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Development of Wellbore Simulator and Verification Test of High Temperature PTS+FLUID Sampler Logging System for a Highly Deviated Geothermal Well

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ABSTRACT

Development of geothermal energy has been restricted in Japan because approximately 80% of the abundant resources are located in national parks. To promote the energy diversification and utilization of the resources in the national parks efficiently, a R&D (Research and Development) project funded by the Ministry of the Environment on geothermal well drilling technology is under way in Japan. The project's purpose is to develop an environmentally friendly low-cost drilling technology for a highly deviated well (2,500m deviation, 70deg. inclination) to access the high-temperature geothermal resources from the outside of the national parks. The goal is to keep power generation cost as-is, even if a highly deviated well is drilled. To achieve the goal, there are concrete targets of the project such as 10% drilling cost reduction and 50% productivity increase through technology developments, including cutting-edge technologies to increase ROP (Rate of penetration), optimal CSG design, logging and so on. In the course of the project, a wellbore simulator and PTS+fluid sampler system with roller centralizers were developed. A wellbore simulator applicable for a HDW was developed to compare steam flow rates with drilling costs for different well deviations. The drift-flux correlation was identified as most suitable for these wells, and integrated into the existing GFLOW wellbore code to simulate the HDW. We confirmed applicability of this correlation by the model calculation and the comparison with the actual logging result. The wellbore simulator was used to estimate the optimal drilling direction that maximized the economic return from the well. In order to evaluate productivity of the HDW, roller centralizers were added to a PTS/two-phase sampler logging tool. The tool can simultaneously acquire PTS data and collect fluid samples. The pressure and temperature specifications are maxima of 34.5MPa and 350deg.C respectively. The capacity of the sample chamber is 500mL and the sampler can acquire brine, vapor and/or two-phase fluid. The tool was applied to geothermal production wells for the first time in Japan, and PTS data and downhole fluid samples were successfully collected simultaneously. Because the roller centralizer was effective in centering the tool in the hole, the tool's up-and-down behavior was very smooth and the spinner data was of excellent quality. In this paper, outlines of the project, the development of a combined wellbore simulator and the PTS+fluid sampler system are presented in detail.

1. INTRODUCTION

Among the high-temperature geothermal resources of above 150deg.C in Japan (reserves 23,470MW), the potential within the national parks that mainly hold volcanic areas is the third-largest in the world (Muraoka, 2009), and the total amount of resources in the special protection zones (19,220 MW) accounts for 81.9% of the total. Geothermal development within the national parks is essential for the promotion of geothermal power generation as a renewable energy resource with stable output that reduces emissions of carbon dioxide, but it has a trade-off relationship with protection of the natural environment. Therefore, the development has not proceeded under the current situation. In order to promote geothermal energy development in line with conservation of the natural environment, techniques for geothermal power generation that avoid or minimize adverse effects on the natural environment are required to be developed. One of such techniques is control drilling, which can extract geothermal energy inside the national parks from the outside.

The maximum displacement and the deviation angle of a geothermal well in Japan is 1,500m and 75deg. respectively. Drilling a highly deviated well (here after referred to as "HDW") under the conditions of hard rocks, high temperatures, and complex formations etc. that features the geothermal resources often involves unknown factors in the aspects of techniques and costs, and also it is challenging (Glynn-Morris et al., 2009). Therefore, achieving the HDW drilling under geothermal conditions safely at low cost is essential. However, there are few examples of comprehensive discussions including the costs and risks involved in the HDW drilling techniques.

The present technical development carries out R&D into a low-cost, controlled, directional drilling technique for the drilling of the HDW for efficient geothermal power development, and aims for the development of geothermal resources in the national parks in line with conservation of the natural environment. Specifically, the technical development for approximately 2,500 m deviation and 70deg. inclination well drilling is targeted.

2. OUTLINES OF THE PROJECT

The cost reduction targets in this project are as follows:

(1) Cost per well (cost per unit drilling distance): 10% reduction in well drilling compared to the current cost is targeted;

(2) Productivity per well: 50% increase in steam generation by drilling into high temperature and permeable zones in the national parks;

(3) Cost of power generation (cost per unit steam flow rate): Reduce the cost of power generation with 3,000m class drilling to the same level as the standard power generation cost with the existing 2,000m class drilling.

The present project consists of three aspects: the overall design, development of the control drilling system in the HDW, and demonstration tests. The overall design includes surveillance of cutting-edge techniques, development of a cost analysis tool, and manual creation, etc. Development of the control drilling system in the HDW consists of the following seven component techniques: the technique to increase rate of penetration in hard rocks, the control drilling technique in the HDW, the mud design and control technique in the HDW, the wellbore cooling technique in the HDW, the technique to cure lost circulation in the HDW, the technique to design optimum casing in the HDW, and the logging technique in the HDW. By combining these techniques, including the introduction of cutting-edge techniques, we will enhance the efficiency of controlled drilling of the HDW, and through demonstration tests will achieve the cost reduction targets mentioned above. The following is a brief description of the purpose of each component technique:

(i) Technique to increase rate of penetration in hard rocks: achieves improvement in the rate of penetration (ROP) in geothermal-specific hard, high temperature, and complex formations by using the latest drilling motor, bit, and top drive. (ii) Control technique in the HDW: in order to improve control drilling in the geothermal-specific hard, high temperature, and complex formations, we are executing the optimal directional drilling plan, conducting optimal control drilling using MWD, optimizing BHA, reviewing and evaluating torque-and-drag reduction tools, and reviewing and evaluating of drilling fluid lubricants. (iii) Mud design and control technique in the HDW: using large-scale experiment facilities; experiments are carried out on the behavior of mud water, and the optimal control of mud water in geothermal highly deviated drilling is considered through analysis results. (iv) Wellbore cooling technique in the HDW: in order to improve the cooling efficiency inside the HDW under a high-temperature environment, we are reviewing and evaluating the drilling fluid cooling device and considering the predictive simulation of wellbore temperature for the HDW by improving Geotemp2 (Mondy and Duda, 1984). The prediction of wellbore temperature is important from the viewpoint of the heat resistance of drilling tools. (v) Technique to cure lost circulation in the HDW: in order to improve the measures for lost circulation in HDW, we are implementing review and evaluation of aerated mud drilling and large pump rate fresh water drilling techniques as well as review and evaluation of ultra-light weight cement. (vi) Technique to design optimum casing in the HDW: in order to optimize the casing program for optimal production and safe drilling in the HDW, we have improved the wellbore flow simulator GFLOW (Kato et al., 2001) to cope with the HDW, and are considering the optimal design of casing (CSG), casing centralizers and cementing. (vii) Logging technique in the HDW: we are developing a logging system by using roller centralizers required for the formation evaluation in the HDW. By using the roller centralizers, production logging tools that operate in the HDW are realized.

The above-mentioned techniques (i) to (vi) allow achievement of geothermal HDW drilling (deviation of 2,500m approx. and inclination of 70deg. approx.: hereafter referred to as Plan 1) and improvement of ROP by about 50%, as well as reduction of drilling risks so as to achieve a 10% cost reduction per well (per unit drilling distance). Technique (vi) is also expected to contribute to a 50% increase in productivity per well. Formation evaluation, such as confirmation of productivity in the HDW, is conducted by technique (vii) (Okabe et al. 2013).

During the period from FY 2011 to FY 2013, this project was carried out with verification of techniques and verification tests. Through this project, the feasibility of HDW in the geothermal field was evaluated and cost reduction targets achieved.

3. IMPROVEMENT OF WELLBORE SIMULATOR (GFLOW)

As part of the aforementioned (vi) Technique to design optimum casing in the HDW, existing wellbore simulator was developed.

There have been many wellbore simulators developed (ex. Freeston and Hadgu, 1988; Iwai and Furuya, 1995; Takahashi, 1999), and various methods (correlations) for calculating the relative flow rate between the vapour and liquid phases have been applied. We have developed the GFLOW wellbore simulator based on GWELL (Aunzo et al., 1991), whose source codes are available to the public (Kato et al., 2001). In GFLOW, the following equations, functions, etc. are added to the existing correlations of Orkiszewski: Miller's correlation (Miller, 1980), CO_2 and NaCl simultaneous processing function, super-critical area calculation function, and a user interface (Kato et al., 2001). For HDW, the applicable correlation equation is not included in GFLOW, and this may create an error in the pressure loss calculation. Thus, in order to develop a wellbore simulator applicable to the HDW, the introduction of a Drift flux model has been studied.

3.1 Investigation of Drift Flux Model

The Drift flux model is formulated by introducing the difference between the total volumetric rate of flow and vapor phase velocity, or between the total volumetric rate of flow and liquid phase velocity; or, in other words the model is formulated by introducing the drift velocity in each phase. The Drift flux model has the following features:

(1) When the fluid phase velocity is low, the model can represent counter flow in which flow direction is opposite between vapor phase and fluid phase.

(2) The model can support more precise analysis of the two-phase flow regime.

(3) The model can handle non-steady flow in a production well. Since the equations in the model are continuous and differentiable it can be coupled with a geothermal reservoir simulator.

(4) The experiment has been carried out at an angle as small as the horizontal plane with water/gas or oil/water, and the parameters to be used in the model have been precisely determined (Shi et al., 2005).

3.2 Evaluation of Drift Flux Model

The Drift flux model is compared with a model that does not support the HDW (a model supporting a well with small deviation). Figure 1 shows a cross sectional view of the well and calculation conditions used in the model, Figure 2 shows the comparison of calculation results, and Figure 3 shows the comparison of production output curves. This comparison of calculation results shows that the pressure loss is small in the Drift flux model but large in the model supporting the well with a small deviation, implying that the well capacity could be underestimated. This is because the highly deviated well is less influenced by buoyancy than nearly vertical wells, and the velocity in the highly deviated well is relatively slow.

The model accuracy was evaluated for a well having a small deviation using actual data. It was verified that for nearly vertical wells the Drift flux model has calculation accuracy almost identical to that of a model of a well with a small deviation (Figure 3).

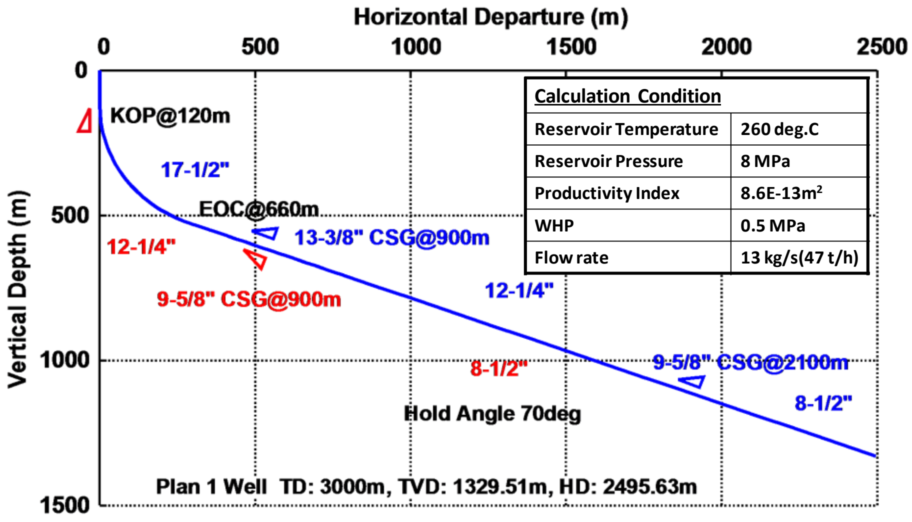

Figure 1: Cross sectional view of directional drilling path and calculation conditions used in model calculation.

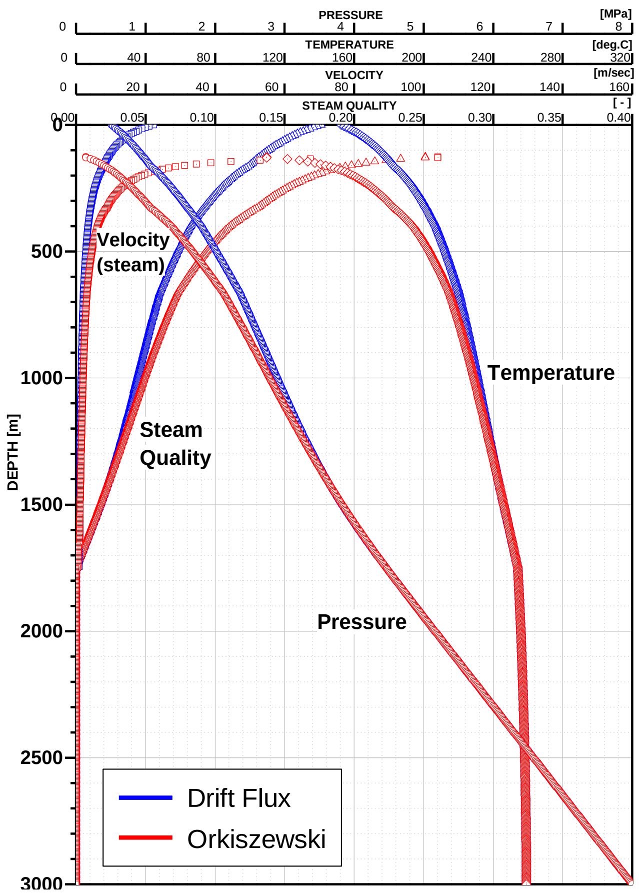

Figure 2: Comparison of calculation results.

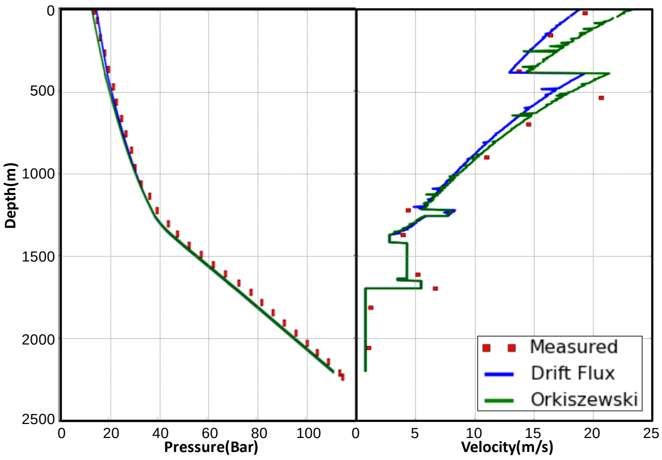

Figure 3: Comparison between the drift flux model and Orkiszewski using actual data.

3.3 Casing Program Optimization

The cost effectiveness (drilling cost/production rate) of well drilling is not simply proportional to the hole diameter or well length, and there exists an optimal point in terms of both production and drilling cost (NEDO, 1998).

In order to optimize the casing program for a possible new well, a study has been carried out with the new wellbore simulator. In the study, it is assumed that a well is drilled at high deviation into a national park. The well is drilled from the lower-temperature area outside of the park toward the high-temperature area inside the park (Figures 4 and 5). In the area used in this study, a geothermal deviated well (WELL-A; Measured depth = 1,750m, Maximum inclination = 48.5deg., and Deviation = 984m) has already been drilled toward the inside of the park and the well is producing steam, which allows comparison between the simulation results and actual data (steam flow rate and other data).

The trajectory of WELL-A is slightly offset from the center of the heat source, but in the simulation the well is drilled toward the center. The well used in the simulation is assumed to have a 9-5/8” casing installed from the ground surface to 2,000m deep and a 7” slotted liner installed below 2,000m, and the well length is varied from 2,500 to 3,000m (L). The maximum deviation of the well in the simulation is approximately 2,500 m. In addition 100% of the inflow is assumed to come from the bottom hole, and the bottom hole pressure in each simulation case is determined based on the vertical depth assuming that the water level is constant. The kick off depth is set to 200m, and the final inclination is varied from 20deg. to 70deg.. In this case study, the PI (Productivity Index) is varied from 7.41E-14 to 1.39E-13m^3, taking into account the finding that the permeability of the wells surrounding this area tends to be smaller with increasing depth (NEDO, 1990).

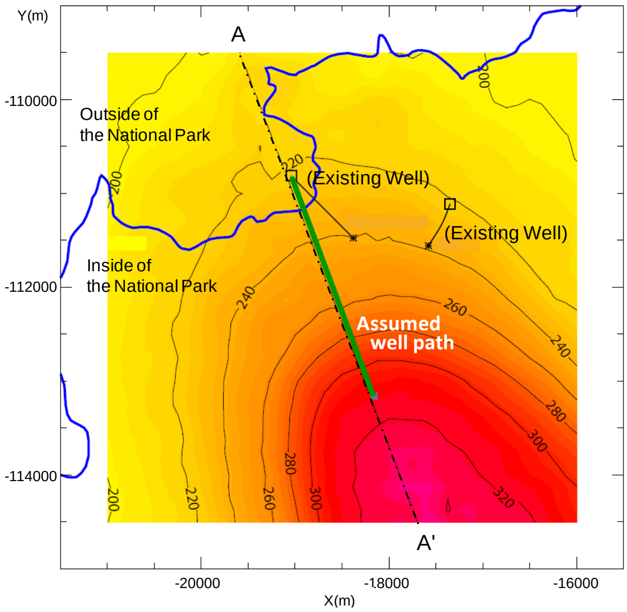

Figure 4: Temperature horizontal distribution at Japanese geothermal area and assumed directional drilling path.

Figure 6 shows the bottomhole temperature distribution used in the calculation. As shown in this figure, the temperature reaches its peak when the well inclination is 65deg. at the well length of 3,100m. On the other hand, it is found that the best cost effectiveness in terms of steam flow rate and drilling cost is achieved when the well inclination is 60deg. at the well length of 3,100m (Figure 7). The steam flow rate at this optimal point is about 1.7 times higher than that for WELL-A. Note that the steam flow rate in WELL-A, which is drilled from the outside toward the inside of the park, is also about 1.7 times higher than the average steam flow rate in the other production wells within this area. Based on these observations, the expected production steam flow rate at the optimal point will be about 2.9 times higher than the average steam flow rate in the other production wells within this area (Kato et al., 2013).

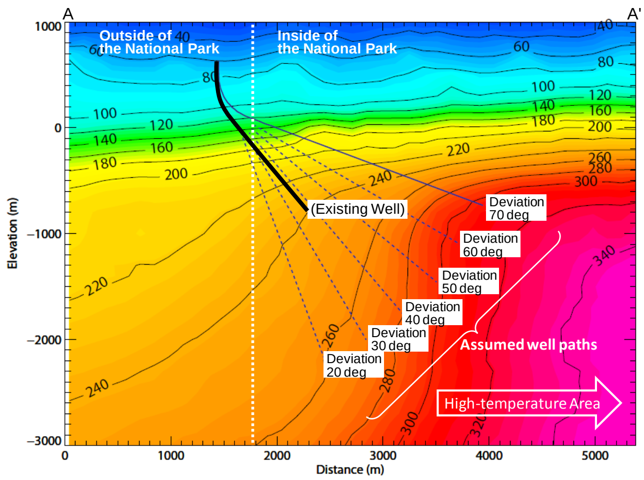

Figure 5: Temperature vertical distribution at Japanese geothermal area and assumed directional drilling path.

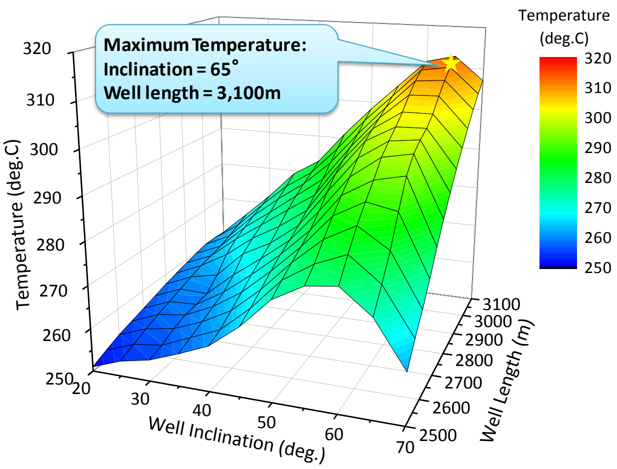

Figure 6: Bottomhole temperature distribution used in the calculation.

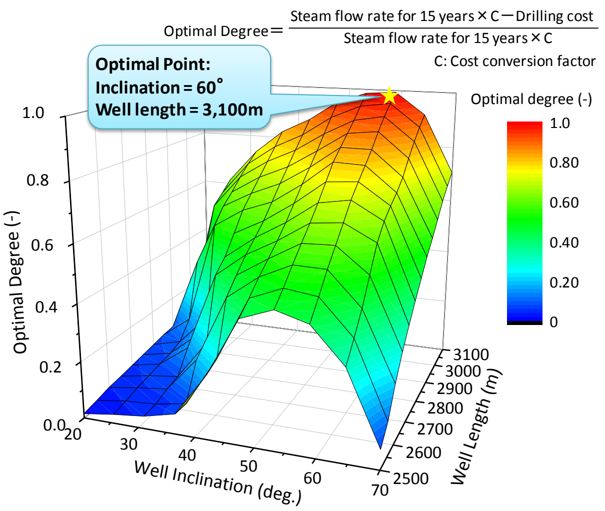

Figure 7: Optimal point in terms of steam flow rate and drilling cost.

4. DEVELOPMENT OF THE LOGGING SYSTEM FOR HIGHLY DEVIATED WELLS

Logging by wireline is naturally restricted to well inclinations of up to 65deg. (Spreux, 1988). Also, production conditions make it more difficult for a logging tool to descend. In this R&D effort, as part of the aforementioned (vii) Logging technique in the HDW, roller centralizers were added to a PTS/two-phase logging tool in order to conduct formation evaluations of the HDW.

4.1 Outline of the Logging System

To evaluate the production performance of the HDW, a production logging tool capable of measuring pressure (P), temperature (T), flow rate (S) and fluid chemistry (by sample collection) will need to be used. We added roller centralizers to the PTS / two-phase sampling tool to allow for the tool to descend smoothly into the HDW. The roller centralizer is designed such that 1) centering of the tool is secured even in the HDW (Optimization of the spring strength), 2) the tool does not get stuck in the slots of the liner (Adjustment of the roller thickness), and 3) the tool can smoothly descend through the liner hanger section (step section) of the casing (Drivability of roller section). In consideration of production phase operations, the strength of the section connecting the tool and centralizer is reinforced. The roller centralizer is composed of five arms, and the spring strength of the arms is adjustable. Two rollers are mounted on each arm, whose size can be modified. Figure 8 illustrates the outline of the production logging system for the HDW.

The logging tool consists of PTS and sampler sections. The diameter of the PTS section is 59.4mm, with a total length of 2,210mm and a weight of 55kg. The pressure sensor is a strain gauge sensor capable of measuring up to 34.5MPa. The temperature sensor is a platinum resistance type sensor capable of measuring up to 350deg.C. The spinner sensor is capable of detecting normal or positive rotation (+), or reverse or negative rotation (-) with its magnetic switch, and the impeller in the sensor can be exchanged with one suitable for the specific flow rate (flow velocity). Data is saved in the on-board computer memory, with a maximum sampling rate of 1 second (the rate is adjustable), and a maximum of 1,000,000 data sets can be recorded. The depth is measured with a dual digital encoder, which provides precise measurement. Pressure and temperature ratings of the sampler section are up to 10.35MPa and 350 deg.C respectively. The sampling is controlled with an electric solenoid valve controlled with a microprocessor timer. The titanium sample chamber has a capacity of 500mL, and can accommodate a single phase of hydrothermal water or steam, or a multi-phase fluid (hydrothermal water + steam + gas).

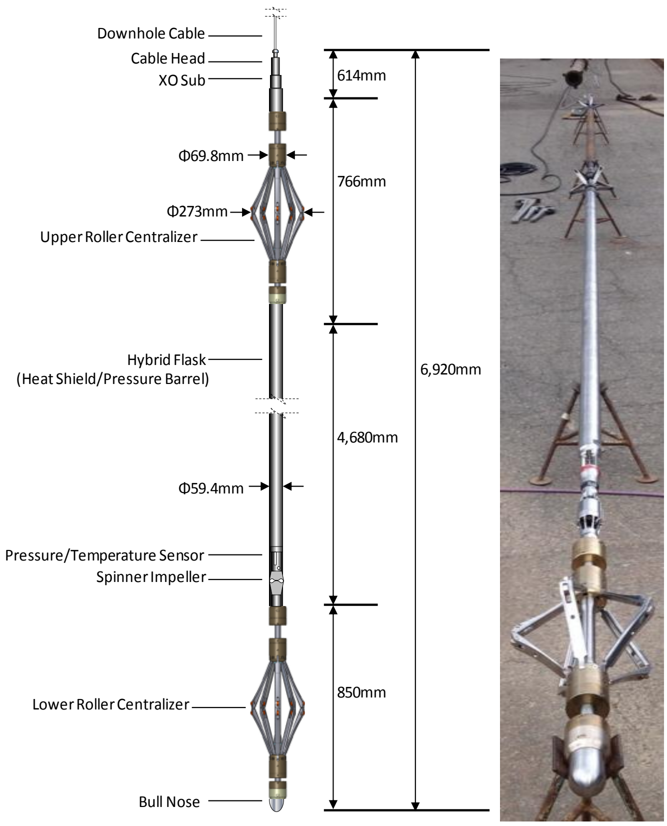

Figure 8: Outline of the logging system for a highly deviated well.

4.2 Verification Test in the Laboratory and under the Static Condition

In order to verify the performance of the roller centralizer, a liner hanger simulated with a combination of the polyvinyl chloride (PVC) pipes was tested. Two types of PVC pipe, 4" and 8" pipes, were combined to simulate the pipe; the liner hanger section (step section) is formed at the connection section of these two types, and the entire pipe is set at 84° from the vertical (Figure 9). Transparent PVC pipes are used around the liner hanger section to allow observation of operation of the roller centralizer. Smooth operation of the roller centralizer when it passes through the liner hanger section (step section) has been verified through the tests (Figure 10).

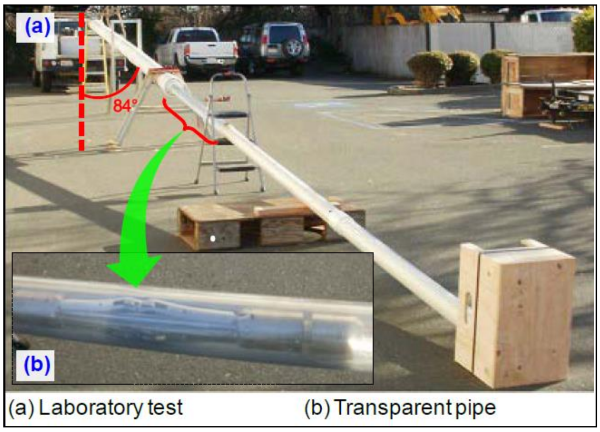

Figure 9: Laboratory test.

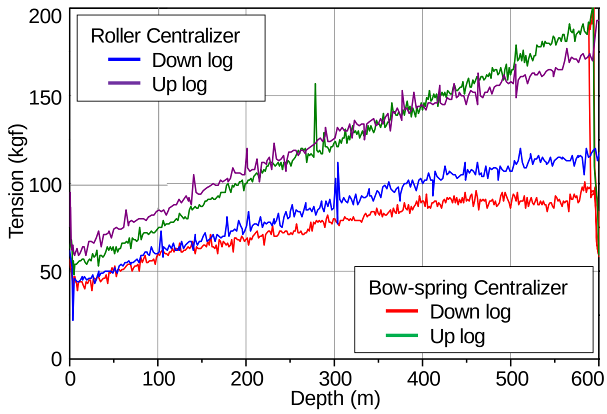

Figure 10: Comparison of wireline tension between the logging tool with the bow-spring centralizer and that with the roller centralizer.

The performance of the logging system in the actual well (WELL-B, Measured depth = 1,355.39m, Maximum inclination = 48.25deg. and Deviation = 742.33m) was tested under a static condition. In order to evaluate the performance of the roller centralizer, the wireline tension was measured while the logging system was descending. The tension was measured with the bow-spring-type centralizer installed. Figure 11 shows the wireline tension while the logging system was descending. The total weight of the logging system for both the bow-spring-type centralizer and the roller-type centralizer is almost the same, but the tension measured with the roller-type centralizer was found to be generally higher than the tension measured with the bow-spring-type centralizer while descending. The test well starts inclining at a depth of about 100m, and from this depth the logging equipment with the bow-spring-type centralizer keeps descending while the bow-spring blades scrape the borehole wall, which would cause the wireline tension to decrease. On the other hand, the roller centralizer reduces the friction between the logging tool and the borehole wall, which causes tension to be higher than that for the bow-spring type centralizer. It is also shown that the tension created with the roller centralizer decreases below 400m (relatively higher inclination section) while retrieving the logging system. From this observation it can be inferred that the friction with the roller centralizer is decreased more than with the bow-spring type centralizer while retrieving the logging system in the higher inclination section.

Figure 11 shows the logging results. Although a conventional PTS tool was used for comparison purpose, both logging results are coincident with each other. In addition, a single-phase borehole sample was collected with a total weight of 442.1g (Kato et al., 2013).

4.3 Verification Test under the Production Condition

In order to verify the performance of the logging system under the production condition, verification tests were conducted in two wells (WELL-C, WELL-D) of Japanese geothermal areas. Table 1 and Figure 12, 13 show the logging results. The findings of these tests were summarized as follows:

(1) The logging system for HDW was applied to production wells for the first time in Japan, and thereby PTS data and a borehole sample were successfully acquired at the same time. In addition, it was confirmed that borehole sampling can be successful with either the liquid-water single-phase flow or steam-water two-phase flow.

(2) It was confirmed that the logging system passed the liner hanger smoothly. Also, from the comparison of the measured pressure, the logging system descended smoothly compare to the conventional PTS tool with bow-spring-type centralizer (Figure 12). Therefore, the roller centralizer demonstrated the good performance even in the production wells.

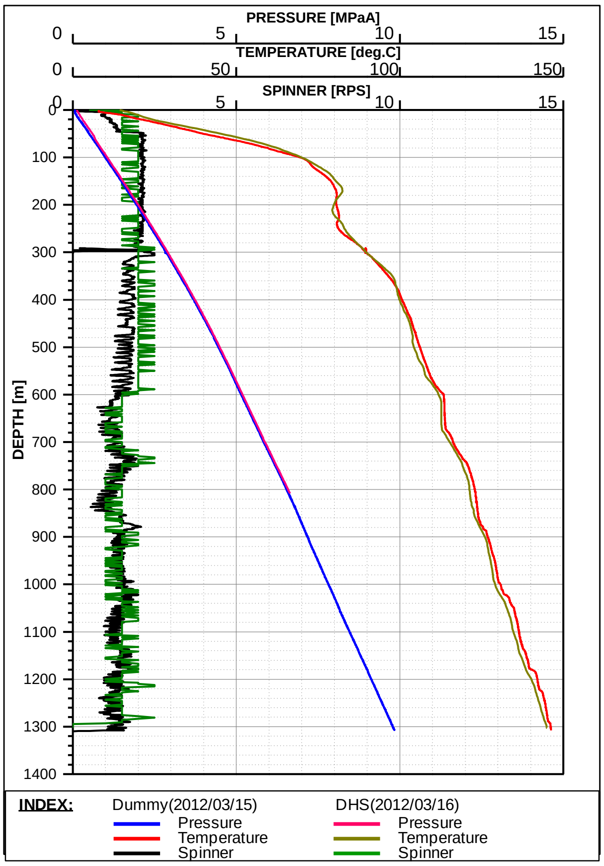

Figure 11: Logging results (WELL-B).

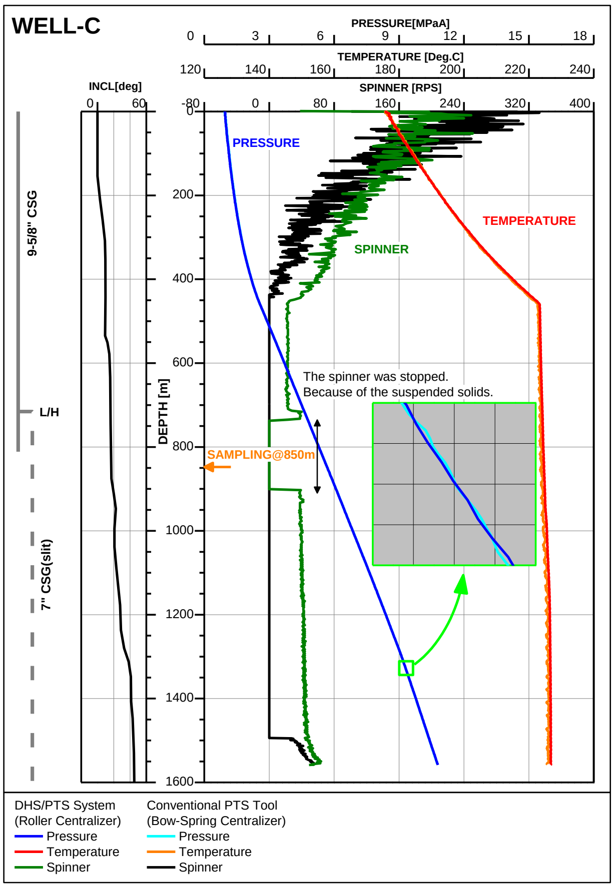

Figure 12: Output curve of the verification test under the production condition (WELL-C).

(3) The swing width of the spinner data of the logging system reduced as a whole than that of the conventional PTS tool with bow-spring-type centralizer (Figure 13). This means that the logging system was centered in the wellbore by the roller centralizer, and as a result data quality stability was acquired.

(4) From the result of the chemical analysis compared with surface sample, both of the downhole samples were properly collected.

Table 1: Results of the verification test under production condition (WELL-C, D).

Well Name		WELL-C	WELL-D
Max. Inclination	[deg]	42	28
Wellhead Pressure	[MPaG]	0.86	1.80
Steam Rate	[t/h]	5-6	20-22
Vapor Rate	[t/h]	35-38	20-25
Cable Speed	[m/min]	30	30
Logging Depth	[m]	1,560	1,832
Max. Pressure	[MPaA]	10.80	3.41
Max. Temperature	[deg.C]	227	239
Sampling Depth	[m]	1,800	850

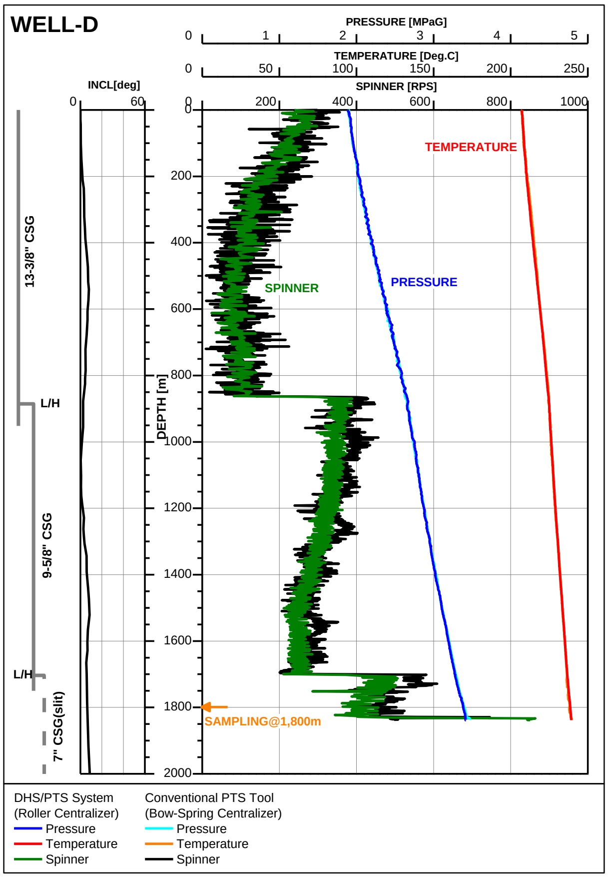

Figure 13: Output curve of the verification test under the production condition (WELL-D).

4.4 Verification Test in the High Inclined Well under the Production Condition

Confirming that the developed logging system worked properly under the production condition, the verification test was conducted in the high inclined well (WELL-E) of Japanese geothermal area under the production conditions. Table 2 and Figure 14 show the logging results. The findings of this test were summarized as follows:

(1) PTS data and a borehole sample were successfully acquired at the same time in the high inclined well of Japanese geothermal area under the production condition. In addition, it was confirmed that borehole sampling can be successful with the steam single-phase flow.

(2) It was confirmed that the logging system went smoothly down through the well without any problems, even in the liner hanger section (45deg.).

Table 2: Result of the verification test in the high inclined well under production condition (WELL-E).

Well Name		WELL-E
Max. Inclination	[deg]	48.5
Wellhead Pressure	[MPaG]	1.80
Steam Rate	[t/h]	20
Vapor Rate	[t/h]	<1
Cable Speed	[m/min]	30
Logging Depth	[m]	1,747
Max. Pressure	[MPaA]	2.85
Max. Temperature	[deg.C]	233
Sampling Depth	[m]	1,700

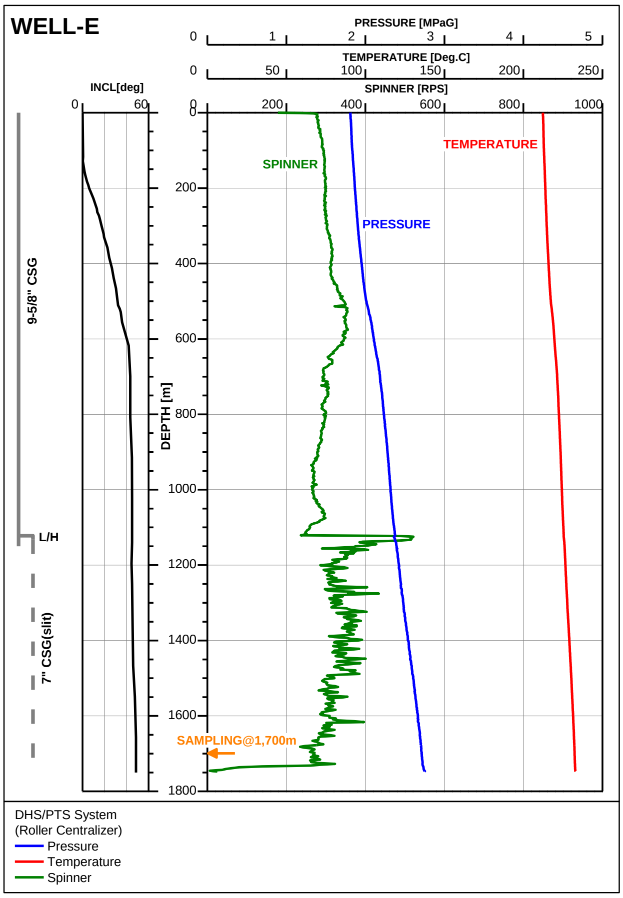

Figure 14: Output curve of the verification test in the high inclined well under the production condition (WELL-E).

4.5 Ground Flow Loop Test

Since the verification test had a shortage of deviation, ground flow loop tests were conducted to determine the applicability of the developed logging system to HDW.

A ground flow loop test is intended to simulate the downhole situation during production by installing the inclined casing pipes on the ground, and circulating water from below. Applicability to the HDW was confirmed by measuring the suspension load of the logging system installed in the casing pipe during the circulation. The test was carried out for the case of using the casing pipe 5-1/2” and 7”, with the pipe inclined to 70 deg. and 60deg. During the test, the flow rate and suspension load were measured and summarized in a graph showing the relationship between them. Figure 15 shows the test outline and Figure 16 shows the relationship between flow rate and suspension load of the logging system. It was confirmed that in case of 5-1/2” casing, suspension load of the logging system is significantly reduced by increasing the circulation flow rate. In case of 7” casing, because the inner diameter is larger than that of 5-1/2” casing, no clear change in the load was observed. Through the ground flow loop test, it was observed that the suspension load did not become zero. This means that the logging system is applicable to the HDW in normal casing program such as 5-1/2” and 7” casing.

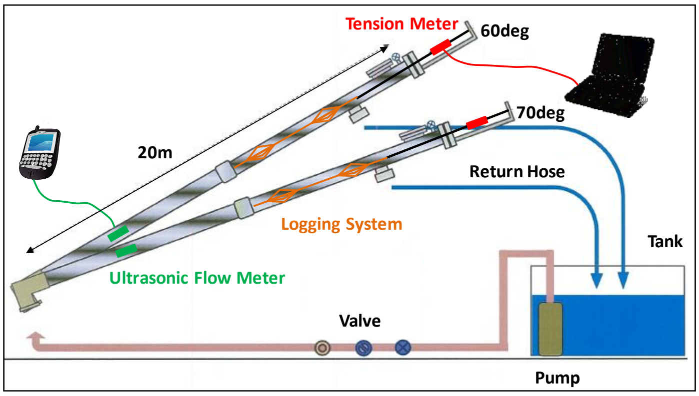

Figure 15: Outline of the ground flow loop test.

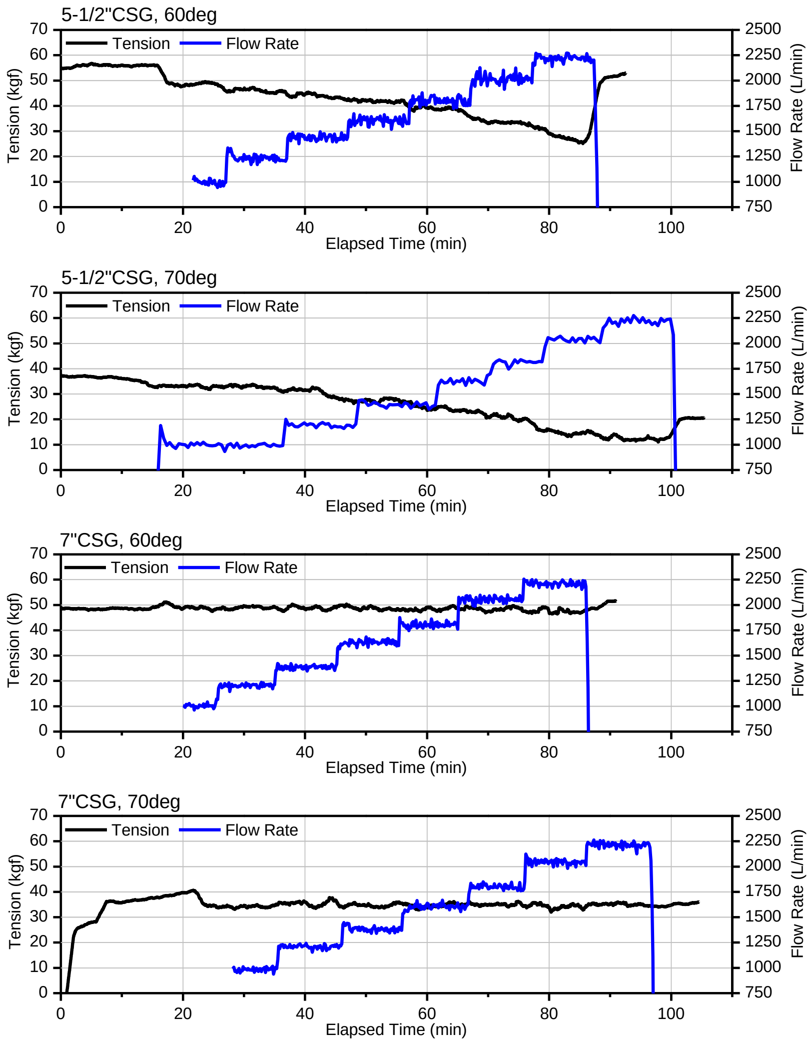

Figure 16: The relationship between flow rate and suspension load.

5. CONCLUSION

(1) The Drift flux model was adopted in the wellbore simulator (GFLOW) for the HDW (well inclination = about 70deg.) and the model can provide enhanced calculation accuracy.

(2) GFLOW was additionally used for an optimization study of the HDW casing program and a case study of an actual geothermal area was carried out. It was verified that the steam flow rate at the optimal point in terms of cost and efficiency increases to about 2.9 times higher than the average steam flow rate in the other production wells within the same area.

(3) In order to evaluate productivity of the HDW, roller centralizers were added to the logging system. It was verified in laboratory tests, where a well inclination of 84deg. was simulated, that the roller centralizer could smoothly go through the liner hanger section (step section).

(4) Performance of the logging system equipped with the roller centralizers was checked in an actual static well. It was verified with the test that, thanks to the roller centralizer, the friction between the logging system and borehole wall was reduced based on the wireline tension measurement result.

(5) The logging system for highly deviated wells was applied to production wells for the first time in Japan, and thereby PTS data and a borehole sample were successfully acquired at the same time. In addition, it was confirmed that borehole sampling can be successful with either the liquid-water single-phase flow or steam-water two-phase flow.

(6) PTS data and a borehole sample were successfully acquired at the same time in the high inclined well of Japanese geothermal area under the production condition. In addition, it was confirmed that borehole sampling can be successful with the steam single-phase flow.

(7) Since the verification test had a shortage of deviation, ground flow loop tests were conducted to determine the applicability of the logging system to HDW. Through the test, it was confirmed that the logging system is applicable to the HDW in normal casing program such as 5-1/2” and 7” casing.

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