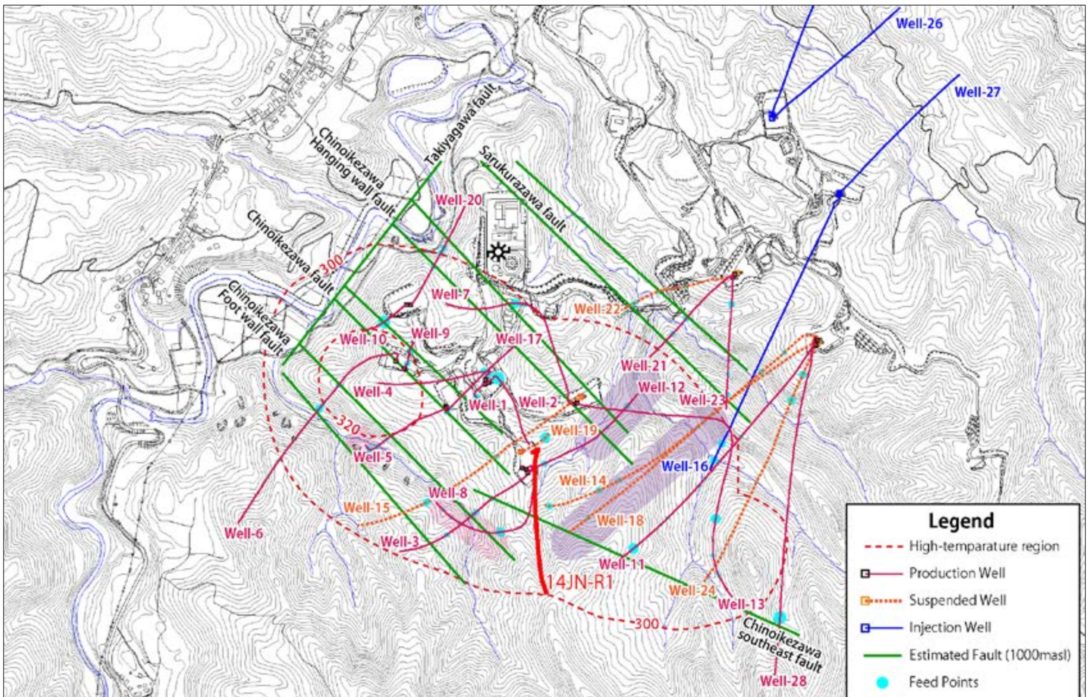

Figure 2: Okuaizu geothermal field (Plan view)

2.2 Outline of the project

The duration of this project is five years starting from 2013, and the purpose is to optimize and/or stabilize the production rate by improving the accuracy of prediction of the reservoir behavior through a verification test and numerical simulation of artificial water recharge, clarifying the impact on the geothermal reservoir and hot spring aquifers. A guideline for an artificial water recharge technology and a technical manual will be produced at the end of the project.

The R&D project consists of project planning, design & management, survey and modeling, design and construction of a test facility, drilling of a recharge well, well test and logging, operation of a recharge test, numerical reservoir simulation, monitoring, and preparation of a technical operation manual.

The project is separated in two stages Phase I and Phase II. Phase I runs from 2013 to 2015 and the object was to locate the recharge well and start the injection experiment. Phase II runs from 2016 to 2017, aiming to maintain injection, calibrate the simulation model and make a guideline to wrap up the project (Okabe et al., 2015).

3. THE PROJECT PROGRESS

3.1 Determination of the recharge well location

The recharge well location was determined by a comprehensive evaluation of an extensive numerical simulation, a tracer test and past field injection tests (Okabe et al., 2015). The recharge simulation was conducted using the reservoir simulator TOUGH2 (Pruess et al.,1999) using a MINC (Multiple Interacting Continua) model. The tracer test suggested that there is fast fracture flow that could result in a short circuit and injection water from the shallow depths may have a severe influence on production wells, locally. According to the past field injection tests, severe interference such as stopped production has occurred when production feed points are at the same level as injection feeds or shallower. The results suggest that the fractures which cause a local short circuit exist in a shallow region of the reservoir. Thus a shallow recharge location was avoided and a deep part was selected as a drilling target. The chosen target depths were 1,975m and 2,075m located in an extension of the Chinoikezawa footwall fault.

3.2 Drilling and logging results

The recharge well was drilled based on the comprehensive study above. As expected before drilling, total lost circulation(L/C) at 1,926m and a drilling break at 2,034m were encountered and the well was completed at 2,100.26m with a 7” slotted liner and 5.5” injection pipe to protect 9-5/8” casing on Dec. 12, 2015 (Figure 3 and Figure 4).

Temperature, Resistivity, Sonic and Borehole Televiewer (BHTV) and PTS logging were conducted. The static temperature at 1,350m is 296°C. Most of the fractures detected from the BHTV are steeply north dipping. Four L/C depths (1,930m, 1,980m, 2,040m and 2,080m) were detected from injection PTS logging. The main L/C depth was 2,040m and 76% of the injection fluid was lost at that depth. However the main L/C depth changed from 2,040m to 1,890m as detected by the step rate test at the beginning of June. Characteristics of L/C fractures detected from injection PTS logging are a NW-SE strike steeply dipping to the north which is consistent with the characteristics of the Chinoikezawa footwall fault. Drilling induced fractures which indicate the present stress state were observed showing approximately an E-W direction in the 12-1/4” casing and N-S direction at around 1,950m. Permeability evaluated from a falloff test was 0.5darcy-m with a skin factor of -4.2.

3.3 Outline of the recharge operation

Before starting the recharge operation, a PT monitoring system was installed in the well and an AE/Micro seismicity array was prepared. Regular two phase and gas tracer tests, geochemical sampling and PTS+fluid sampler logging close to the recharge well were organized. In addition steam, brine, wellhead pressure etc were monitored by the DCS (distributed control system) of the power plant.

Recharge operations started in the beginning of June 2015 with short term step-rate tests to confirm the capacity of the well (see Figure 5 in 3.4). Although the original plan was to change the injection rate in 3 steps (50, 70, 100t/h) before the power plant preventive maintenance check-up scheduled for September 1, only two step-rate tests were done before the check-up because of a decline of superheat in Well-5 and river water pumping limitations during the summer.

After the check-up, recharge re-started from November 27 with short term step-rate tests, after which recharge continued at a rate of 70t/h. Due to decreases of the amount of superheat and steam rate and cyclic effect of the steam with the production of brine that was observed in late December at Well-8, the recharge operation was stopped on Dec. 26.

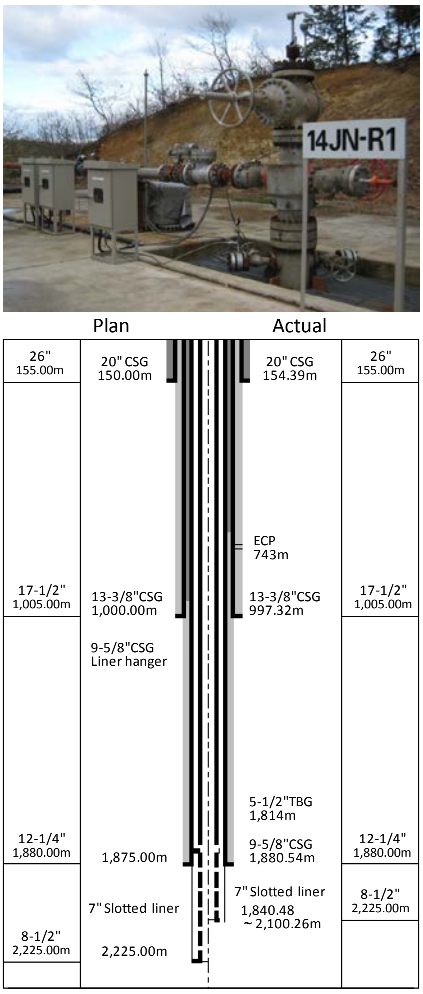

Figure 3: Casing program and a picture of the wellhead

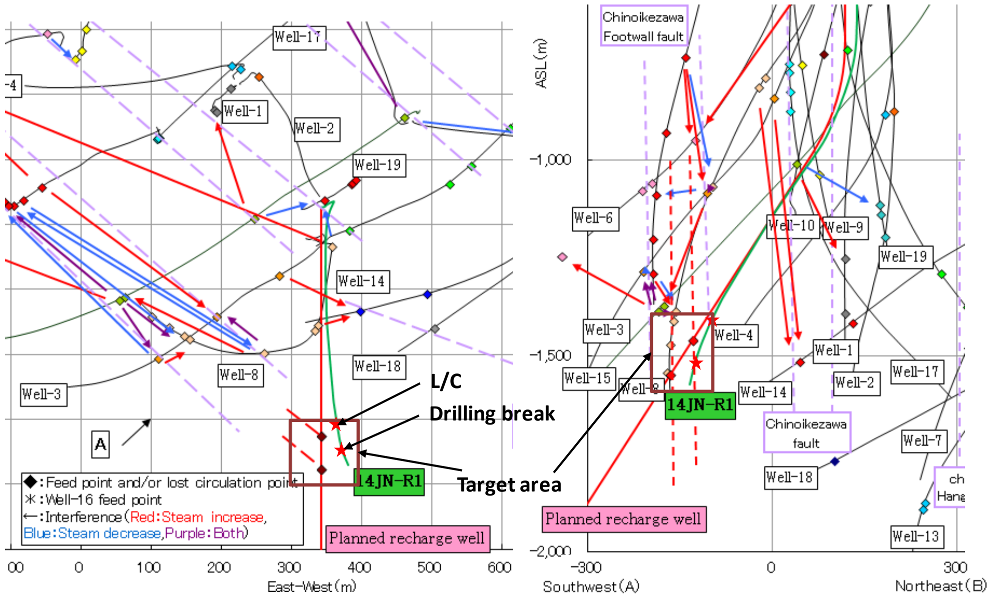

Figure 4: Drilling target and result shown with field injection test results(Plan view)

3.4 Acquired data

(1)PT monitoring data in the recharge well

A high temperature and pressure monitoring tool was installed at 1,895m in the recharge well. The reservoir pressure and temperature before recharge are 9.2MPa and 313°C respectively (Figure 5). Injection pressures increased and temperatures decreased once injection started. Injection pressures after the power plant preventive maintenance check-up decreased by about 1.5 MPa and temperature increased by about 10°C despite using the same injection rate (70t/h).

(2)Production data close to the recharge well

Production restarted from Nov. 13 and an initial steam decline was observed but the steam rate was almost steady from Dec.5 to Dec.23 in Well-8 (Figure 6). The amount of superheating decreased from 22.4 to 18.0°C on Dec 23-24. Steam flows decreased from 19.6t/h to 16.8t/h on Dec 24-25. Note that the injection rate was reduced from 70t/h to 50t/h on Dec 25. The amount of superheating decreased to 0.8°C on Dec 26. The recharge operation was stopped on the same day. The well was separated from the power plant because of the cyclic effect between Dec 28 and Jan 14. The well was connected to the power plant again on Jan 14. The steam rate for Well-5 and Well-6 were almost steady with small increases by a few tons per hour after the check-up.

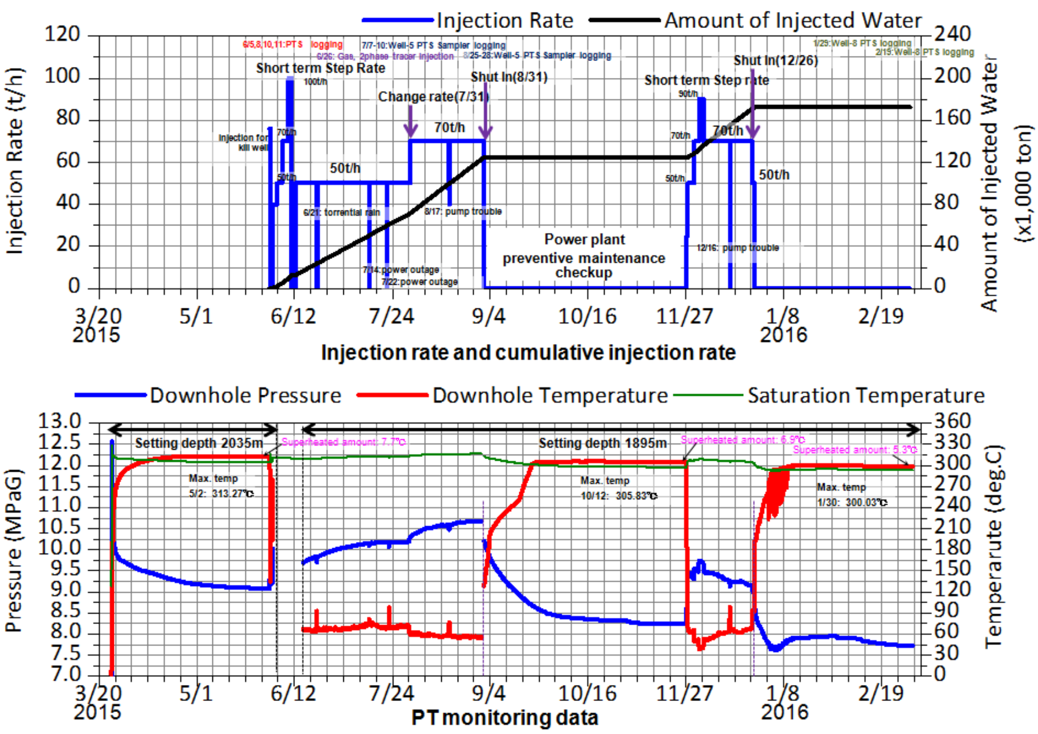

Figure 5: Recharge history and downhole pressure and temperature data in the recharge well at 1,895m

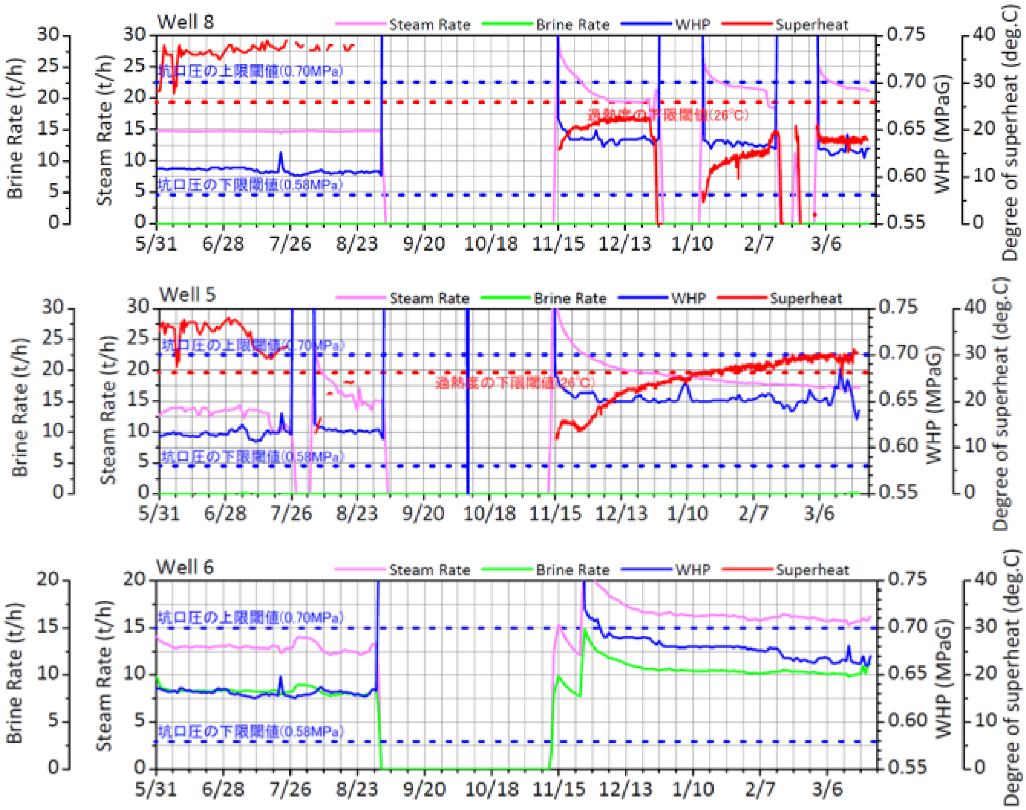

Figure 6: History of production at Well-8, Well-5 and Well-6

(3) Geochemical data at Well-8

During the recharge test, the isotope ratio moves to meteoric water (red arrow in Figure 7). It is supposed that the production fluid includes the injected river water.

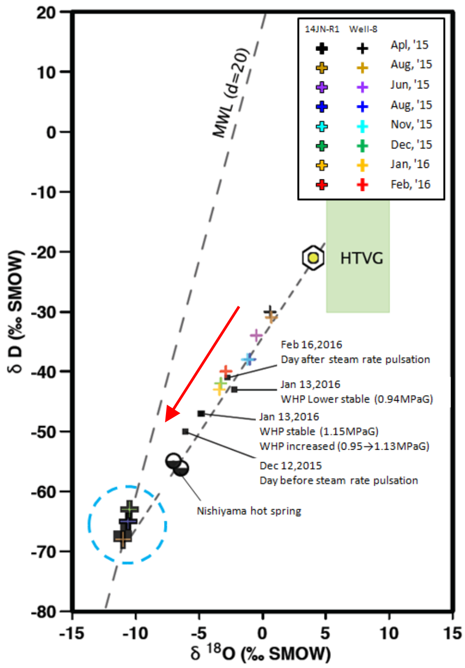

Figure 7: Isotope analysis at Well-8

(4) Tracer test data

Figure 8 shows a tracer (PDMCH:Perfluorodimethyl Cyclohexane) test result. The tracer was detected at wells mainly in the east and to the north of the recharge well (circles painted in pink in Figure 8).

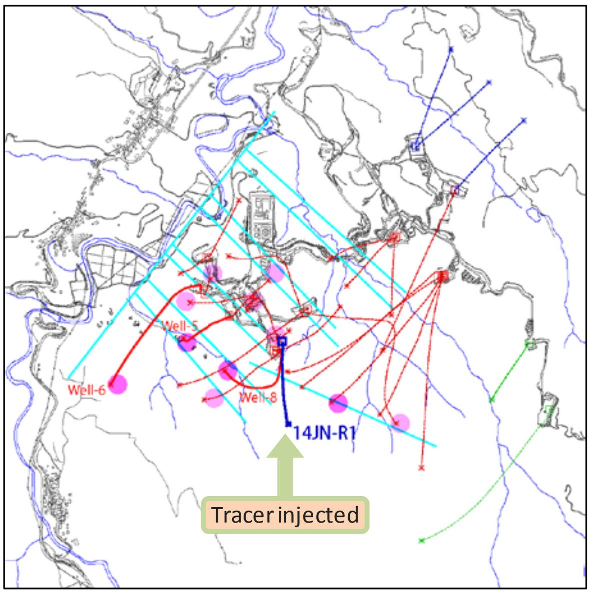

Figure 8: Tracer (PDMCH:Perfluorodimethyl Cyclohexane) test result, pink painted circles show wells that the tracer was detected

(5)AE/Micro seismic data

The installed AE/Micro seismicity array is shown in Figure 9. Ten surface stations and four borehole stations were used to observe AE/Micro seismicity. There were five existing surface stations and the other five surface stations and four borehole stations were newly installed for the project. AE/Micro seismicity was observed during the recharge experiment (May 1, 2015 to February 29, 2016) and 1,201 events were determined their locations out of 2,535 observed events. Table 1 shows the average number of events per day at different stages of the recharge operation. Because borehole stations were installed, AE/Micro seismicity observed increased by approximately 3-4 times more than with the previous array. During background monitoring before the experiment, AE/Micro seismicity occurs at the north-east part of the recharge well (Pink dots in Figure 10). It occurs at the south-east part of the recharge well also below the Chinoikezawa south-east fault during 70t/h injection. Since the events below the fault do not occur during the background period, these events are considered to be injection induced micro seismicity. Figure 11 shows the frequency of AE/Micro seismicity with time. AE/Micro seismicity was at a maximum in August during the 70t/h recharge rate. Although the events increased with increasing the injection rate from 50t/h to 70t/h, the events do not correspond with increase of the recharge rate directly. Peak events at the end of July was in the 50t/h injection period and the peak events at the beginning of August was three days to a week later than the increase of the injection rate to 70t/h.

The tracer test and the fact that the west part of the recharge well is aseismic suggest that the west part could be more permeable than the east part of the recharge well.

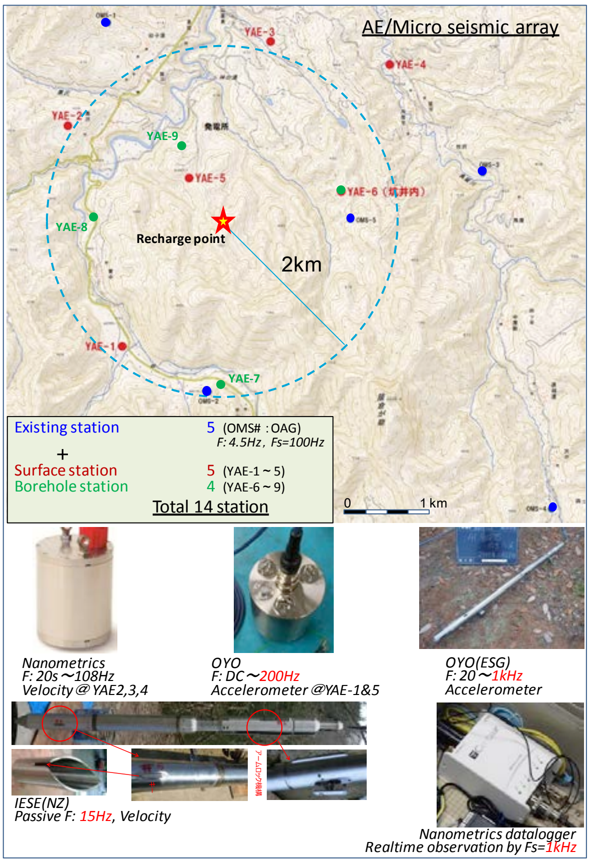

Figure 9: AE/Micro seismic array

Table1 : AE/Micro seismic event at recharge stages

Recharge stage	Back ground (May)	Step rate (Jun.)	50t/h (Jun.-Jul.)	70t/h (Jul.)	After injection (Aug.-Nov.)
Number of events per day	2.8	1.8	4.0	7.5	4.5
Local magnitude	-0.53	-0.58	-0.38	-0.37	-0.59

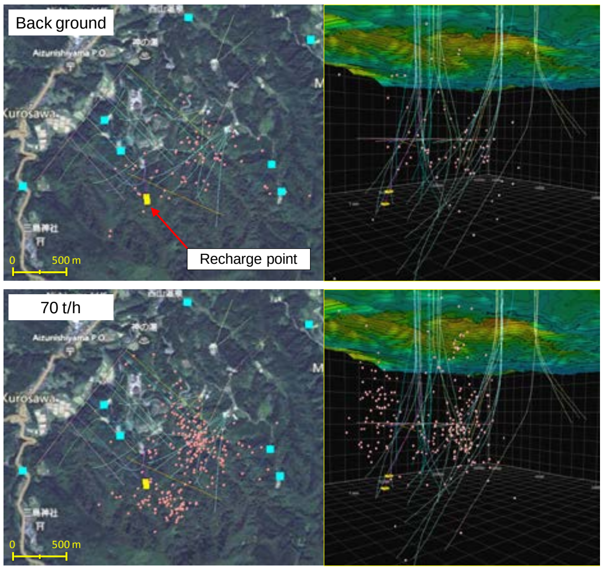

Figure 10: AE/Micro seismicity monitoring result

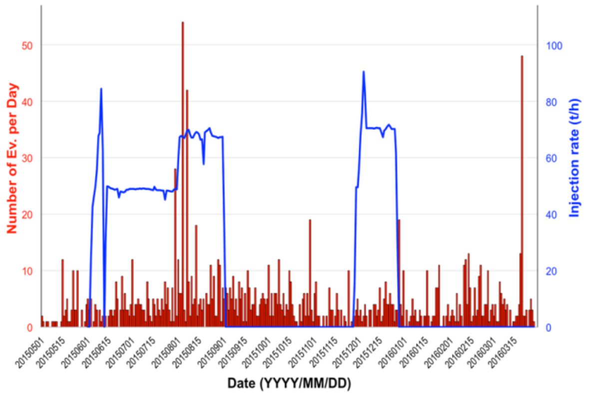

Figure 11 Frequency of AE/Micro seismicity

4. DISCUSSION

4.1 Spatial distribution

Figure 12 shows a plan view of the Okuaizu geothermal field and spatial distribution of the recharge well and feed points of Well-8. The shortest distance is 237.4m between the recharge point (1,890m) and 1,873m feed point of Well-8.

Total injection over the experiment is approximately 170k tons. With an assumed porosity of 0.1 (used in the simulation) and a thickness of the reservoir either 10m or 20m the effective radius of the injected water can be evaluated (Table 2). The effective radius changes depending on assumption of the thickness. It is possible for the recharge water to reach Well-8.

Table 2: Evaluated effective radius

Porosity	Thickness(m)	Effective radius(m)
0.1	10	232.6
	20	164.5

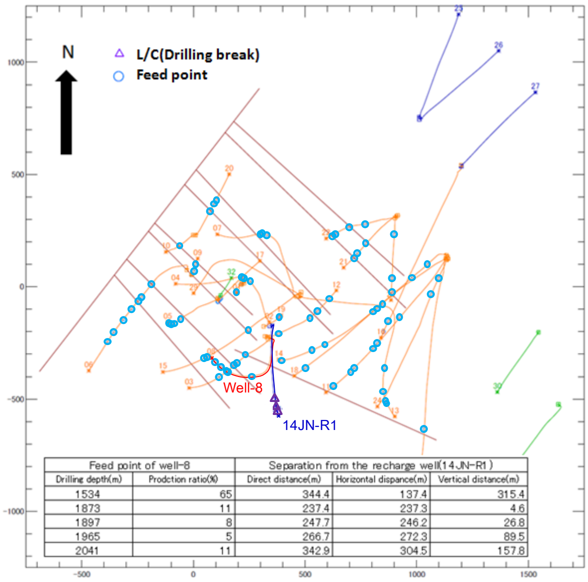

Figure 12 Plan view of the Okuaizu geothermal field and separation between the recharge well and feedpoints of Well-8

4.2 Recharge effect interpreted by the PT data

As mentioned in 3.4(1), injection pressures after the power plant preventive maintenance check-up decreased by about 1.5MPa despite of the same injection rate. After the check-up the temperature increased by about 10°C.

The suggested reason is an increase in fracture permeability and a reduction of the injection rate below 1,895m. The permeability close to the well could be enhanced due to micro seismicity, increase in fracture aperture due to thermal contraction or scale dissolution during the check-up. The injection water level estimated from the downhole pressure is around 850m. It may be possible for the recharge water to affect all of the feed points, including the shallowest one at 1,534m of Well-8, if fractures are well developed and connected in the reservoir.

4.3 Recharge fluid flow

According to the Well-8 production data, geochemical analysis, tracer test and AE/Micro seismic data, recharge water moved to the west side of the recharge well. Recharge water from 1,890m is considered to travel down to the deeper feed points of Well-8 (Figure 13).

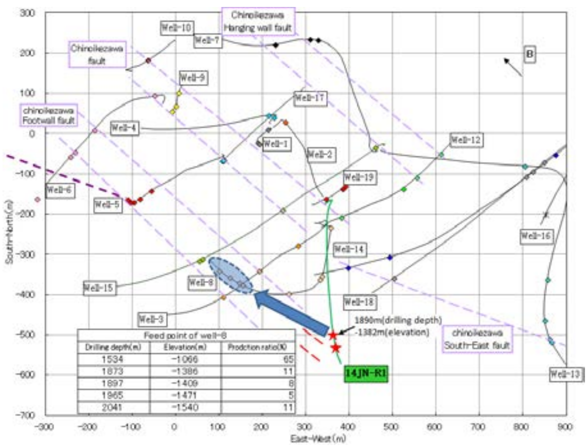

Figure 13: Recharge fluid flow to Well-8

4.4 Recharge induced production increase

The steam rate of Well-8 is stable at about 20t/h between Dec.5 and Dec.23. Also the amount of superheat tends to be constant (about 22°C) over that period. This is thought to be one of the benefits of the recharge operation. In order to evaluate the recharge effect on Well-8 quantitatively, the behavior of the well was compared with that from 2011. As a result, approx. 5t/h steam increase was estimated. Based on the analysis of a steam decline curve after the power plant check-up in 2015, approx. 3t/h steam increase was estimated (Figure 14).

The wellhead pressure of the productions wells 5 and 6 increased after the check-up. This could be caused by the reservoir pressure increase generated by boiling of the injected water (300°C) as well as recovery of the natural reservoir pressure.

The amount of superheat lowered after the check-up at Well-5. This is thought to be a diffusion effect of the injection water in the reservoir. It is possible that the stable steam production of both Well-5 and Well-6 near the recharge well is caused by the recharge operation. The tracer result suggests a connection between the production wells and the recharge well. It is possible to increase the steam rate by the pressure propagation generated by boiling of the recharge water (Figure 15). The production rate at the other wells will be reviewed and evaluated with regard to the recharge effect.

Although the duration of the recharge is about 4 months, the steam production at the field is consistent with the simulation result for the moment.

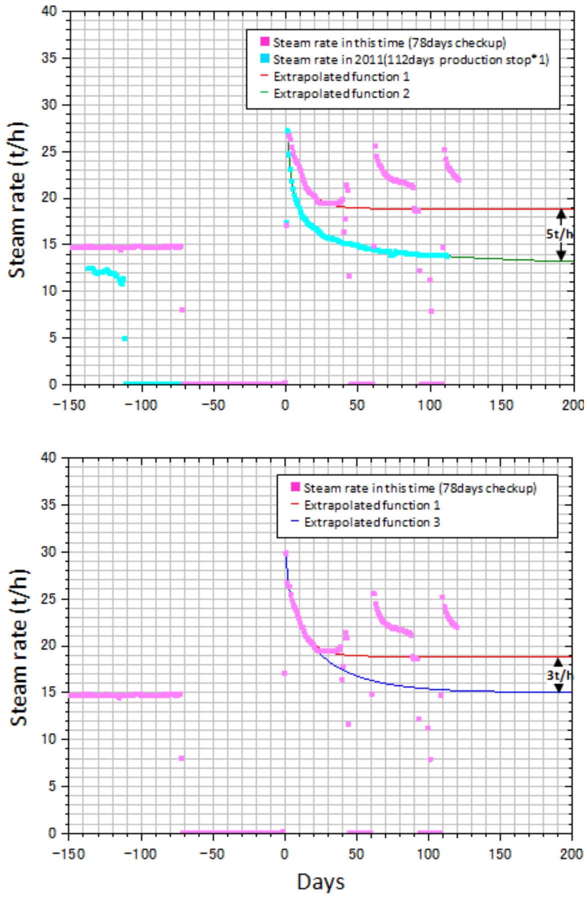

Figure 14 Comparison between 2011 drawdown and that in 2015 (this time) and different extrapolation

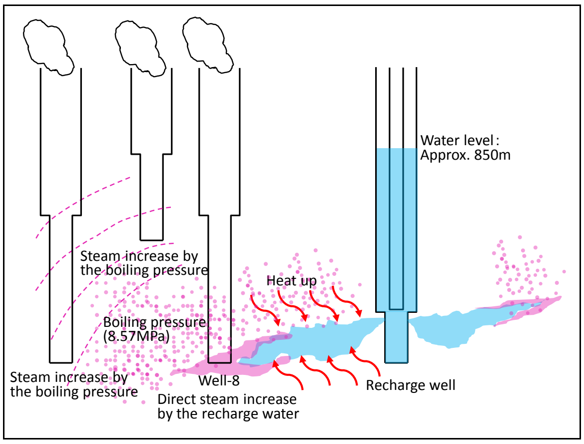

Figure 15: Recharge induced effect in the superheated reservoir

5. CONCLUSION

This paper presents the current status of the development of a technology for geothermal reservoir evaluation and control. It is based on an extensive recharge simulation study, including an investigation of the Okuaizu superheated geothermal reservoir in order to find a recharge well target. The well was drilled successfully and recharge operation started in June, 2015. Data such as downhole PT, AE/Micro seismicity, geochemistry, and a tracer test were acquired and interpreted during the injection period and the effect of the recharge was discussed.

The following is a summary of the achievements so far:

i) The cyclic behaviour of the steam production in Well-8 is thought to be caused by the recharge.

ii) A response to recharge (increase in steam flow) at Well-8 is observed and is estimated to be approx. 3t/h to 5t/h.

iii) The wellhead pressure and steam rate of the production wells 5 and 6 increased after the power plant preventive maintenance check-up. This could be caused by the reservoir pressure increase generated by boiling of the injected water (300°C).

iv) The tracer result suggests connections between the recharge well and wide variety of production wells in the field. It is possible to increase steam rate by the reservoir pressure increase generated by boiling of the recharge water.

v) It is possible to maintain and/or increase steam production by proper control of the recharge operation by comprehensive analysis of the amount of superheat, isotope analysis and so on.

Although further investigation is required about the recharge effect, production rate at wells close to the recharge well increased. In addition non-condensable gas (NCG) decreased at those wells, as another benefit of the recharge operation. Currently, together with evaluating the steam rate increase and NCG trends at the other production wells in the field, the root cause and the countermeasures for the cyclic effect at Well-8 are being discussed. Hopefully the recharge operation will re-start soon.

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REFERENCES

Capetti, G., Parisi, L. Ridolfi, A. and Stefani, G. : Fifteen years of reinjection in the Larderello-Valle Secolo area: Analysis of the production data. Proceedings of the World Geothermal Congress 1995, Florence, Italy, May, 1997-2000 (1995).

New Energy Development Organization, Geothermal development research report. No.8. Okuaizu region (in Japanese) (1985).

Nitta, T., Suga, S., Tsukagoshi, S. and Adachi, M. Geothermal resources in the Okuaizu, Tohoku district, Japan., Chinetsu24, 26-56 (in Japanese) (1987).

Nitta, T., Suga, S., Tsukagoshi, S. and Saiki, K. : Recent development of geothermal energy in the Okuaizu field, Fukushima prefecture. Annual Meeting Geotherm. Res. Soc. Japan Abst., D-14 (in Japanese) (1990).

Okabe, T., Sato, T., Osato, K., Saeki, K., Sakaguchi, K., Fujimoto, K., Shimada, T. and Tosha, T. : Current Status of Technology Development for Geothermal Reservoir Evaluation and Management, Proceedings World Geothermal Congress 2015, Melbourne, Australia, 19-25 April 2015.

Pruess, K., Oldenburg, C. and Moridis, G. : TOUGH2 USER'S GUIDE, VERSION 2, Lawrence Berkeley National Laboratory Report, LBNL-43134 (1999).

Seki, Y. : The physical and chemical structure of the Oku-aizu geothermal system, Japan, Geochemical Journal, Vol. 25, pp. 245 - 265 (1991).

Sanyal, K. and Enedy, S. : Fifty Years of Power Generation at the Geysers Geothermal Field, California; the Lessons Learned., Proceedings - Workshop on Geothermal Reservoir Engineering 191 (2011).