CONTROL SYSTEM FOR DRILLING GEOTHERMAL WELLS AT HIGH ANGLES OF DEVIATION IN NATIONAL PARKS

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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 utilize the resources in the national parks efficiently, an 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 purpose is to develop an environment-friendly low-cost drilling technology for a highly deviated well (2,500m deviation, 70° inclination) to access the high-temperature geothermal resources from the outside 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.

For instance, to reduce the drilling costs by 10%, high performance motors and long lifetime high-speed rotation tri-cone bits were selected and tested. As a result, it was found that ROP increased by about 1.5 to 3 times compared with conventional techniques and that the system was very effective for difficult drilling conditions (hard formations, high temperature, a lot of LC (Lost Circulation)) in Japan.

To achieve a 50% productivity increase, the optimal casing design is determined by comparing steam flow rates with drilling costs for different well deviations, using the GFLOW wellbore simulator. According to a case study in a geothermal field in Japan, it is found that the steam flow rate at the optimal casing design is about 1.7 times higher as compared with conventional wells, which are existing production wells drilled in outside of the national parks. The conventional wells are typically drilled down to around 2,000m deep whose averaged inclinations are 35deg. approximately and completed 8-1/2" diameter with 7" slotted liner. Further, a production logging tool, equipped with roller centralizers to evaluate the formation in a highly deviated well was newly introduced. The tool was applied to a well in Japan and successfully collected PTS (Pressure, Temperature and Spinner) data and fluid samples simultaneously.

This paper outlines the detail of the project and the main R&D results.

1. INTRODUCTION

Among the high-temperature geothermal resources of above 150°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). The total amount of resources in the special protection zones (the zones protected from geothermal development in order to preserve wildness) and the special zones (the zones where geothermal development is accepted on condition of the consideration to environment) is 19,220MW, accounting 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. This, however, has a trade-off of protecting the natural environment. 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 to the natural environment are required to be developed. One of such techniques is controlled 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 75° respectively. Drilling a highly deviated well (hereafter 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). Achieving the HDW drilling under geothermal conditions safely and at low cost is essential. Although several HDW drillings are reported so far (e.g. Glynn-Morris et al., 2009; Prihutomo et al., 2012), comprehensive discussions that include the costs and risks involved in the HDW drilling techniques targeted for 2,500m deviation drilling are not conducted.

The present technical development carries out R&D into a low-cost, controlled, directional drilling technique of HDW. Specifically, the technical development for approximately 2,500m deviation and 70° inclination well drilling is targeted.

2. THE PROJECT OVERVIEW

2.1 Targets of the project and cost reduction process

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 with the current cost is targeted;
2. Productivity per well: 50% increase in steam generation by drilling high temperature and permeable zones in the national parks;
3. Cost of power generation (cost per unit steam flowrate): 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.

Table 1 shows the cost reduction process. According to New Energy and Industrial Technology Development Organization ; NEDO (1998), the drilling costs of the current 3,000m class (four-stage CSG and five-stage CGS) are 1.63 to 1.92 times higher than those of the current 2,000m class (four-stage CSG) (Table 1 (1)). Further, when the steam flowrate per production well is 40t/h and the depth of the re-injection well is 1,500m, the power generation cost of the 3,000m class drilling is approximately 1.25 times that of the 2,000m class drilling. Assuming that the drilling cost of the current 3,000 m class is 1.77 times (average of 1.63 and 1.92) that of the 2,000m class, and if we were to reduce it by 10% through this project, the drilling cost of the 3,000m class will be 1.593 times the 2,000m class. Then, the power generation cost will be reduced to about 1.23 times (Table 1 (2)). In addition, if a 50% increase in the steam flowrate due to the increased number of permeable fractures as well as the access to the higher temperature zone in the national parks is expected, the power generation cost can be reduced to 0.9 (Table 1 (3)). Thus, the power generation cost, including the drilling cost of the 3,000m class, will be about 1.1 times that of the 2,000m class. Moreover, since shortening of the ground pipelines is made possible by the aggregation of bases in highly deviated drilling, the power generation cost of the 3,000m class becomes 0.97 times that of the 2,000m class (New Energy Foundation; NEF, 1991), and the power generation cost resulting from the drilling cost reduction and the increase in steam will be reduced to 1.07 times, which is roughly the same as the current level.

With respect to the productivity of the well, the wellbore flow simulation has confirmed in advance that the steam flowrate increases as the reservoir temperature rises, and an improvement of about 50% is possible.

Table 1: Process of cost reduction

(1) Current drilling cost

Item	Current standard	HDW drilling in the national park	Remarks
Drilling length (m)	2,000	3,000	Conduct a HDW drilling from 2,000m to 4,000m in the national
Standard drilling cost*1	1	1.63-1.92	2,000m class (four-stage CSG) and 3,000m class (four-stage CSG and five-stage CSG)
Power generation cost*1	1	1.25	Steam flowrate: 40t/h per production well; re-injection well depth: 1,500m

* Under the current situation, a 25% increase in power generation cost is expected due to development within the national parks

(2) Effect of drilling cost reduction

Item	Current situation	Improvements	Remarks
Drilling length (m)	3,000	3,000	Conduct a HDW drilling from 2,000m to 4,000m in national park
Standard drilling cost*1	1.77	1.593	A 10% reduction in the standard drilling cost
Power generation cost*1	1.25	1.23	*1: Coefficients of drilling and power generation cost: calculated based on NEDO(1998)

(3) Effect of the production rate increase due to the reservoir temperature increase due to approaching the heat source in the national park

Item	Current situation	Improvements	Remarks
Steam flowrate	1	1.5	A 50% production increase is expected
Power generation cost*1	1	0.9	*1: Coefficients of drilling and power generation cost : calculated based on NEDO(1998)
Power generation cost including the drilling cost	1.23	1.10	

Reasons for the expected increase in production: (1) increase in the steam flowrate due to the rise in temperature increase because the subjected national parks are generally in the heart of heat sources such as volcanoes are in the national parks; (2) large displacement of highly deviated wells → collection of more geothermal fluidis possible as going through multiple highly permeable fracture systems (passage of hot water).

(4) Effect of the shortening of ground pipelines due to the drilling bases being aggregated in HDW drilling

Item	Current situation	Improvements	Remarks
Construction cost	1	0.5	Costs for pipeline construction, road reclamation, land acquisition, steam-water separators, etc.
Power generation cost*2	1	0.97	*2: Coefficient of power generation cost: calculated based on NEF(1991)
Power generation cost taking into account the drilling cost reduction and the increased steam	1.10	1.07	Achieved generation cost roughly the same as the current level (about 7% increase)

2.2 Solution for the targets

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 seven component techniques, which are the following:

(i) **Technique to increase rate of penetration in hard rocks**: Improvement in the 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**: Executing optimal directional drilling plan, conducting optimal control drilling using MWD (Measurement While Drilling), optimization of BHA (Bottomhole Assembly), reviewing and evaluating the torque-and-drag reduction tools and of the drilling fluid lubricants.

(iii) **Mud design and control technique in the HDW**: Using large-scale facilities, experiments are carried out on the behavior of mud water, and the optimal control of mud water in HDW drilling.

(iv) **Wellbore cooling technique in the HDW**: Improvement of the cooling efficiency inside the HDW, under a high-temperature environment, is done by reviewing and evaluating the drilling fluid cooling device, and considering the predictive simulation of wellbore temperature for the HDW using Geotemp2 (Mondy and Duda, 1984). GEOTEMP2 is a wellbore temperature simulator developed by Sandia National Laboratory and it simulates wellbore and formation temperature by using finite difference method. We have been improving the simulator (e.g. Takahashi et al., 1997). 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**: 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**: Optimize the casing program for optimal production and safe drilling in the HDW by improving the wellbore flow simulator GFLOW (Kato et al., 2001). GFLOW is developed based on Gwell (Aunzo et al., 1991). It reproduces the measured flowing temperature and pressure profiles in flowing wells and determine the relative contribution, fluid properties(e.g. enthalpy, temperature) and fluid composition(e.g. CO2, NaCl) of each feed zone for a given discharge condition. Further, in GFLOW, the following equations, functions, etc. are added to the existing correlations of Orkiszewski: Miller's correlation (Miller, 1980), CO2 and NaCl simultaneous processing function, super-critical area calculation function, and interface.

(vii) **Logging technique in the HDW**: Developed a logging system with roller centralizers, required for the formation evaluation in the HDW. By using the roller centralizers, production logging tools that actually work in HDW is realized.

The above-mentioned techniques (i) to (vi) allow achievement of geothermal HDW drilling (deviation of 2,500m approx. and inclination of 70° 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). It is the aim to reduce the power generation cost to the current level by combining the component techniques. The period of this project is three years, from fiscal 2011 to 2013. In the final year, the plan is to evaluate the achievement of the cost reduction targets by using a cost analysis tool, as well as to evaluate the feasibility of geothermal HDW drilling through demonstration tests.

Below is an outline of the achievements of this project so far.

3. THE PROJECT PROGRESS

3.1 Technique to increase ROP in hard rocks

Although drilling geothermal wells involves the drilling of hard, high-temperature, and complex formations, it is possible to achieve a cost reduction by shortening the drilling period by improving ROP. For improving ROP, increasing the weight on bit (WOB) and the bit rotation speed is effective. Therefore, for efficient drilling and cost reduction, appropriate drilling equipment from Extended-Reach Drilling (EDR) techniques have been selected. These techniques were cultivated in the oil and gas development field, including a high performance downhole motor (hereafter referred to as a high performance PDM) and a bit, and introduced it for the evaluation of geothermal well drilling. In this project, performance evaluation of a high performance PDM, a high speed long life bit (hereafter called a long life bit), and the top drive drilling system (TDS) was conducted in geothermal areas in Japan, and improvement in ROP through the combination of this equipment was examined. Further, acquisition of drilling parameters by mud logging was carried out at the time of performance evaluation. Here, a high performance PDM from SDI (Scientific Drilling International) and a high speed long life bit from TIX (TIX-TSK Corporation) were used. Figures 1 and 2 show their specifications respectively.

8.0", (4:5), 5.3 Stage, Extended Drilling Motor

Outside Diameter: 8"
Weight: 4,050 lbs.
Length: 31' (medium speed) 4:5, 5.3 Stages
Connections : 5-1/2" or 6-5/8" API reg. box up
6-5/8" API reg. box down (bit box)
Max Flow Rate : 1,000 GPM
Speed Range : 58-245 RPM at 300 PSI diff. press.
Rot/Gal : .25
Man Crush Weight for Brg. pack : 75,000 lbs.
Max Bit Pressure Drop : 1,000 PSI
Optimum Bit Pressure Drop : 100-800 PSI for continuous use
Max Motor Pressure Differential : 640 PSI (see chart)
Optimum Motor Pressure Differential :
100-550 PSI for continuous use
Max Operating Motor Torque : 7,100 ft-lbs (see chart)
Max Sand Content : 2%
Bit to Bend : 90.0" for fixed, 104.50" for adjustable
Max. Overpull for Re-run : 120,000 lbs.
Overpull To Yield Motor : 240,000 lbs

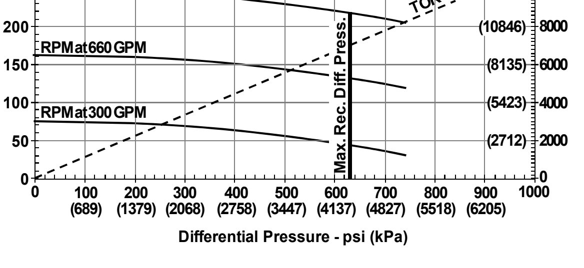
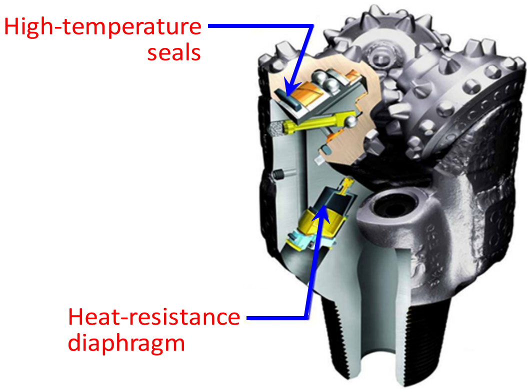


Figure 1: Specifications of the high performance PDM



Manufacturer	TIX TSK Co., Ltd.
IADC	537M
RPM	50-250
Seal	HNBR (Hydrogenated nitrile rubber) improved type
Heat resistance	For high-temperature use (180˚C or higher)

Figure 2: Specifications of the high speed long life Tricone bit

In order to evaluate the performance of the high performance PDM, drilling using the said PDM is carried out in proven geothermal area A, where a conventional downhole motor (hereafter called the conventional PDM) had been used in the past, and ROPs were compared. Figure 3 shows the ROP comparison between Well A-1 drilled by the conventional PDM and Well A-2 drilled by the high performance PDM within the same drilling base. In the drilling of Well A-1 and Well A-2, two 8P-80 triplex pumps (manufactured by National Oilwell Varco; input power: 800HP@160spm) which are frequently used in geothermal well drilling as mud pumps were used. The results show a significant improvement in ROP of 1.5 to 3 times by the use of the high performance PDM. On the other hand, in the case where the drilling was carried out using only one 8P-80 mud pump (Figure 4), no improvement in ROP was observed in the comparison between the conventional PDM (Well A-3) and the high performance PDM (Well A-4). These results suggest that when using the high performance PDM, the performance of mud pumps plays an important role in demonstrating its performance. The increase in RPM of the high performance PDM, due to the increased flow rate of mud pumps, is thought to be the cause of the improved ROP.

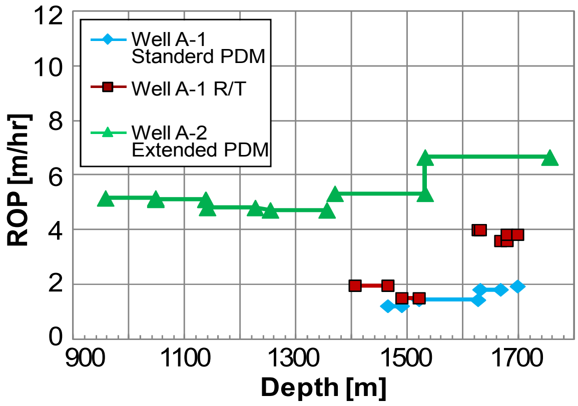


Figure 3: ROP comparison with the high performance drilling motor when two mud pumps were used

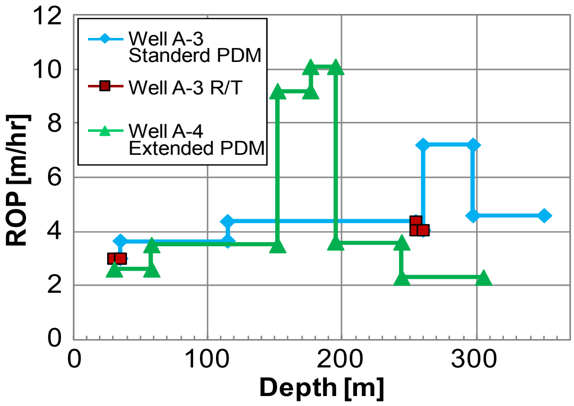


Figure 4: ROP comparison with the high performance drilling motor when one mud pump was used

In order to consider the improvement in ROP by combining the high performance PDM and the long life bit, a performance evaluation was conducted at Well B-1 in geothermal area B, which is different from the above geothermal area. Figure 5 compares ROP of Well B-1 and ROPs of the neighboring Wells B-2, B-3, and B-4, which had been drilled in the past in the same area. In order to demonstrate the performance of the high performance PDM, two 8P-80 mud pumps were used. The overall ROP of Well B-1 was high as compared with those of the neighboring wells. This is especially true at a depth deeper than 800 m sections, where ROP increased three-fold. Figure 6 shows a comparison of bit performance between Well B-1 and the neighboring wells. By comparing the conventional bits used in the neighboring wells (Well B-2 and B-3) and the long life bit (Well B-1), a significant improvement in total drilled depth against drilling time of the long life bit can be observed. Also, the result of the investigation of the long life bit after use shows overall wear on the surface, but the inside of the bearings was in a mirror surface state and the wear amount was also immaterial._Moreover, it was found that the internal grease remained in sufficient quantity, was in a good condition, and withstood reuse.

Meanwhile, the top drive system is more capable of efficient wellbore cooling than the Kelly method. It has been suggested that the use of TDS extends the bit life about five times and the multiplier effect for long life of bits has been confirmed (Saito and Sakuma, 2000). Possible effects for the above-stated performance of the long life bit include the use of TDS.

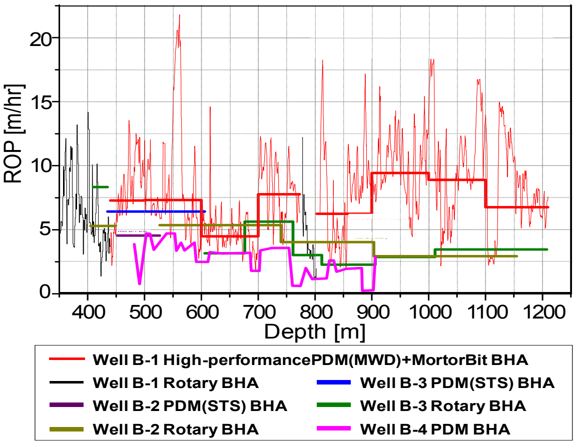


Figure 5: ROP comparison in 12-1/4" holes

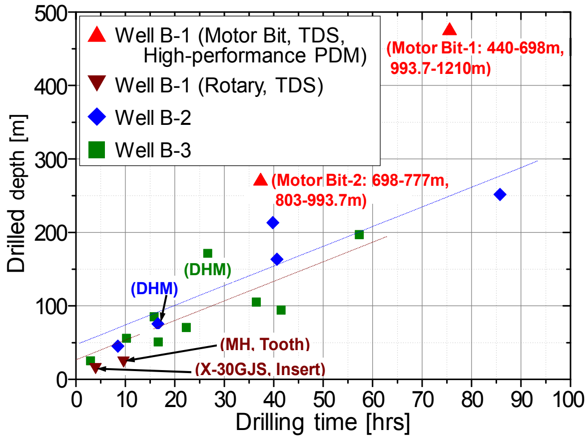


Figure 6: Comparison of bit performance in 12-1/4" holes

3.2 Control drilling technique in the HDW

In order to improve orientation inclination control in the hard, high temperature, and complex formations, the following are implemented:

- Designed an optimal directional drilling plan to minimize the resistance of the drill pipe during drilling. This consequently reduce accidents such as detention of the drill pipe
- Optimally controlled drilling using MWD
- Optimization of BHA based on drilling data
- Implementation of review and evaluation on torque-and-drag reduction tools and drilling fluid lubricant

Here, the coefficient of friction between the drilling tools and the wellbore wall (hereafter the “friction factor”) was evaluated from the mud logging data to review the HDW drilling. There are few examples of reviews on torque-and-drag including the friction factor in geothermal HDW drilling.

Since there is a concern for increased torque and drag in the HDW, and its consequence such as the drill pipe getting stuck, evaluation of drilling parameters of existing wells and torque-and-drag simulations are required before drilling the HDW. Therefore, a drilling plan and BHA for Plan-1 was reviewed according to the following procedure.

1. Find the friction factor by torque-and-drag analysis using the mud logging data obtained from the existing highly deviated well, with an approximate deviation angle of 60°.
2. By assuming BHA in the torque-and-drag analysis of the drilling of Plan-1, calculate the hook load and torque using the coefficient of friction found above. Confirm that the hook load and torque satisfy the specifications of the 3,000m class rig.

Torque-and-drag analysis was performed using the mud logging data of Well F (measured depth: 1,600m; displacement: 959m; maximum deviation: 60.0°). For the torque-and-drag analysis, the Wellplan software was used (Landmark product). Figure 7 compares the measured and calculated values. From these results, the friction factors were evaluated as 0.2 (CSG) and 0.25 (open hole). Assuming the evaluated friction factor to be a typical one in geothermal areas in Japan, torque-and-drag analysis for Plan-1 was performed. Figure 8 shows a cross section of Plan-1. The BHA used in the calculation was the same assembly as normal deviated well drilling for 26" and 17-1/2" holes, but for 12-1/4" and 8-1/2" holes the number of drill collars was decreased compared with the normal drilling, and the torque-and-drag force was reduced by increasing the number of used heavy weight drill pipes instead.

The results of the torque-and-drag analysis have shown that the maximum hook load was 96 tons and the penetration torque was 2,300kg-m. Since the drilling rig of the 3,000m class uses drawworks of about 200 ton winding capacity, the hook load was within the acceptable range (NEF, 1996). When a 5" DP of grade S-135, Class 2 was selected, it was determined that the penetration torque also had no problem for drilling, as it was less than the make-up torque (3,400kg-m) (NEF, 1996).

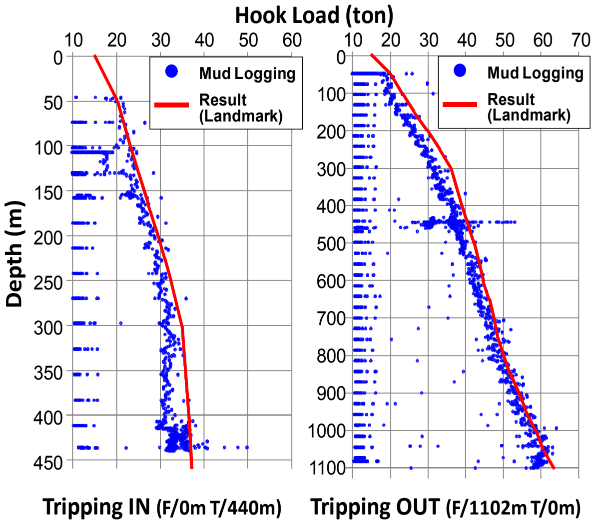


Figure 7: Comparison of the torque-and-drag analysis results with the measured values for Well F

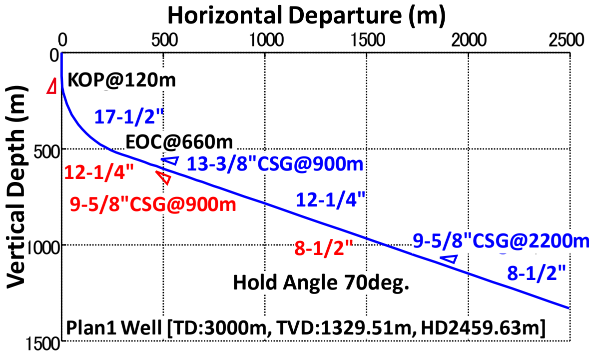


Figure 8: Cross section of Plan-1

3.3 Consideration of hole cleaning and wellbore cooling

Although feasible prospect of a reduction of some amount of drilling cost is already achieved due to the improvement of ROP with cutting-edge techniques as mentioned above, it is necessary to examine hole cleaning and wellbore cooling with regard to the drilling risks in the HDW. Drilling while lost circulation in highly deviated geothermal wells requires maintenance of adequate ECD (Equivalent Circulating Density) and sufficient hole cleaning within many constraint conditions such as mud control technical problems. In the mud design and control technique in the HDW, Cuttings Transport Behavior experiments are performed using the cuttings transport flow loop system (CTFLS) experimental equipment. This is to examine the behavior of mud water and cuttings in the HDW while drilling. Effective drilling conditions and mud properties in the HDW drilling are evaluated, and the problems and future tasks are derived through the experiment. The results of the wellbore flow experiment that assumed a drilling section of well deviation angle of up to 75° from vertical using CTFLS, have clarified that if the mud was circulated with a flow rate that could secure an annular velocity of 1.3 m/s or more, sufficient hole cleaning was possible even in highly deviated drilling with the maximum deviation exceeding 70°.

In drilling operations, it is important to predict the wellbore temperature against the temperature rating of MWD tools, downhole motors, and bits to prevent wellbore troubles in advance. Therefore, the existing borehole temperature simulator (GEOTEMP2) is improved for the temperature calculation in the HDW (approximately 70°), and an optimal wellbore cooling design that is lower than the temperature rating of the drilling equipment (approximately 175°C) is studied through simulations.

The study of the hole cleaning and the wellbore cooling is still ongoing. In the future, the comprehensive evaluation of drilling risks, including measures for lost circulation will be continued.

3.4 Formation evaluation logging system

In order to evaluate the production performance in the HDW, a production logging tool capable of measuring pressure (P), temperature (T), flow rate (S) and fluid sampling is introduced. Since the logging tools usually cannot descend by gravity for wells with deviation exceeding about 65° (Spreux et al., 1988), roller centralizers are equipped on the logging tool in order to conduct the formation evaluation of the HDW. Logging was carried out in the actual well and has successfully obtained PTS data and borehole samples simultaneously, using the system in a geothermal well. It was found that the tools descended inside the borehole smoothly thanks to the roller centralizers.

3.5 Development of the cost analysis tool

One of the objectives of the present project is to reduce drilling cost per unit drilling distance by 10%. Therefore, a tool for properly evaluating the effect of the drilling cost reduction is developed, through the technical development, analysis, and evaluation of the drilling costs.

The cost analysis tool consists of: (1) drilling specification input; (2) drilling costs input; (3) drilling scenarios input; (4) cost analysis; and (5) parametric study. It calculates the working times and costs based on the parameters of operating efficiency such as ROP and the RIH/POOH (Run-in/pull-out), the costs required for drilling (rental and/or service costs of the equipment, consumables, etc.), and a series of drilling scenarios from rig construction to its removal, and displays them on graphs. In addition, for the case when different component techniques are used for drilling the same well, and for the purpose of comparing the costs and working times when changing operating efficiency, it is possible to display the cost analysis results based on multiple scenarios graphically.

4. CASE STUDY (THE STUDY OF COST REDUCTION EFFECT)

A case study was performed for three wells including Plan-1 with regard to (1) the high speed long life tricone bit, and (2) the high performance drilling motor. For (1), since it has been confirmed that the bit life is approximately twice that of the conventional tricone bit, it was assumed that the same effect would be obtained in this bit as well. As for (2), since it has been confirmed that the ROP of high performance PDM is 1.5 to 3 times compared with the conventional PDM in the R&D, the analysis was performed assuming that the ROPs were 1.5-fold and 3-fold. Table 2 shows the specifications of each well, and Table 3 shows the results of the cost analysis.

Table 2: Well specifications for each Case

Case	Case 1	Case 2	Case 3
Well name	Well X	Well Y	Plan 1
Measured depth	1,600 m	2,100 m	3,000 m
Inclination	70°	48°	70°
Deviation	1,007 m	1,227 m	2,500 m
Controll section	130-1,320 m * DHM used to the bottom	(1) 60-540 m (2) 810-900 m	(1) 120-1,500 m (2) 2,100-900 m

Table 3: Cost analysis results

Component technique		Bit		Drilling motor (PDM)			Cost reduction percentage[*2]
		Conventional PDM	High-speed rotation long-life type	Conventional PDM	High performance PDM		
Effect		-	Bit life×2	-	ROP×1.5	ROP×3	
Case 1	1-1	○		○[*1]			-
	1-2		○		○[*1]		12.7%
	1-3		○			○[*1]	23.9%
Case 2	2-1	○		○			-
	2-2		○		○		7.6%
	2-3		○			○	12.8%
Case 3	3-1	○		○			-
	3-2		○		○		11.2%
	3-3		○			○	21.8%

*1: Drilling motor used in all sections from kick off

*2: Reduction percentage in each Case against cost for the normal bit and the normal motor being used

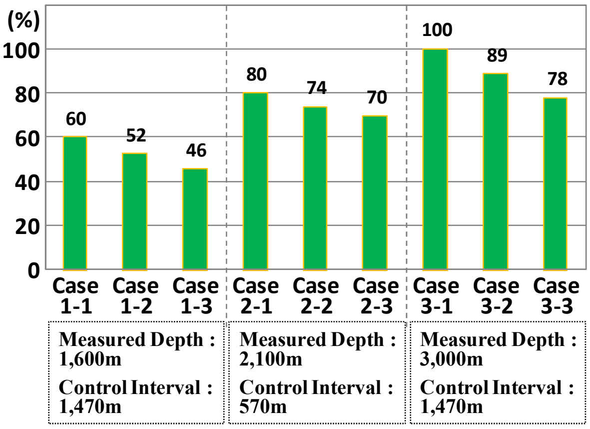
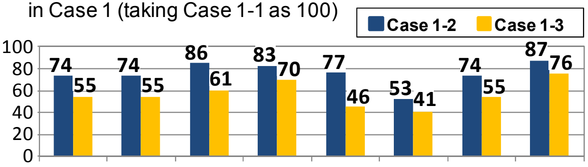
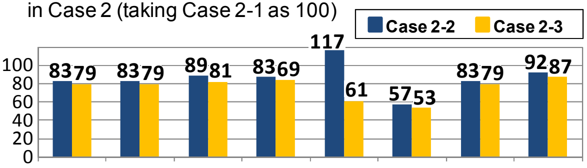


Figure 9: Comparison of total drilling costs

(a) Cost reduction percentages for the respective expense items in Case 1 (taking Case 1-1 as 100)



(b) Cost reduction percentages for the respective expense items in Case 2 (taking Case 2-1 as 100)



(c) Cost reduction percentages for the respective expense items in Case 3 (taking Case 3-1 as 100)

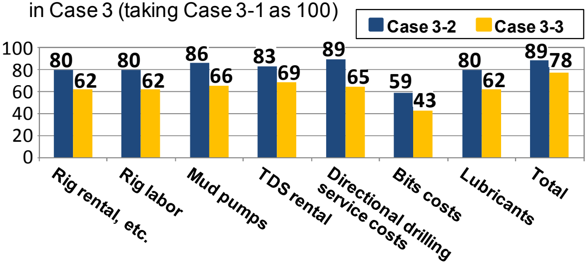


Figure 10: Comparison of cost reduction percentage for the respective expense items in each Case

In Case 1, it was found that an approximate cost reduction of 13-24% was possible as compared with the Cases in which the component techniques were not applied. The variation observed in the cost reduction percentage in each Case is dependent on the length of the controlled sections. Figure 9 simply compares total drilling cost in each Case, with the drilling cost for Case 3-1 being taken as 100. Here, the drilling cost of Case 3-3 is 78, which is below that of Case 2-1. This indicates the possibility that wells of 3,000m class can be drilled with the drilling cost of the conventional 2,000m class wells by applying the component techniques. By comparing the cost reduction percentage for the respective expense items in each Case, it can be observed that the cost reduction effect due to the component techniques is significant for the longer controlled sections (Figure 10). The directional drilling service costs in Case 2-2 are higher than the base Case (Case 2-1), but this is because the increase in cost by using the high-performance tools could not be compensated by the reduction in the tool operating time through the improvement in ROP, due to the controlled section being short (Figure 10 (b)). However, the overall cost decreased, because the construction period was shortened by the improvement in ROP, resulting in reduction of renting costs for the rig, etc. and reduced rig labor costs.

5. CONCLUSION

In order to carry out the technical development of low-cost control drilling techniques for the highly deviated drilling, and to make it possible to develop the geothermal resources that exist in the national parks in line with conservation of the natural environment, the seven component techniques (technique to increase rate of penetration in hard rocks, control drilling technique in the HDW, mud design and control technique in the HDW, wellbore cooling technique in the HDW, technique to remedy lost circulation in the HDW, technique to design optimum casing in the HDW, and logging technique in the HDW) is being studied. In order to properly evaluate the cost reduction effect in the present technical development, a cost analysis tool was created. Through a case study, the prospects to achieve the drilling cost reduction target were obtained. The following is a summary of the achievements so far:

1. A significant improvement in ROP (1.5- to 3-fold) through the application of a high performance PDM and a long life bit was confirmed. Although there are factors leading to increased costs, such as employing cutting-edge techniques and therefore slightly more expensive than the conventional techniques, and that two mud pumps are required in order to demonstrate the performance of the high performance PDM, the results of detailed analysis by the cost analysis tool have shown that the drilling process was shortened due to the increased ROP by using the latest techniques, and as a result, the prospects of achieving about a 10% reduction in drilling cost, which was one of the initial targets, were obtained.

2. In order to examine the drilling of the HDW with an approximate inclination of 70° and an approximate deviation of 2,500m, the friction factors were evaluated as 0.2 (CSG) and 0.25 (open hole) from the mud logging data of an existing well, and torque-and-drag analysis was performed. The results of both hook load and penetration torque show that drilling with the assumed 3,000m class rig was possible. The results of the wellbore flow experiment show that sufficient hole cleaning was possible even in highly deviated drilling with the maximum inclination exceeding 70°, and the prospects of achieving highly deviated drilling were obtained. However, it is necessary to examine and comprehensively evaluate the drilling risks, such as measures against lost circulation and wellbore cooling in the future as well.

3. A production logging tool equipped with roller centralizers to evaluate the formation in the HDW was newly introduced. We applied the tool to a well in Japan and successfully collected PTS data and fluid samples simultaneously.

In the future, we plan to consider verification of the control drilling system in the HDW, as well as to compile the technical documentation.

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