Applying EGS (Artificial Water Recharge) to a Geothermal Reservoir in Japan

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ABSTRACT

The power generation output of many Japanese geothermal power plants has been declining over time. One of the reasons is the imbalance between their production and the natural recharge of meteoric water. To mitigate or improve the decline, JOGMEC, an independent administrative agency in Japan, has focused on artificial recharge technology, which is classified as a type of enhanced/engineered geothermal system (EGS).

In 2013, JOGMEC set out a project to apply the technology to Japan's geothermal power plants. The purpose of this project is to establish appropriate recharge methods for their long term stable production, including techniques for predicting and evaluating the effects of the EGS (artificial water recharge). To establish methods and verify the effectiveness of the project, recharge tests were carried out in 2017 and 2019 through to early 2020 at the Yanaizu-Nishiyama geothermal power plant in Fukushima prefecture, of which production has been gradually declining. Although some positive effects of the EGS have been confirmed, continued recharge and further verification are required to establish the appropriate methods and prove their effectiveness.

1. INTRODUCTION

1.1 Motivation

Although Japan is known to have the geothermal power potential of approximately 23 GW, the third largest in the world, the total installed capacity of Japan's power plants was only 493 MWe as of 2018 (Thermal and Nuclear Power Engineering Society, 2019), much lower than the potential. Moreover, as shown in Figure 1, the total capacity has hardly increased since its peak in 1997, and total output has been gradually declining since 1997. One of the reasons is the imbalance between production and the natural recharge of meteoric water. Once the water stored in a geothermal reservoir decreases, the reservoir becomes superheated and acidic, resulting in a decrease in steam. To mitigate or reduce the decrease, JOGMEC has focused on artificial water recharge technology, which is classified as a type of enhanced/engineered geothermal system (EGS) as described in Chapter 1.2.

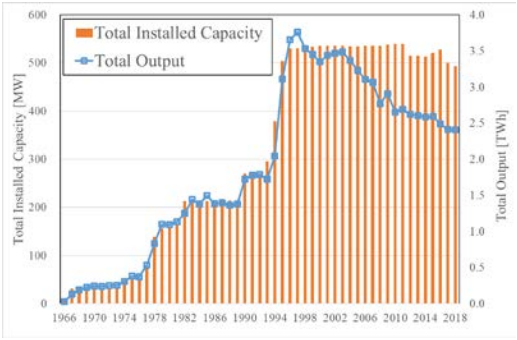

Figure 1: Total installed capacity and total output of geothermal power plants in Japan.

1.2 Overview of EGS

EGS generally refers to the systems that create engineered reservoirs to produce energy from geothermal resources that are not economical. It has been studied, developed and used in power plants around the world since the late 1970's (MIT, 2006). There are many different approaches to EGS, therefore, JOGMEC has classified it into three categories as shown in Table 1 and Figure 2.

Table 1: Classification of the EGS type by JOGMEC.

Type-A	Artificial reservoirs creation by a hydraulic fracturing, and energy extraction (HDR system).	Ex.) Hijiori Fenton-Hill Cooper
Type-B	Extension of natural fractured zones and increasing permeability by well stimulation.	Desert Peak Landau Paralana
Type-C	Recharge water into geothermal reservoir via wells.	The Geysers Larderello

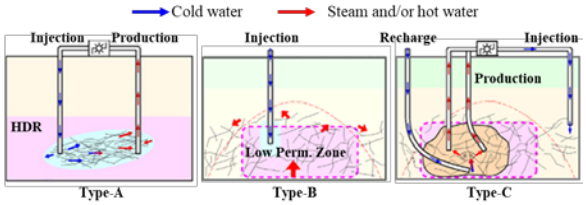

Figure 2: Conceptual models for three types of EGS.

Type-A EGS creates artificial reservoirs in hot but dry rock regions by fracturing with a pressurized water, then extracting heat via a closed-loop of the pressurized water. It is generally called a hot dry rock (HDR) system. In Japan, HDR tests were carried out in Hijiori, Ogachi and Hachimantai. Although these tests were terminated because of political reasons, many new findings were acquired (Matsunaga et al., 2005) and they have contributed to the development of HDR systems.

During Type-B EGS well stimulations, such as injecting low-pressurized water and/or acidic agents, expand natural fracture regions with low permeability, and thereby increases productivity or injectivity of the reservoir. Tests were conducted in Germany and several other countries. JOGMEC also conducted a Type-B test in Namarikawa in FY2019 and is currently evaluating its results.

Type-C EGS improves decline of reservoir pressure and water shortage in the reservoir by injecting river water or household waste water directly into the reservoir. It can also improve the superheating and acidification of the reservoirs. Power plants such as The Geysers in the United States have applied this Type-C EGS since 1997 and it has contributed to improvements in their power output (Sanyal et al., 2011).

A survey was conducted among geothermal engineers in Japan to investigate difficulties they have been facing in their power plants. The results showed that they had been experiencing not only the decline of their production but also reservoir troubles such as the superheating and acidification of the reservoirs. In addition, it was further found that they had been interested in applying Type-C EGS to their field to solve their troubles. Some of them were interested in Type-A and Type-B EGS, however, almost all of them were reluctant to apply it to their power plants due to concerns about earthquakes. Therefore, JOGMEC decided to work on the R&D of Type-C EGS.

2. PROJECT OVERVIEW

2.1 Purpose

Careful planning for applying Type-C EGS (hereinafter, just referred to as "EGS") is important because haphazard recharge can lead to reservoir cooling and earthquakes. Therefore, the R&D project of the EGS aimed to establish proper methods. A verification test was set out in 2013 for geothermal engineers to suitably apply EGS to their power plants. Findings from this project will be compiled as a technical manual, which will include the following.

- Method to determine recharge regions by simulation.
- Method to design a casing program of a recharge well.
- Method to plan the proper recharge.
- Method to predict and evaluate recharge effects and risk.
- Method to monitor environmental impacts.

The final goal of this project is to ensure that EGS leads to stable power generation in the long term. This paper mainly describes the provisional results of the recharge test carried out in FY2019.

2.2 R&D process

As a part of the project, a verification test at the Yanaizu-Nishiyama power plant was carried out. Before the test began, a geological model and a reservoir model were built based on existing well-log data and geophysical survey data. Recharge target regions and a recharge plan were then determined by numerical simulations. Finally, the recharge well was drilled toward the target regions. In order to evaluate its recharge effects, PTS Logging, chemical properties analysis and tracer tests were periodically conducted at several production wells. In addition, acoustic emission (AE) monitoring and hot spring monitoring have been conducted during the project period to detect any adverse environmental impacts of the water recharge in advance.

2.3 Test field overview

2.3.1 Geothermal power plant in the test field

Figure 3 shows a bird's-eye view of the Yanaizu-Nishiyama geothermal power plant, single flash type, in Oku-Aizu region of Fukushima prefecture in Japan. The power plant is operated by Tohoku Electric Power Co., Inc. and is supplied with steam by Okuaizu Geothermal Co., Ltd (OAG). As shown in Figure 4, when its commercial operation began in 1995, its installed capacity was 65 MW, however in 2017, its turbine was renewed for 30 MW of power generation due to declining output mainly because of shortages of the natural recharge water. Moreover, its geothermal system was liquid dominated at first, however, it has been shifting to steam dominated with production over time.

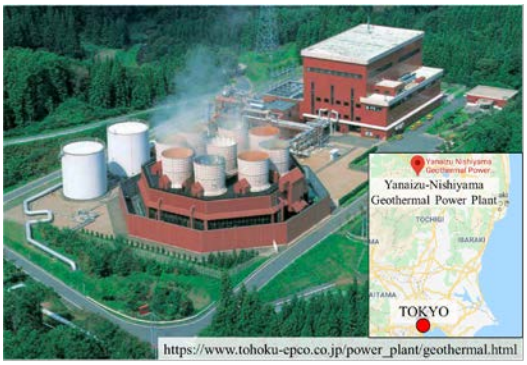

Figure 3: Bird's-eye view of the Yanaizu-Nishiyama geothermal power plant (provided by Tohoku Electric Power Co., Inc.).

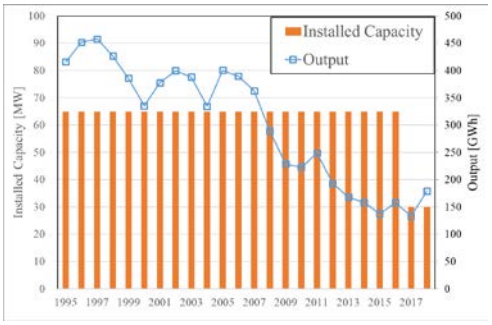

Figure 4: Output per operating year at the Yanaizu-Nishiyama geothermal power plant.

2.3.2 Geological setting

Nitta et al. (1995) have described the geological setting of the Yanaizu-Nishiyama area. Tertiary volcanic sediments called Green tuff are extensive and deep, and cover Quaternary caldera sediments in this area. Basement rock has never been confirmed directly, but assumed to be composed of a granite dating from the Paleozoic to the Mesozoic and from the late Cretaceous to the Paleogene period. The geothermal reservoirs have mainly formed by two faults zones named the Chinoikezawa fault zone (CFZ) and the Sarukurazawa fault zone (SFZ), both which have NW-SE strikes and steep NE dips. Fractures in the reservoirs have opened in deep zones, but have closed at several 100 meters below the surface due to clay altered rocks (Cap rocks). As shown in Figure 5, the meteoric water penetrating deep underground through faults is heated by heat sources which are assumed to exist several kilometers just below this area and is stored in the reservoirs. The maximum fluid temperature reaches almost 350 degrees

Celsius. In addition, magmatic gas is mixed into the water during the convection process.

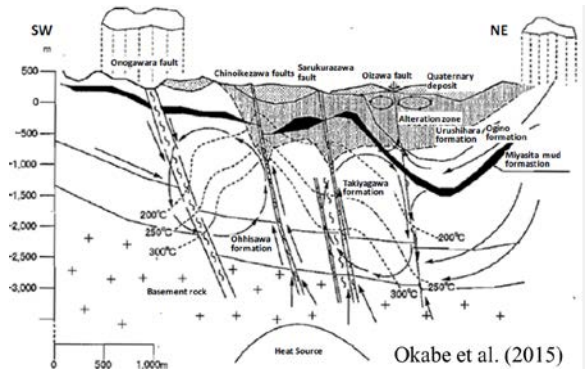

Figure 5: Cross sectional view of the geothermal system in the Yanaizu-Nishiyama area.

2.3.3 Production wells

Figure 6 shows a location map of the twenty production wells and three injection wells drilled by OAG so far. In order of proximity to a recharge well, Well-8, Well-3, Well-5 and Well-6 have been drilled as a production well on a Chinoikezawa footwall fault zone (CFFZ), which forms the CFZ. The other production wells referenced in this paper, Well-1, Well-2, Well-4, Well-12 and Well-17 have been drilled in the other reservoirs.

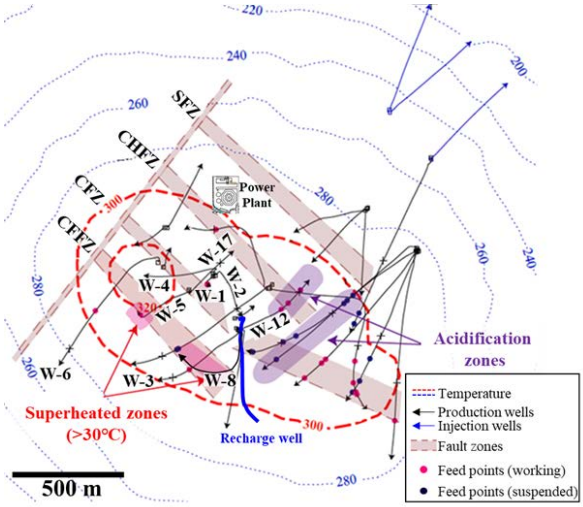

Figure 6: Well locations in the Yanaizu-Nishiyama area.

In this area, the superheating and acidification of the reservoirs are the main problems. The pink regions around Well-5 and Well-8, and the purple regions (both shown in Figure 6) represent superheated reservoir zones over 300 degrees Celsius and acidification reservoir zones, respectively. Production wells, including Well-12, located on the acidification zones have ceased production due to acidified fluid production. These regions have been chosen as targets for verifying the recharge effects in this project.

3. PRE-SIMULATION OF RECHARGE TEST

Okabe (2015) has described in detail the how the feasibility study of the recharge test was carried out and how the recharge region was determined. Here we briefly describe an overview.

3.1 Geothermal structural model

Although the basic geothermal structures of this test field are well known, a detailed geothermal structural model with clear ranges of the water migration for recharge simulations was required to determine the recharge regions. The model was built based on a geological map from existing well-log data and geophysical survey data such as the magnetotelluric (MT) method. Figures 7 to 9 show the final structural model used for our project. After the recharge test in 2015, a range of cap rock regions in the model were updated based on the AE monitoring that occurred during the test, and were finally classified into twelve blocks. Block 1, 2 and 3 have relatively high permeability to the extent that steam production is possible. Although Block 2, below the depth of the kaolinite alteration zone, was assumed to be cap rock due to its low resistivity, it has been reinterpreted as a region of the hot water migration because the AEs occurred there. Blocks 4, 10, 11 and 12 are low and high permeability mixed zones. Block 5, which shows high resistivity, is a very low permeability zone where dense rocks were confirmed, constricting the movement of the water. Blocks 6, 7, 8 and 9 have 300 m to 500 m thick cap rock composed of altered clay.

Note that the model's update has not affected the results of the simulation, described below, for determining the recharge region and predicting future production. This is because the simulations were carried out using an extraction from the model which encompassed only the reservoir region, which was not updated.

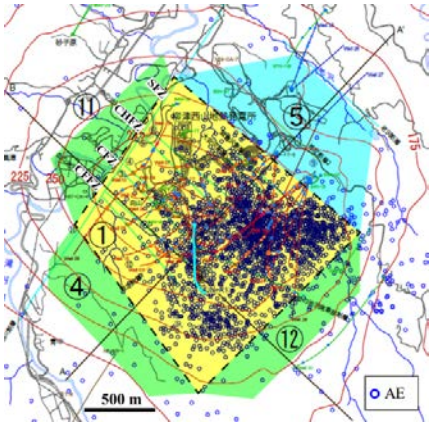

Figure 7: Plan view of the geothermal structural model.

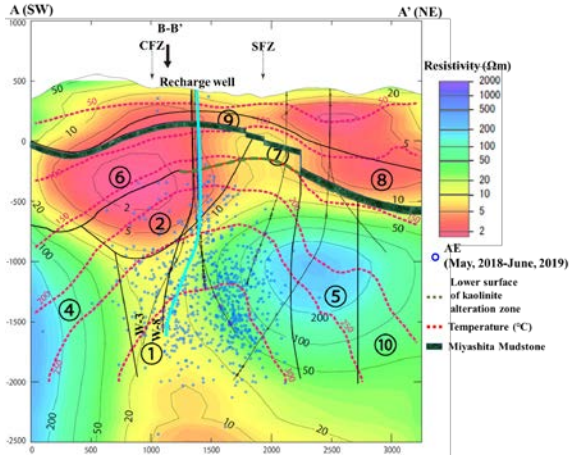

Figure 8: A-A' sectional view of the geothermal structural model.

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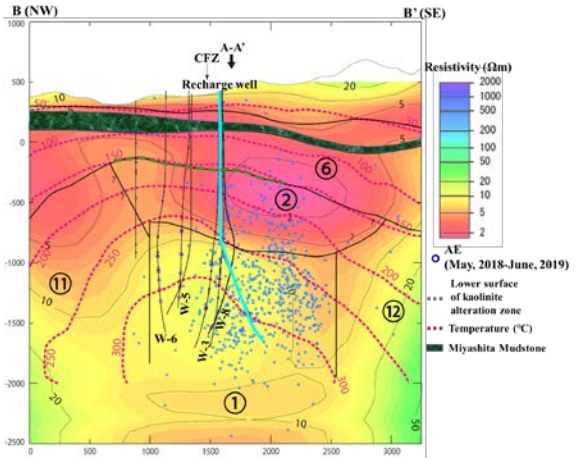

Figure 9: B-B' sectional view of the geothermal structural model.

3.2 Prediction of future production without EGS

Since operation of the power plant commenced, OAG had assessed their geothermal resources and have predicted future production based on a 3D reservoir model optimized by history matching simulation. However, the reservoir model had not considered the influence of the superheating that developed within the reservoir, so the original simulation model was updated into a new model. Future production from the new model, without the EGS recharge, was predicted and the results are shown in Figure 10. The results show that production in 2030 would be almost two-thirds lower than in 2013 (the date the simulation was conducted), if no EGS was applied.

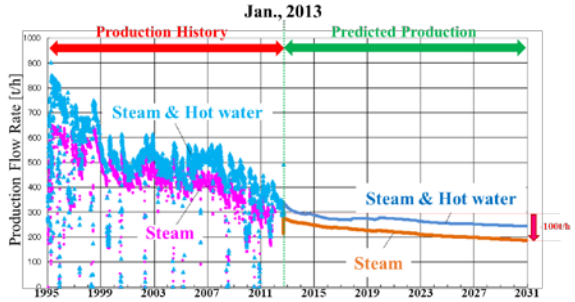

Figure 10: Predicted production without the recharge.

3.3 Determination of recharge region

The recharge region was determined considering the superheated region, the balance of the positive effects of the recharge with risks such as over cooling of the reservoir and the short circuit between the recharge well and each production well. Considering the above, as well as geographical constraints, the recharge well's location was determined.

Determining the recharge well's feed zone / recharge region was more involved. First, the production zones of the reservoir model discussed in sections 3.1 and 3.2 were built as a MINC model. Second, several candidates for the recharge regions were selected outside of the existing production zones, as shown in Figures 11 and 12. Third, a production and recharge simulation was run, using five cases of artificial water recharge injection rates of 0, 15, 30, 50 and 100 t/h at each selected region, respectively. Figure 13 shows a part of the simulation results of the 15year future production with/without the recharge. Finally, we compared all the results and decided on the recharge region.

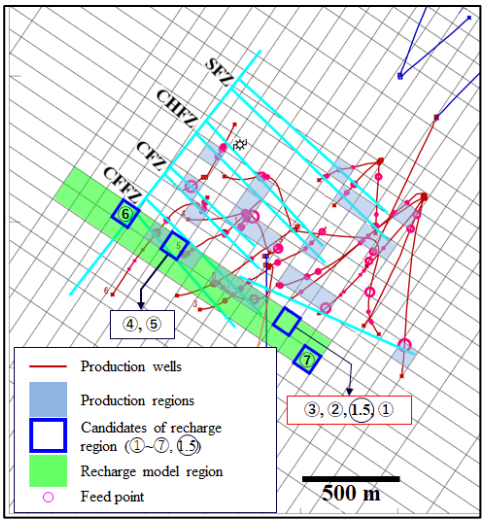

Figure 11: Plan view of the simulation model with the artificial recharge region candidates.

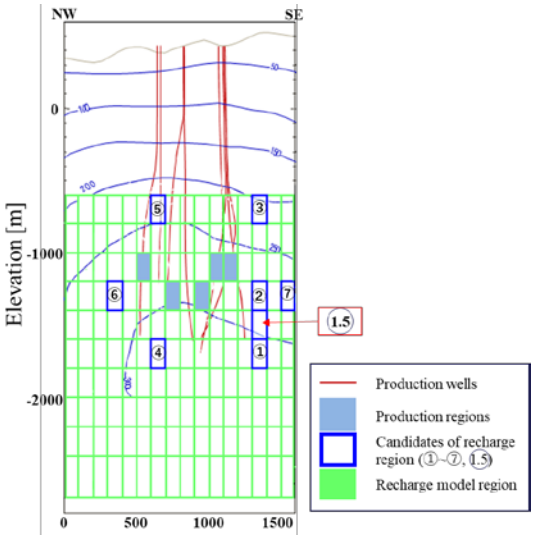

Figure 12: Sectional view of simulation model.

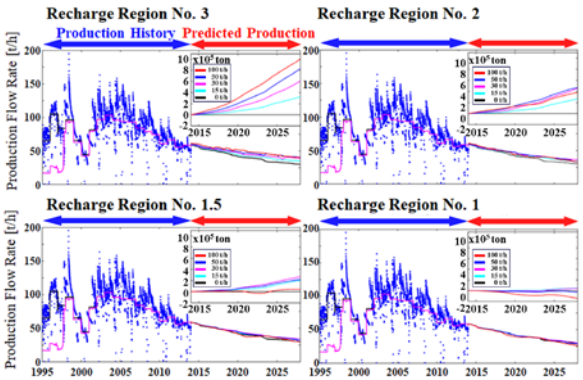

Figure 13: Simulation results of predicted production with/without the recharge. The upper right-hand graph within each graph shows the difference between the cumulative steam when recharging at each water injection rate and the base case (0 t/h).

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The selection of simulation results, showing the resulting flow rate depending on the various recharge regions, and a comparison of which recharge rate is most effective are shown in Figure 13. Region No.3, right near the surface had the greatest recharge effect. However past results of water injection by OAG suggested that injecting water into shallow regions had been likely to cause production problems in well-5 and well-8 because the cool water flowed into them. Therefore, the recharge point was set at the region No. 1.5, 1 km below the surface but in the same vertical location was chosen. In addition, it was found that the steam may decrease when the recharge water injection rate is set above 100 t/h in some simulation cases, so the maximum injection rate was determined to be 100 t/h.

3.4 Recharge well

The casing of the recharge well was designed considering both the geographical constraints and the determined recharge region. The recharge well was drilled in 2014, and then the recharge testing began in Jul., 2015. However, the test was suspended because a production problem in Well-8 occurred in December 2015 while the recharge water was being injected. Upon investigation, it was revealed that the recharge water flowed through behind Well-8's casing where the cement had deteriorated by heat shock between the 9-5/8" casing shoe and the shallow regions where there had been fears of production problems as mentioned above. Therefore, the recharge well was buried up to about 650 mMD and a sidetrack well was drilled from 1,450 mMD (KOP) to 2,200 mMD, completed in Apr., 2019. In order to not have a repeat of the problem, a metal packer was used in 8-1/2" hole to isolate the shallow region. Figure 14 shows the recharge well's final casing program. The locations of lost circulation (LC) points in the open hole section were 1,957-1,970 mMD, 2,030 mMD and 2,120 mMD, and their initial outflow rates of water were 11 %, 86% and 3% respectively.

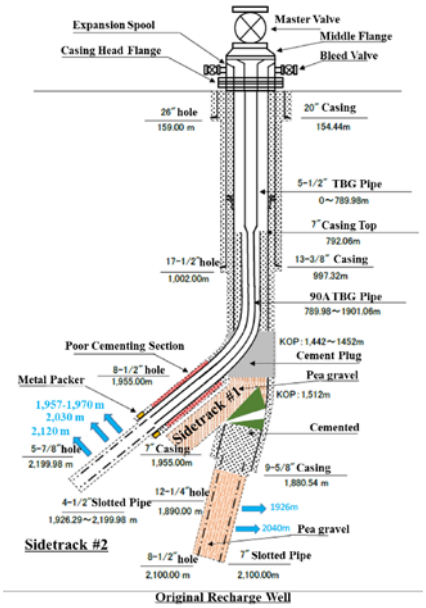

Figure 14: Casing program of the recharge well.

3.5 Overview of recharge test in FY2019

The recharge test was conducted from Jul. 2, 2019 to Mar. 6, 2020 except during a preventive maintenance inspection of the power plant from Sep. 7 to Oct. 22 (hereinafter, referred to as "inspection"). Figure 15 shows the recharge water injection rate and cumulative weight of recharge water injected for the FY2019 recharge test.

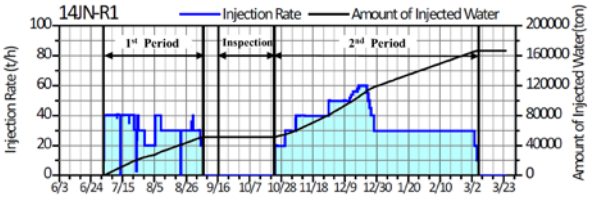

Figure 15: Recharge water injection rate and cumulative amount of the recharge water during the test in FY2019.

During the first recharge period before the inspection, the river water was injected at 40 tons per hour (t/h), not exceeding 50 t/h (the summer river withdrawal limit). During the second recharge period, the recharge water injection rate was planned to gradually increase up to the 100 t/h. However, on Dec. 25, the steam production and superheating in Well-8 dropped suddenly, so the recharge water injection rate was lowered to 30 t/h. On Mar. 6, 2020, the recharge was halted because the superheating in Well-8 reduced to less than 5 degrees Celsius and it began producing hot water along with steam. The total amount of river water injected during the recharge testing was approximately 166,000 tons.

3.6 Environmental monitoring

AE monitoring and hot spring monitoring have been continuously conducted as environmental monitoring for this project.

In addition to the five AE sensors which had already been installed by OAG, nine AE sensors were newly installed for this project within about 2 km radius around the recharge well as shown in Figure 16. Four of them were installed in the monitoring wells whose depth is about 250 to 400 mMD, and the others were installed at a depth of 2 m below the ground surface. During the recharge test period in FY2019, AEs over 2.0 local magnitude were observed three times. However, we concluded that those AEs were not directly caused by the recharge test because they were created in local seismically active areas away from the recharge regions.

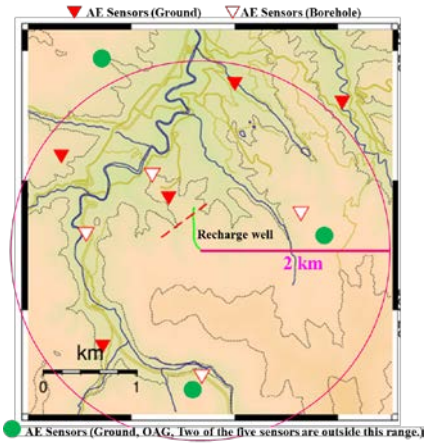

Figure 16: Location of the AE sensors.

For hot springs monitoring, the temperature of several hot springs around the power plant were continually observed. No temperature decreases due to this recharging test were observed.

4 Results

During the recharge test period, various data were observed to investigate and verify what changes are occurred in and around the geothermal reservoir by recharging water. Some of these results are described here.

4.1 AE

Figure 17 shows plan views of where AEs occurred before, during and after the inspection, respectively, from left to right. At first, the AEs occurred intensively southward of the recharge well for a while after the recharge began. This likely indicates that the recharge water improved its permeability and/or expanded the reservoir. Compared to where the AEs occurred during the recharge test in 2015, as shown in Figure 7, the AEs' location was obviously southward. After the inspection, there were no remarkable clusters of the AEs even after the recharge restarted. This was probably because the improved permeability made them less liable to occur, or the recharge water flowed into another regions.

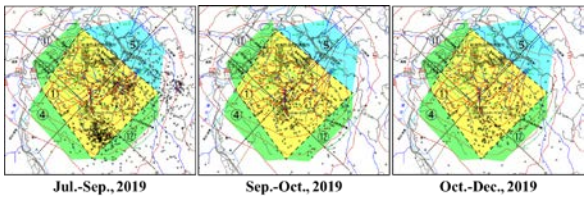

Figure 17: Plan views of the AEs events (left) before, (center) during and (right) after the inspection, respectively.

Figure 18 shows the A-A' sectional view of the resistivity map plotted the AEs' location occurred during the recharge test in 2019. As can be seen by comparing Figure 8 and 18, the depth of the AEs in 2019 shifted deeper than that in 2015. It was most likely because that the depth of the main LC point has been shifted deeper as mentioned in Chapter 3.4.

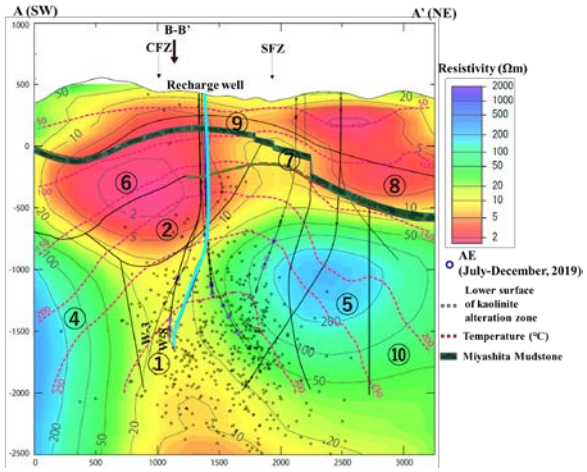

Figure 18: A-A' sectional view of the resistivity map plotted the AEs location occurred during the recharge test in 2019.

4.2 PTS Logging

PTS Logging was carried out three times in the recharge well in FY2019 as shown in Figure 19. As mentioned in Chapter 3.4, the depth of the main LC was 2,030 mMD. However, the temperature and spinner curves measured on Jul. 2, 2019 and Jan. 31, 2020 show the main LC point moved to 1,957 to 1,970 mMD below the 7" casing shoe. This was likely because the local permeability around the new LC point was improved by the recharge water. In addition, the gradual decrease in the reservoir pressure indicated the improvement of the permeability of the overall reservoir.

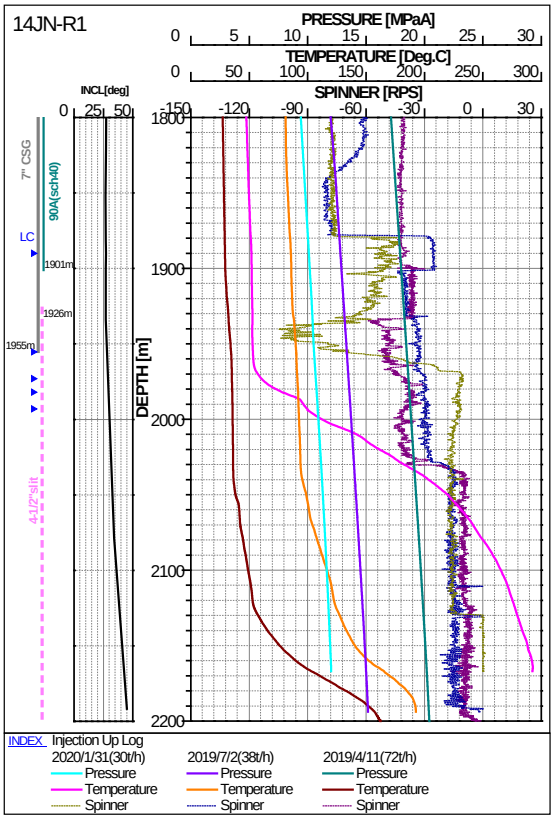

Figure 19: PTS Logging curves while water injection (Upward) conducted on Apr. 11, 2019, Jul. 2, 2019 and Jan. 31, 2020.

4.3 Water level in the recharge well

A pressure and temperature sensor has been installed at 726 mMD in the recharge well, and its water level has been continuously observed. Figure 20 shows the time series of the recharge water injection rate and the water level. The water level changing has been linked with the recharge water injection rate. As can be seen in the water level change, the reservoir's permeability was improved during the recharge test, and moreover the water level was dropped suddenly on Nov. 11, 2019, despite maintaining the recharge injection rate of 40 t/h. This sudden drop was possibly caused by the aforementioned changes in the main LC point.

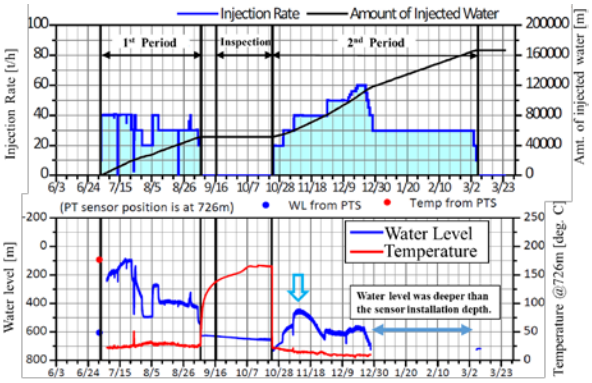

Figure 20: Water level in the recharge well.

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4.4 Geochemical analysis

Various geochemical analyses of the steam produced in several wells have been conducted once a month. The ratio of meteoric water to magmatic water in the steam (hereinafter, referred to as "meteoric water ratio") calculated from isotope ratios of hydrogen and oxygen was analyzed. To compare changes in each well, we evaluated how much the meteoric water ratio has relatively changed in each well since Apr., 2014. Figure 21 shows the relative change rate in percent of the meteoric water ratio in each well. Namely, the relative change rate as of Apr., 2014 is 0%, and the "positive" relative change rate means that the meteoric water ratio has increased compared to that as of Apr., 2014. The wells under this analysis here were Well-5, Well-6 and Well-8 on the CFFZ and Well-1 for comparison. The results shows that the relative change rate in Well-6 was slightly increased at the end of the recharge test, and that in Well-5 and Well-8 were clearly increased after the inspection. Moreover, their relative change rate was found to be increased according to their distance from the recharge well. Meanwhile, the relative change rate in Well-1 was almost unchanged. These results indicated that much of the recharge water likely reached each well on the CFFZ through the CFFZ after the inspection, in order of proximity to the recharge well.

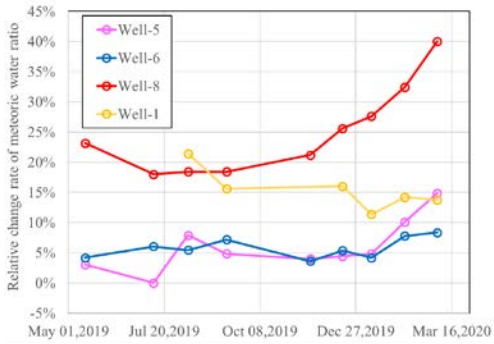

Figure 21: Relative change rate of the meteoric water ratio since Apr., 2014 in each well.

4.5 Steam production

The pink line in Figure 22 shows the steam rate in Well-8 during the recharge test. It was temporarily increased due to the operation of the valve in Well-8 for the inspection, however, at the end of the test it settled down to about the same level as before the test began.

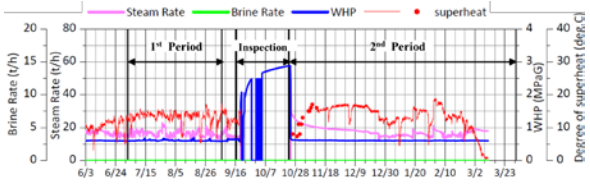

Figure 22: Steam rate of Well-8 during the recharge test.

However, the steam rate in several wells has increased from a long-term perspective. Figure 23 shows steam production histories in each well on the CFFZ since 2000, while Figure 24 shows those in the others. The production in all wells has been decreasing less and less every year since their production started. However, since the recharge started in 2015, the production in each well on the CFFZ has increased or been even maintained. On the other hand, the production in the others has not changed, except for Well-17 which was washed by chelating agent in 2014.

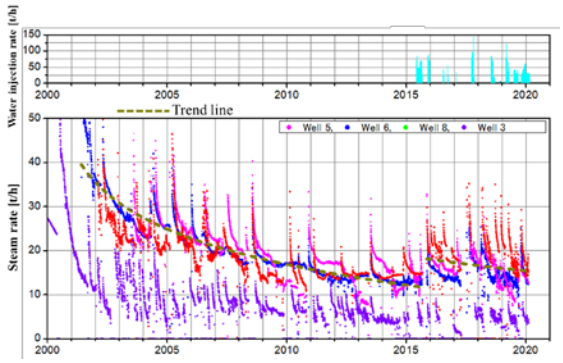

Figure 23: Steam production histories in each well on the CFFZ.

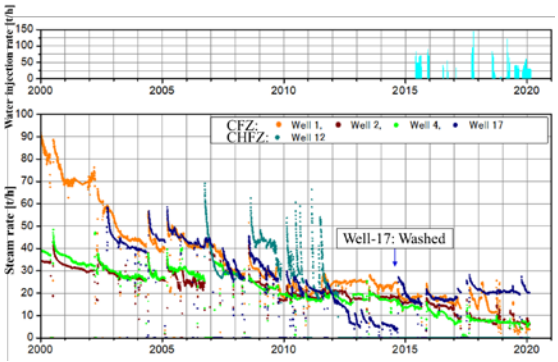

Figure 24: Steam production histories in each well on the other zones.

4.6 Superheat

Lowering the superheat degree of the reservoirs is one of the EGS's main objectives. In this test field, only Well-5 and Well-8 are currently producing the superheated steam. Figure 25 shows the superheat degree of the steam produced in each well on the CFFZ, while Figure 26 shows the others. As shown in Figure 25, the superheat degree of steam in Well-5 and Well-8 has been declining during the recharge period. Meanwhile, that in the others have not been changed. However, the recharge test was halted on Mar. 6, 2020 because the superheat degree of the steam in Well-8 had fallen to around 0 degrees Celsius (see the red line in Figure 22), which could lead to a production of hot water, resulting in a decrease in the steam.

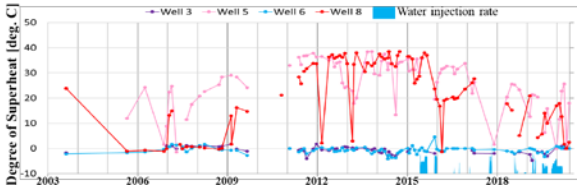

Figure 25: Superheat degree of steam in each well on the CFFZ.

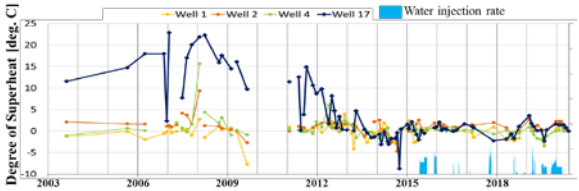

Figure 26: Superheat degree of steam in the other wells.

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4.7 Tracer test

Tracer test was carried out after the inspection. We tried Perfluorocarbon (PFC), a gas tracer and 2,2,2-Trifluoroethanol (TFEA), a two-phase tracer. These tracers were injected in the recharge well on Nov.7, 2019 and tracer sampling was conducted at several production wells including the wells drilled in the CFZ. Tracer analysis and evaluation are ongoing, however, both tracers were detected at Well-3, 5, 6 and 8 on the CFFZ. Especially at Well-8, they were detected within a few days. Moreover, their concentrations were higher in order of proximity to the recharge well. Meanwhile, although both tracers were detected at the other wells, their concentrations were low and their concentration peak had not appeared as of the end of FY2019.

5 Discussions

Observation of AEs, water levels and geochemical analyses during the recharge test in FY2019 indicated the following things.

- The recharge water flowed from the initial LC point at 2,030 mMD mainly to its southward at first, and then contributed to expand the reservoir to the south regions and/or improve their permeability.
- The depth of main LC point has shifted from 2,030 mMD to 1,957-1,970 mMD after the inspection, likely in early Nov., 2019. The recharge water from the initial LC point was less likely to flow out and thereby the new main LC points were stimulated and have improved their permeability.
- Almost all of the recharge water has flowed into the production regions on the CFFZ through the faults due to the shift of the LC points. The results of the tracer tests supported the discussion.
- Although the steam rate was not dramatically increased during the short recharge test period, the recharge has contributed to the steam increment from a long-term perspective.
- The superheat degree of the steam in Well-8 dropped too low and its production became unstable, so the recharge test had to be suspended. The recharge contributed to this problem, it is important to make a proper recharge plan so as to not cool the reservoir too much or too quickly.
- The improvement in the acidification of the reservoir needs to be confirmed in the future evaluation.

6 Conclusions

JOGMEC has carried out the EGS test at the Yanaizu-Nishiyama area in order to verify its effectiveness and establish its methods for geothermal engineers in Japan. The recharge region was determined by the numerical simulation based on the geothermal structural model and the reservoir model. Although the recharge test began in Jul., 2015, it was suspended in Dec., 2015 due to the recharge interference to Well-8. After the sidetrack well was drilled, the test resumed from Jul., 2019. In total 166,000 tons of river water were injected into the reservoir for about 200 days, excluding the inspection day. Based on the results of the various observations, we presumed that the recharge water which flowed out from the LC point at 2,030 mMD improved the permeability southward of the recharge well initially, however, it began to flow into the reservoir on the CFFZ because the main LC point was shifted to the shallower regions. Although the dramatic increase in steam was not observed during the recharge test period in FY2019, the superheat of the reservoir around Well-5 and Well-8 was found to be improved. However, the superheat degree of steam in Well-8 had dropped too low and its production became unstable, so the recharge test was suspended again. The recharge plan is needs to be reviewed in order to not repeat this problem. Further investigation is required to predict the EGS effects more accurately, establish its proper recharge operation procedure, and verification of effectiveness, including improvement of the acidification of the reservoir, is necessary.

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