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ECONOMICS OF INCREASED BIT LIFE IN GEOTHERMAL WELLS BY COOLING WITH A TOP DRIVE SYSTEM

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ABSTRACT

Drilling efficiency largely depends on bit life and rate of penetration. Three-cone bits, however, have temperature sensitive parts such as O-ring seals and diaphragms, which have temperature limitation of 150 to 190 ºC, and are prone to damage by high temperature while running in the hole and during drilling. The new method was adopted to protect O-ring seals from high temperature while running in the hole. Mud was pumped continuously while running a bottom-hole-assembly (BHA) in the hole using a top-drive-drilling-system (TDS). To evaluate this TDS-Cooling method, two high temperature geothermal wells Well-21 and WD-1a , which were drilled without lost circulation for the 8-1/2 inch sections, were selected. The WD-1a well was drilled using TDS-Cooling methods, and Well-21 was drilled with conventional techniques when drilling high-temperature formations. As for the Well-21 bit performance, three bit O-ring seals survived and average drilled hours of the three bits was 28 hours. The deepest depths where O-ring seals survived was 2,105m where the static formation temperature was 350 ºC. Whereas, for the WD-1a well, the depth of the last bit for which O-ring seals were still surviving was 3,451m and bits drilled for 31 hours where the static formation temperature was more than 450 ºC. The average drilled hours of the 5 bits without O-ring seal failures was 50 hours, where the static formation temperature was between 350 and 450 ºC. Judging from the bit performances for the two wells, bit life using TDS-Cooling method would be three to six times more compared with conventional cooling method if the same formation temperature and depths were drilled.

Economic evaluation of using a TDS was made based on the field data when these two high temperature wells were drilled. Two examples are considered that compare the drilling of two 1,000 meter sections of 8-1/2 inch wellbore. Example-1: Drilling 8-1/2 inch section of the well from 2,500 to 3,500 m. Example-2: Drilling 8-1/2 inch section of the well from 2,000 to 3,000 m. The cost factors, times and bit life for each example were given based on the actual data. Simulation results show TDS-Cooling results in more economical drilling costs for both cases. The many other advantages of using a TDS are described and indicate that it will be very economic to use a TDS when drilling high temperature wells.

1. INTRODUCTION

The Kakkonda geothermal field, located approximately 500 km north of Tokyo (Fig.1, Kato et al.,1996) is one of the highest temperature geothermal areas in the world. In this area, geothermal wells have been drilled since 1972, and two power stations have been successfully operated. About 70 wells with depths ranging from 1,000 to 2,000 m were drilled and geothermal fluids were produced from the Tertiary reservoir formations. Since 1989, six deeper wells with depth ranging from 2,463 to 3,000 m were drilled by JMC into the pre-Tertiary and a neo-granite pluton. These wells discovered a promising new reservoir. The neo-granite pluton is thought to be one of the heat source rocks in this area. Well-21, one of the six deep wells, was drilled to 2,800 m without using a TDS. Logging runs estimated maximum formation temperature to be about 450 ºC.

The NEDO (New Energy and Industrial Technology Development Organization) WD-1 survey well was spudded in January 1994 in this area, and the sidetracked well WD-1a reached 3,729 m in July 1995. The formation temperature was recorded to be greater than 500 ºC for this well (Ikeuchi et al., 1998; Saito et al., 1998). This project comprises an evaluation of existing drilling technologies for high–temperature downhole conditions. One of these goals was to evaluate BHA cooling methods by pumping mud using a TDS while running drill-pipe stands in the hole (Saito et al., 1995a). WD-1a was drilled using this technique for the 8-1/2 inch section while running BHAs in the hole.

It is obvious that tapping higher enthalpy geothermal energy results in advantages to the generation of electricity. However, drilling higher temperature formations is more difficult (Saito,1995b). This is because three-cone bits become dull in a short time (Macine and Mesine, 1994; Macine, 1996; Saito, 1996). Three-cone bits have been devised with O-ring seals, between the bit body and rotating cones to keep the lubricating oil contained in the bearing sections, and include flexible diaphragms to compensate for the pressures between lubricating oil and the pressure outside the bit at any depth. O-ring seals and diaphragms are currently made of rubber with temperature limitation of 150 to 190 ºC as reported by the bit manufactures. Borehole temperature commonly exceed these limitations while running BHA in the hole. The high wellbore temperature damage the grease seal resulting premature bearing failure. Bits are often changed with only slightly worn cutting structure, but failed bearing. A TDS (TESCO) was used for the first time in Japan for geothermal drilling (Saito et al., 1995b) so that the BHA could be cooled as it was run into the well. The advantages of a TDS are: preventing stuck pipe, reduced connection time, and enhanced crew safety. The invention and use of TDS BHA cooling techniques was necessary for WD-1a so that deep, high-temperature directional corrections could be made. Cooling of mud motors (PDM) and MWD tools was necessary to accomplish such trajectory control. This paper examines the economic use of TDS, based only on bit life in high-temperature wells.

The dull bit conditions, mainly the O-ring condition were reviewed, and the drilled hours for each bit were analyzed for both Well-21 and WD-1a. Based on these data, an economic study was performed for the use of TDS and the results are reported in this paper.

2. GEOLOGY AND FORMATION TEMPERATURES

The over lying Tertiary formation, which has a thickness of about 2,200 to 2,500 m, consists mainly of dacitic pyroclastic rocks, tuffaceous sandstone and black shale. The pre-Tertiary formation is highly metamorphosed and is a few hundred meters in thickness, as confirmed by drilling. The neo-granite pluton is thought to be one of the heat- source rocks in this area that have intruded into Tertiary and pre-Tertiary formations. Most of the rocks are very abrasive. The location of WD-1 was sited based upon the previous investigations of the area and on previously drilled wells. In general, formation temperatures in this area reach 200 ºC at a few hundred meters, 300 ºC at 1,500 m and over 350 ºC at around 2,000 m.

3. TEMPERATURE LIMITATIONS OF THREE-CONE BITS, O-RING SEALS AND A DISASSEMBLED BIT EXAMPLE

Diamond bits are considered to be uneconomical for geothermal well drilling, (except for coring) because the formations are not favorable for drilling with those bits. So, only three-cone bits were used for drilling. Three-cone bits, however, have temperature- sensitive parts like O-ring seals and diaphragms, which have a temperature limitation of 150 to 190 ºC. Therefore they are likely to be subjected to damage during drilling operations in high-temperature geothermal wells. Once the O-ring seals are damaged, drilling performance decreases greatly and the bit must be changed. In this study, 8-1/2 inch bits were disassembled after use and the O-ring seal and diaphragm conditions were inspected.

4. BHA COOLING METHOD WHILE RUNNING IN THE HOLE

From the bore-hole temperature data of WD-1a drilled in Kakkonda, it became clear that mud circulation temperature in the hole was relatively cool even though the formation temperature was 350 ºC or higher (Saito et al.,1998). But, mud temperatures in the hole became very high while round trips to change BHAs were made. So, if no counter measures were taken, the bore-hole temperature would become higher than the bit O-ring seal temperature limitations. The only method to cool BHA while running them in the hole is to use a top-drive-drilling-system (TDS). A TDS consists of a pipe rotating device, elevator, pipe connection device and water swivel. So, the TDS makes it possible to connect a drill pipe stand directly to the TDS connection sub, and to the BHA. Then mud can be pumped through a BHA before lowering each drill-pipe stands. The bit can be lowered without being soaked by the existing high temperature mud. This BHA cooling method was invented by the authors and was applied for the first time in the world. To find out the cooling effect of this method, an experiment was done using PT-memory gages when the well depth was 2,687 m (Saito et al, 1995a). Fig. 2 shows a borehole temperature comparison between pumping mud at 150 kl/h and no pumping. More than 50 ºC temperature difference was recorded between the two BHA running methods. The most important result was that BHA temperature could be kept below 140 ºC, which is less than the temperature limitation of bit O-ring seals, even where the formation temperature is over 350 ºC or more.

5. COMPARISON OF BIT LIFE WITH AND WITHOUT COOLING BHA WHILE RUNNING IN THE HOLE

The bit life data for wells Well-21 and WD-1a are as follows.

5.1 Well-21

A 9-5/8 inch liner was set and cemented at 1,805 m depth and 8-1/2 inch three-cone bits were used to drill to 2,800 m total depth (Fig. 3). No lost circulation occurred in this section. At 1,852 m pre-Tertiary formation was encountered. Then from 1,957 m the formation changed to neo-granite. Temperature logs were run at 29.5 and 50.8 hour standing time and 310 ºC was recorded at 2,540 m for a 50.8 hour survey. Formation temperature was estimated to be 310 ºC at 2,000 m, 350 ºC at 2,200 m, 412 ºC at 2,540 m by the Horner method. A formation roughly 450 ºC was extrapolated at 2,800 m.

This well did not employ a TDS, and mud was circulated only at 1,000m and 1,800 m for one hour. Two conventional mud coolers were used to keep the inlet mud temperature at 50 ºC.

A total of 23 three-cone bits were used to drill 995 m of the 8-1/2 inch hole. Fourteen bits were disassembled and the O-ring conditions were inspected (Table 1). Of the 14 inspected bits, 11 bits were sealed journal bits and 3 were air bits. These bits were purchased from 5 bit manufacturers from both domestic and overseas sources. O-ring seals from the three bits used to drill 1,889.5 to 2,105.0 m section survived an average of 28 rotating hours where the formation temperature was between 310 and 350 ºC. No O-ring seals survived more than 34.4 hours below 2,105 m where the formation temperature is a little over 350 ºC. No bit performance difference was noted among the different bit manufacturers. Average rotating hours and drilled distance for the 11 sealed journal bits were 26 hours and drilled a 66 m section.

5.2 Well WD-1a

A 9-5/8 inch liner was set and cemented at 2,550 m depth. Below that depth 8-1/2 inch three-cone bits were used (Fig.4). At 2,660m the well entered the pre-Tertiary formation and then at 2,860 m depth, the formation changed to neo-granite. Below 3,451 m, the drilling mud in the hole deteriorated due to increased temperature during round trips to change bits were made. Furthermore, CO_2 gas was ejected when the bottom part of the mud was returned to the surface. Lime was added to the drilling mud to control the CO_2 gas. After a new bit was run to 3,642 m and mud was circulated at that depth, mud with high H_2S gas was returned to the surface. The drilling operation terminated at 3,729 m because of safety concerns.

Several temperature logs and temperature surveys using melting points of temperature-indicating materials were performed. From those results, formation temperatures were estimated to be: 350 ºC at 2,550 m, 360 ºC at 3,000 m, 500 ºC at 3,500 m and over 500 ºC below 3,500 m.

The BHA cooling procedure while running-in-the-hole (RIH) was to circulate mud for one hour at 1,000 and 2,000 m, and from 2,500 m down to the bottom of the well to circulate continuously while running each drill pipe stand.

Fig. 4 shows the 8-1/2 inch bit performance in the well WD-1a. A total of fifteen 8-1/2 inch three-cone bits, purchased from six bit manufacturers, from both domestic and overseas sources were disassembled and O-ring conditions were inspected (Table 2). O-ring seals, except for one seal, of the five bits used from 2,939 m to 3,451 m survived where the formation temperature is between 360 to 500 ºC .The average rotating time and drilled section for those five bits were 50 hours and 101 m respectively.

As shown in Table 2 the performances of the first six bits used after setting 9-5/8 inch casing were not as good as the following five bits. Even though these six bits were used at shallower depths. One of the reasons is thought to be that the formation temperature recovered while waiting on cement to harden after the casing cementing operation. So, the borehole temperature was higher even at shallower depths. Another alternative is the pumping rate and pumping duration were not enough for the first 6 bits while running BHA in the hole. As stated above, this cooling method was being employed for the first time, so it took time to determine appropriate pump rate and volumes.

The pumping rate while running BHAs was 1,500 l/min, and BHA running speed was reduced to about 4 hours to per 1,000 m length of drill-pipe string in the hole.

6. EFFECTS OF USING A TDS AS A BIT COOLING METHOD

Bit performance differences for the two wells can be outlined as follows. In Well-21 bit performance, three bit O-ring seals survived and average drilled hours of the three bits was 28 hours. The deepest depths where O-ring seals survived was 2,105 m where the static formation temperature is 350 ºC. In the WD-1a well, the depth of the last bit for which O-ring seals survived was 3,451 m and bits drilled for 31 hours where the static formation temperature was more than 450 ºC. The average drilled hours of the 5 bits without O-ring seal failure was 50 hours, where the static formation temperature was between 350 and 450 ºC.

It is difficult to evaluate a single bit life directly, and the effect of the BHA cooling method using a TDS, because of different formation types, formation temperatures, and pumped mud temperatures from the surface; and other conditions which are never the same for a specific bit. Bits are often pulled out of the hole, not because of the bit condition but for other reasons; such as to change the BHAs. Also, it is difficult to estimate how many more hours O-ring seals might run when O-ring seals came out without failure.

Judging from the bit performances for the two wells, bit life using TDS-Cooling method would be three to six times more compared with conventional cooling method if the same formation temperature and depths were drilled. Since no lost circulation occurred in the 8-1/2 inch section for both wells, and the same type of bits were selected from the same bit manufacturers; it can be concluded that the TDS-Cooling method was very helpful in prolonging bit life.

7. AN ECONOMIC EVALUATION OF TDS USE BASED ON BIT LIFE

This section presents cost comparisons and an economic study based solely on Well-21 and WD-1a average bit life data, and average time and cost factors for these two wells. It was not possible to consider the economic value of the other advantages of TDS use because these other advantages were too difficult to quantify. Two examples are considered that compare the drilling of two 1,000 meter sections of 8-1/2 inch wellbore: Example-1: Drilling 8-1/2 inch section of the well from 2,500 to 3,500 m. Example-2: Drilling 8-1/2 inch section of the well from 2,000 to 3,000 m. Two basic cooling programs were compared: Case-1: No TDS-Cooling, cooling for one hour at 1,000 and 2,000 m. Case-2: Cool BHA with TDS while running stands in the hole.

The cost factors, times, bit usage and bit life for each Example and for the two cases are summarized in Table-3. It is readily apparent on average that the TDS-Cooling results in three to six times bit life, depending on formation temperature and drilled depth. Therefore, on average, each bit was considered to drill five times the meters in Case-2 for Example-1 and to drill three times the meters in Case-2 for Example-2 with TDS-Cooling, as compared to each bit for Case-1.

7.1 Example-1

Calculations for Example-1 were carried out as follows:
Total hours required to run the BHA will be given by following equations.

Case-1:
BHA running time
= (Tool Preparation + mud circulation at 1,000 and 2,000m) x50 + 50 times for RIH hours +50 times for POOH hours

$$= (3+1+1)\times 50 + \sum_{n=1}^{50}\{2500+20(n-1)\}/800 + \sum_{n=1}^{50}(2500+20n)/800$$

=625.0 hours

Case-2
BHA running time
=(Tool Preparation + mud circulation at 1,000 and 2,000m) x10 + 10 times for RIH hours +10 times for POOH hours

$$= (3+1+1)\times 10 + \sum_{n=1}^{10}\{2500/800+100(n-1)/250\} + \sum_{n=1}^{10}(2500+100n)/800$$

=137.4 hours

Total drilling times are 500 hours for both Case-1 and Case-2, and in addition 50 hour are required for TDS preparation and downtime in Case-2.

Therefore, total hours to drill from 2,500 m to 3,500 m for the two cases are:

Case-1: 625.0 + 500 = 1125.0hours (47days)

Case-2: 137.4 + 500 + 50 = 687.4hours (29days)

Drilling costs can now be calculated using the drilling times and the cost factors from Table-3. Where the total costs are given by the summation:

$$\sum(\text{Total rig cost} + \text{Bit cost} + \text{TDS rental cost})$$

Therefore
Case-1: 47days x 1.2m.yen + 50 x 0.6m.yen = 86.4million yen
Case-2: 29days x 1.2m.yen + 10 x 0.6m.yen + 29days x 0.3m.yen = 49.5 million yen

7.2 Example-2:

Using the data and factors recorded in Table-3, the results can be calculated in a similar manner as was done for Example-1. The results of such calculations are recorded in Table-3. And therefore, it is clearly seen that the lower section drilled from 2,000 to 3,000 m gives more economical for using TDS.

As can be deduced from Table-3 the total costs for drilling with or without a TDS are more economical for using TDS. This is a result of the fact that the use of the TDS increases (three to six times) the bit life; and the costs of bits is reduced, and the number of round trips is also decreased. As the calculations show, the result is that the TDS essentially pays for itself by extending bit life.

Such a result, indicates that TDS could be used, to extend the life of currently available three-cone bits. Therefore, the other benefits of TDS use can be realized.

CONCLUSIONS

1. A study of the drilling data from these high temperature wells shows that cooling bits while running in the hole using a TDS revealed that bit life can be three to six times more compared to bits run by standard cooling methods in a very high temperature well.
2. With this cooling method, O-ring seals survived even after drilling 31 hours where the formation temperature is 450 ºC. The average bit life was about 50 hours even where the static formation temperature was over 350 ºC.
3. An economic study shows that the TDS use is more economical due to the prolonged bit life and resulting reduced rig and bit costs. There are many other advantages in using a TDS. So, it can be very economical to use TDS when deep and very high temperature wells are drilled.
4. Finally, this simulation and calculations show that the use of TDS-Cooling can pay for the cost of the TDS.

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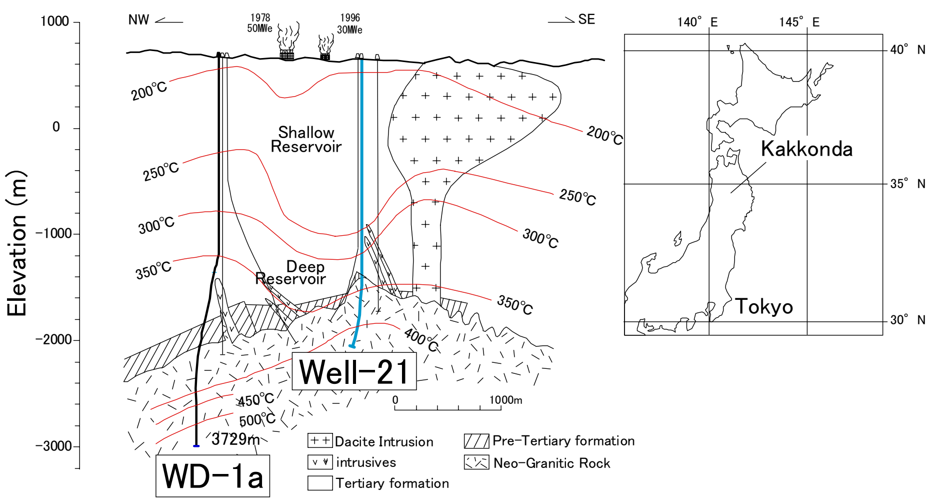

Fig.1 Location Map of Kakkonda and Schematic Geological Section of the Kakkonda Geothermal Area. (modified from Kato et al.,1996)

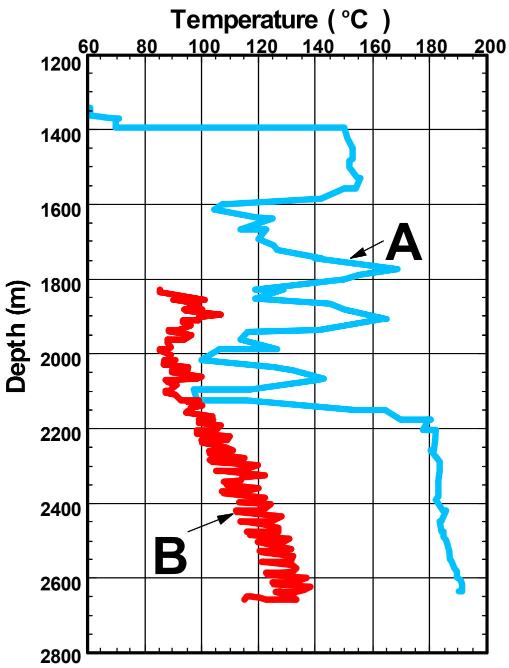

Fig.2 Borehole Temperature Curves of Well WD-1A Recorded by PT-Memory Tools with and without pumping mud while running BHA into the hole. Curve A : ran instrumented BHA without pumping water(from 16.3 to 18 elapsed hours). Curve B : recorded while pumping mud with top-drive system(from 42.8 to 47.3elapsed time).

Table 1. Bit Performance and Dull Bit Summary of 8-1/2 inch Three-Cone Bits Used in the Well-21.

		Drilling data					Dull bit conditions	
No.	†IADC code	From (m)	Meters (m)	Hours (h)	ROP (m/h)	WOB (ton)	O-ring	Diaphragm
32	617	1805	26	20.1	1.3	12	×	×
33	537	1831	58	30.9	1.9	12	×	×
34	537	1890	38	22.2	1.7	12	○	○
35	617	1928	76	29.1	2.6	12	○	○
37	617	2008	97	33.0	2.9	12	○	○
38	617	2105	93	34.4	2.7	12	×	×
39	617	2198	71	31.5	2.2	12	××	×
40	617	2269	53	24.8	2.1	12	×	×
41	617	2321	56	25.0	2.2	10	×	×
42	617	2378	81	33.4	2.4	8	×	×
43	617	2459	66	26.3	2.5	8	×	×
44	617	2525	25	11.2	2.2	8	×	×
47	617	2555	13	6.3	2.1	6	×	×
49	637	2568	24	13.0	1.8	6	×	×
@50	532	2592	19	12.3	1.5	6	—	—
@51	532	2611	23	14.3	1.6	6	—	—
@52	532	2635	29	15.5	1.9	10	—	—
53	617	2664	107	23.1	4.6	9	×	×
54	617	2771	29	8.4	3.5	9	×	×

ROP:rate of penetration, WOB:weight on bit, ○:still functioning, ×:damaged or worn out, ××:one O-ring disappeared,
@ is air bit (no O-ring,oil nor diaphragm from initial condition)
†:First two numbers of IADC code signify cutter types; 53 and 54 are for soft to medium formation, 61 is for medium to hard
The last numbers signify bearing types; 2 is air bit, 5 is sealed roller bearing gage protection,
7 is sealed friction bearing gage protection.

Table 2. Bit Performance and Dull Bit Summary of 8-1/2 inch Three-Cone Bits Used in the WD-1a.

		Drilling data					Dull bit conditions	
No.	†IADC code	From (m)	Meters (m)	Hours (h)	ROP (m/h)	WOB (ton)	O-ring	Diaphragm
53	537	2550	50	23.8	2.1	13	×	×
*56	537	2600	15	3.1	4.8	11	×	×
57	537	2615	72	37.7	1.9	12	×	×
59	537	2690	110	55.3	2.0	13	×	×
60	617	2800	42	22.1	1.9	13	××	○
62	537	2844	92	48.1	1.9	13	▲	△
65	537	2939	65	39.3	1.7	13	○	○
66	617	3004	122	62.1	2.0	13	○	○
67	547	3126	103	53.6	1.9	13	○	○
69	617	3231	119	63.5	1.9	13	△	○
70	617	3350	100	31.2	3.2	13	○	○
72	617	3451	76	20.9	3.6	13	××	×
73	617	3527	115	30.1	3.8	13	××	××
74	617	3642	28	13.8	2.0	13	×	×
75	617	3670	56	13.1	4.3	10	××	×

ROP:rate of penetration, WOB:weight on bit, ○:still functioning, ×:damaged or worn out, ××:disappeared,
△:two still functioning but one damaged,▲:one still functioning but two damaged,
*:used for downhole motor, other bits were used for rotary drilling.formation.
†:First two numbers of IADC code signify cutter types; 53 and 54 are for soft to medium formation, 61 is for medium to hard
The last numbers signify bearing types; 5 is sealed roller bearing gage protection, 7 is sealed friction bearing gage protection.

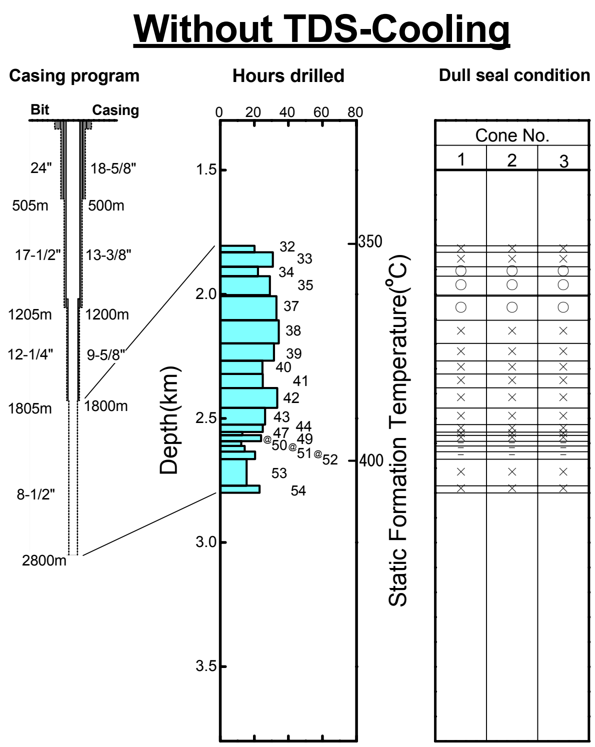

Fig.3 Bit Performance and Dull Seal Condition of 8-1/2 inch Bits Used in the Well-21. ○:Still functioning, ×:Damaged or worn out, @:Air bit (no seals used)

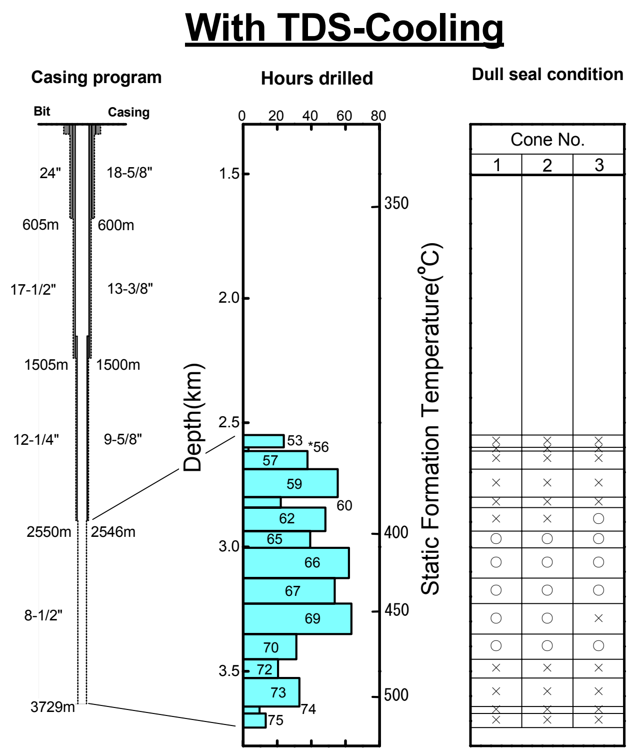

Fig.4 Bit Performance and Dull Seal Condition of 8-1/2 inch Bits Used in the WD-1a. ○:Still functioning, ×:Damaged or worn out,* :Used for downhole motor

Table 3. An Economic Evaluation of TDS-Cooling Method Based on Bit Life for Drilling Deep, High-Temperature Geothermal Wells.

	ITEM / PARAMETER	EXAMPLE-1		EXAMPLE-2	
SIMULATION INPUTS	Well Depth	3,500 m		3,000 m	
	Simulated Section	**2,500-3,500 m (8-1/2 inch section)**		**2,000-3,000 m (8-1/2 inch section)**	
	TDS-Cooling Method	**NO (Case-1)**	**YES (Case-2)**	**NO (Case-1)**	**YES (Case-2)**
	Bit Life & Drilled Section	10 hours, 20 m	50 hours, 100 m	20 hours, 40 m	60 hours, 120 m
	Pumping Procedure While RIH & POOH	At 1,000 and 2,000 m pump mud for one hour	At 1,000 and 2,000 m pump mud for one hour From 2,500 m to bottom of the hole, pump mud while RIH	At 1,000 and 2000 m, pump mud for one hour	At 1,000 m pump mud for one hour From 2,000 m to bottom of the hole, pump mud while RIH
	BHA RIH & POOH Speed	800 m/hour	800 m/h while not pumping 250 m/h while pumping	800 m/hour	800 m/h while not pumping 250 m/h while pumping
	Hours for Changing BHAs after POOH	3 hours	3 hours	3 hours	3 hours
	Hours for TDS Rig-up and Rig-down	-----	50 hours	-----	50 hours
	Number of Bits	50	10	25	9
TIME & COST RESULTS	A. Total Hours for: 1.Tool Preparation, and Mud circulation at 1km and 2km 2. RIH 3. POOH 4. Drilling 5. TDS rig-up and down	250.0 hours 186.9 188.1 500.0 ----	50.0 hours 49.3 38.1 500.0 50.0	125 hours 77.5 78.8 500.0 ----	36.0 hours 39.8 29.1 500.0 50.0
	TOTAL HOURS	1125.0 hours (47 days)	687.4 hours (29 days)	781.3 hours (33 days)	654.9 hours (28 days)
	B. Total Cost for: 1.Rig Cost (1.2m.y/day) 2.Bit Cost (0.6m.y/piece) 3.TDS Rental (0.3m.y/day)	47 days x1.2 m.y. 50 x 0.6 m.y. 0	29 days x1.2 m.y. 10 x 0.6 m.y. 29 days x 0.3 m.y.	33 days x1.2 m.y. 25 x 0.6 m.y 0	28 days x 1.2 m.y. 9 x 0.6 m.y. 28 days x0.3 m.y
	TOTAL COST (m. Yen)	86.4 m. Yen	49.5 m. Yen	54.6 m. Yen	47.4 m. Yen
	COST SAVINGS (Million Yen)	-----------	**36.9 m Yen**	-------------	**7.2 m Yen**