MWD and Downhole Motor Performance in Very High Temperature Geothermal Wells in Kakkonda, Japan

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ABSTRACT

The formation temperature in Kakkonda, northern Honshu Island, Japan, exceeds 300 deg.C below 1,500m and 350 deg. C below 2000m. To introduce recent deep and high temperature well drilling technologies in Kakkonda, the drilling histories of Well-20 and Well-22 are described. This paper focuses on retrievable type MWD and downhole motor performances related to drilling fluid temperatures. The temperature limitations of the MWD and downhole motors are about 150 deg. C, but those tools can survive to certain depth where formation temperature exceed 350 deg.C with the proper mud cooling system. Various temperature data are also introduced, such as temperature logs at total depth (TD), mud temperature in and out of the wells, mud circulation temperature recorded by MWD, and bottom hole temperature recorded by thermometers installed on top of the magnetic single shot tool.

Key Words: drilling, directional drilling, measurements while drilling (MWD), downhole drill motors, high-temperature wells.

1. INTRODUCTION

Forty years have passed since the first geothermal exploration well was spudded in Japan. Since then more than 470 geothermal wells, a total drilled length of about 600 km, were drilled by Japanese geothermal developers in 14 areas. By 1977 and 1982, maximum well depths had reached 2,000 m and 3,000 m respectively. A total of seventy 2,000 m wells and six 3,000 m wells have been drilled to date. The deepest geothermal well, at a 3,226 m TD and the maximum temperature of 280 deg.C, was drilled in Mori of Hokkaido Island. Very high temperature wells, which have maximum temperatures of over 350 deg.C, were reported in Kakkonda and Fushime, Japan.

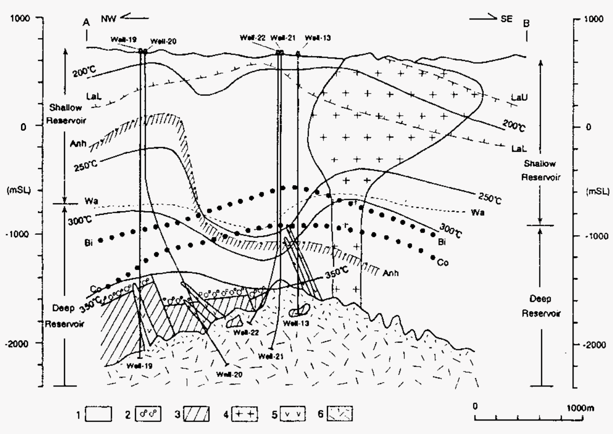

Figure 1. Schematic geologic cross section of the Kakknoda geothermal field along the kakkonda river(350°C isothermal line is added to Kanisawa et *al.*,in press).

1:Tertiary formations, 2:Basal conglomerate in the tertiary formations, 3:Pre-tertiary formations, 4:Torigoeno-taki dacite intrusion, 5:Old granitic intrusives, 6:Neo-granitic pluton. LaU:Upper limit of laumontite, LaL:Lower limit of laumontite, Anh:Upper limit anhydrite, Wa:Lower limit of wairakaite, Bi:Biotite isograde, Co:Cordierite isograd.

In Kakkonda, geothermal wells have been drilled since 1972 and 50MW Kakkonda No.1 power station (PS) has been successfully operated since 1978. Now, 30MW Kakkonda No.2 PS is planned to start operation in 1996. About 70 wells with depths ranging from 1,000 to 2,000m were drilled and geothermal fluids were produced from the tertiary formation. Recently Well-20 and Well-22, and another three deep wells, with depths ranging from 2,463m to 3,000m, were drilled into the pre-tertiary formation and a neo-granitic pluton (Fig.1). These wells discovered a deeper promising reservoir. Well-20 was drilled as a production well for Kakkonda No.2 PS by Tohoku Geothermal Energy Co.,Ltd. under the technical support of Japan Metals & Chemicals Co., Ltd. (JMC). And Well-22 was drilled as a make up well for Kakkonda No.1 PS by JMC. The NEDO 4,000m test well has been drilling since January 1994 from the same drilling pad as Well-20.

Retrievable type MWD (Anadrill SLIM-1), with a temperature limitation of 150 deg.C, was first employed for the high temperature geothermal wells where the formation temperature is over 350 deg.C. Also several downhole motors were operated for both of the wells.

In this paper, general drilling technologies are introduced with Well-20 data. Various temperature data, MWD and downhole motor performances are introduced with Well-20 and Well-22.

2. GEOLOGY

Tertiary and pre-tertiary formations, neo-granite and other intrusive rocks were recognized from drilled cuttings and cores in this area. The tertiary formation which has the thickness of about 2,200 to 2,500m, consists mainly of dacitic pyroclastic rocks, tuffaceous sandstone and black shale. The pre-tertiary formation is highly metamorphosed and is about a few hundred meters thick as confirmed thus far. The neo-granitic pluton is thought to be one of the heat source rocks in this area, that has intruded into tertiary and pre-tertiary formations. Some older intrusive rocks are recognized by both drill cuttings and surface outcrops.

Most of the rocks are very abrasive. Also the geological structure is characterized as a folded structure. Therefore, bit walk is often encountered and well trajectory control is very difficult in this area.

Formation temperatures in this area reach 200 deg.C at a few hundred meter depths and 350 deg.C at around 2,000m depths.

3. DRILLING OF Well-20

Well-20 was planned as a production well to tap the deeper reservoir existing in the pre-tertiary formation and the neo-granitic pluton. Planned depth of the well was 2,800m with 8 1/2 inch bit diameter. The drilling strategy was devised to drill with 5 different diameter holes to safely reach the planned depth. Many lost circulation zones were expected in the shallower depths where previously drilled wells are producing geothermal fluids. The well was spudded in May 1992 with EMSCO D-3 rig and two NATIONAL 8P-80 mud pumps. A total of 180 days was spent to reach 3,000m including 33 days for lost circulation treatments and 27 days for trajectory correction runs with downhole motors (Fig.2). Many lost circulation zones were encountered until the 1,500m depth was reached. A total of 25 cement slurry plugs and 3 lost circulation material treatments were placed to cure lost circulations. The well target was assigned at a true vertical depth of 2,670m, horizontal offset of 640m and the azimuth of south 20 degrees east. The well trajectory plan was designed to kick off at 1,100m, build inclination continuously to 24 degrees from vertical at around 1,500m depth, and then drill straight to the target. But the actual trajectory started to build angle consistently from 200m depth, so

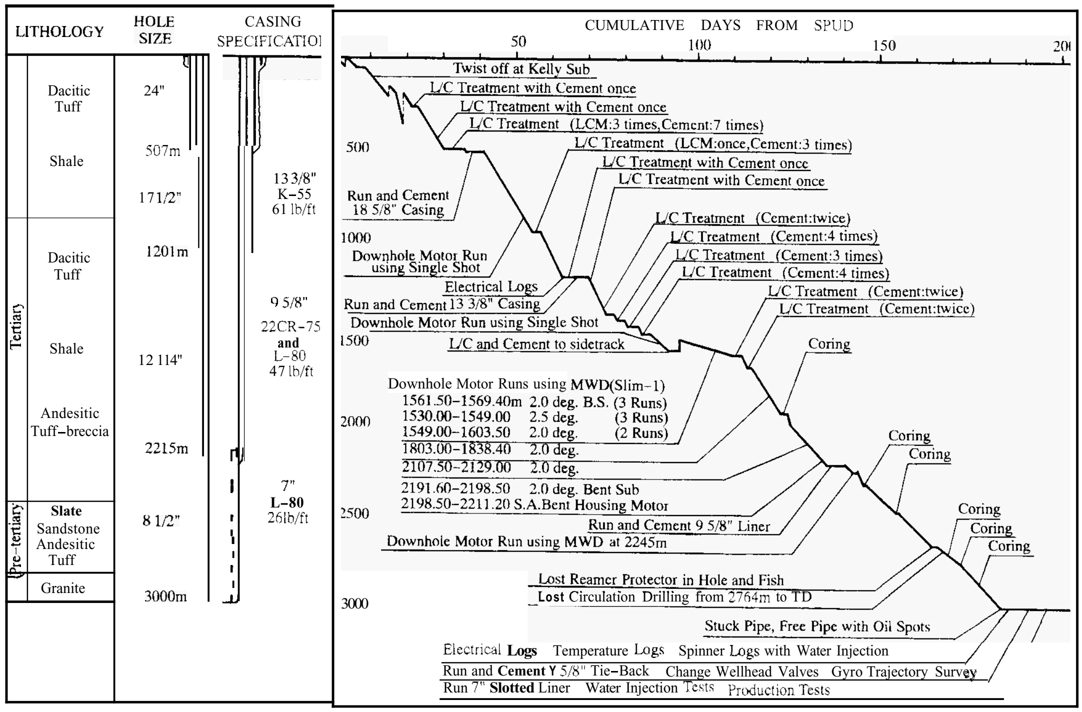

Figure 2. Drilling history of Well-20 at Kakkonda.

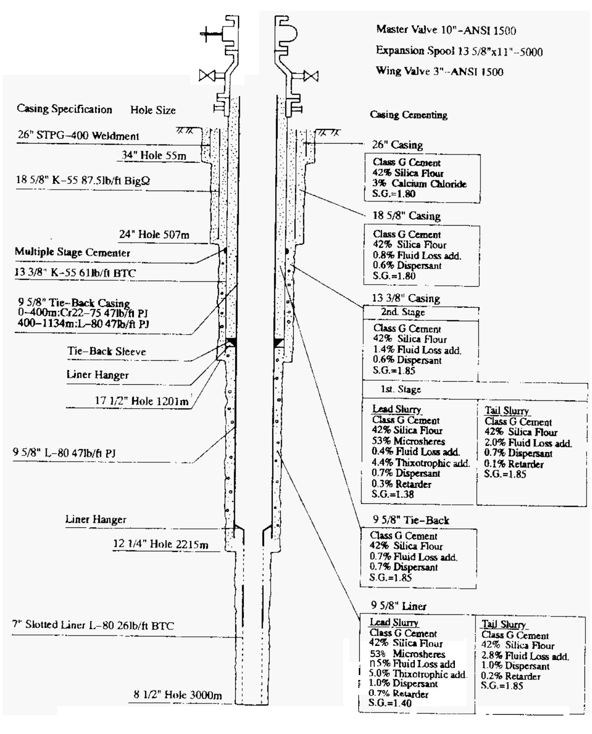

Figure 3. Casing and cementing program of Well-20.

downhole motor and bent sub assemblies were employed at depths of 860 and 1,500m to correct the well trajectory. Single shot survey methods were used to set the bent-sub tool face orientation, but finally failed to correct the trajectory runs. Therefore retrievable MWD tools were adopted to orientate the tool face. In addition to two mud cooling towers, a 500 kl pit was devised to cool the returned mud before pumping into the well. But fiom 2,200m well depth, stator rubbers started to unbond and to break up. So, only packed hole rotary assemblies were used to minimize bit walk tendency and hit the given target area. The pre-tertiary formation was encountered at 2,450m and first lost circulation occurred at 2,764m since the 9 5/8 inch liner was set at 2,215m. Drilling was continued with lost circulation and the well was deepened to 3,000m because deep reservoir was expected to exist in the neo-granite from drilling information and core samples. The 9 5/8 inch tieback string was run and cemented following the running of electric logs, temperature logs, and spinner surveys with water injection.

From the test results of another deep well, acid fluid was expected to be produced, therefore a duplex tieback casing was installed from surface to 400m depth (Fig.3). **A** multiple stage cementing method was employed for the 13 3/8 inch casing and ultra low density cement slurry was used for the 13 3/8 inch first stage and the 9 5/8 inch liner slurry to insure maximum slurry placement for the entire installed casing lengths. Both API-5000 and ANSI-1500 rated wellhead equipment were used **because** the wellhead pressure was expected to be over 100ksc.

4. MUD AND MUD COOLING SYSTEMS

To prevent drilling mud gelation, bentonite contents were kept below 4% and high temperature dispersant was used for the 12 1/4 and the 8 1/2 inch holes. Also surfactant and diesel oil were added to reduce rotary torque. It was well known from previous deep well drilling experience that mud cooling effects played an important role for high temperature well drilling (Saito,1993). Therefore two mud cooling towers and a 500 kl mud cooling pit were devised to get the maximum mud cooling effects (Fig.4). Also solid control systems were employed to minimize solid contents in the mud.

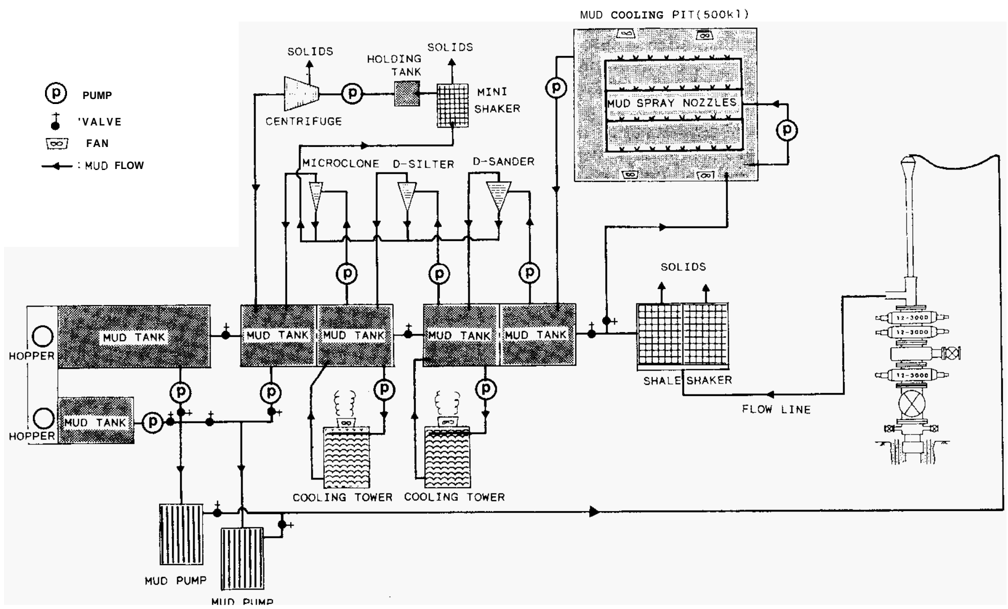

Figure 4. Schematic of mud cooling and solid control system of Well–20.

4.1 Temperature Data

4.1.1 Well–20

Well–20 was drilled with partial lost circulation below 2,764m and drilled with total lost circulation below 2,883m to 3,000m. Eventually the well was cooled very much by the time the well had reached TD. Curves F,G and H-I of Figure 5 show temperature logs after standing times (ST) of 24, 46 hours and 9 days. The mud cooling influence still exists for the log data after ST 9 days. No further temperature logs were run for longer standing times, so the true formation temperature was not evaluated from Well–20 data. But fortunately slim-hole Well–18, a continuously cored well, had been drilled before drilling Well–20 from the same drilling pad and a temperature log was recorded after 4 months standing time. The resulting temperature profile is considered to represent the deep temperature of Well–20 without cooling effects (Fig.5–J). Curve J is only available to 1,900m depth, but over 350 deg.C formation temperature is estimated below 2,000m from this curve. Curve E shows log data after 12 hour standing time, before running the 9 5/8 inch liner. Curves A and B are mud temperature measured at the suction tank and the flow line respectively. One mud cooling tower was used from 100m, two cooling towers were

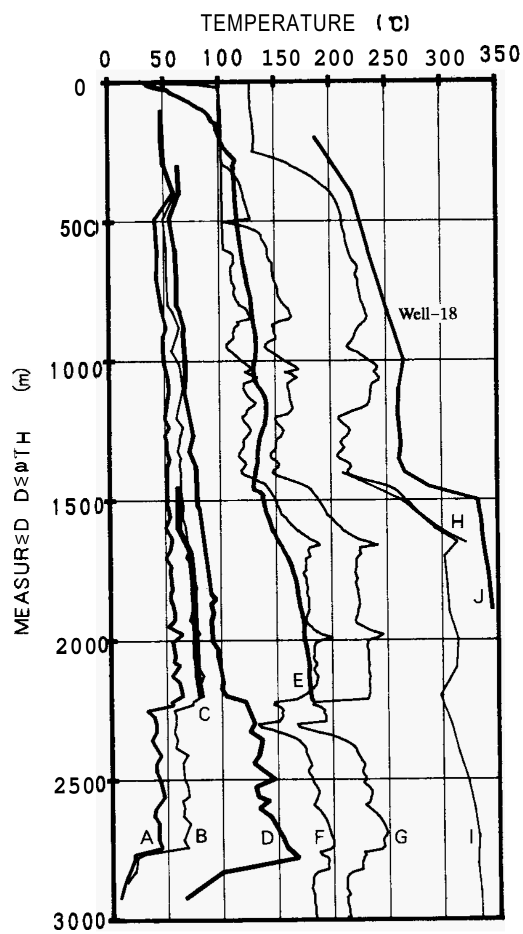

Figure 5. Temperature distribution curves of Well–20 and Well–18 at Kakkonda.(Saito,1993b) From 2,764m Well–20 was drilled with lost circulation.

Well–20
A,B:Drilling fluid temperature measured at suction tank (A) & flow line (B).
C:Bottom hole circulation temperature measured with MWD (Slim–1).
D:The temperature inside the NDC about 15m above the bit within one hour after circulation ceased. Recorded with thermometers
E:The temperalure log data at 13 3/8" casing depth after standing time 12 hours.
F,G,H–I:Temperature log data at TD after standing time 24, 49 and 9 days.

Well–18
J:Temperature log data after standing time 4 months.

E,F,G and H were recorded with Platinum resistance thermometers
I and J were recorded with Kuster thermometers

used from 450m, and two cooling towers and a cooling pit were used from 2,250m well depth. Curve C is the mud circulation temperature recorded by a MWD tool placed inside the drill string about 15m above the bit. The MWD temperature sensor is installed inside the MWD housing, but from laboratory tests it is known that temperatures inside and outside of the housing equalize within a few minutes. Thus curve C effectively records mud circulation temperature inside drill strings. The retrievable MWD temperature data was only taken horn the 12 1/4 inch hole for this well. Curve D was recorded by maximum temperature thermometers installed on top of the magnetic single shot tool. Standing times for these data are within 1 hour. Curve D is measured at the same position as curve C.

From these data in the 12 1/4 inch hole the mud circulation temperature is less than 80 deg.C whereas the formation temperature is over 300 deg.C. And the mud temperature within the drill string increases about 20 to 30 deg.C within 1 hour standing time, and increases about 70 to 100 deg.C within 12 hour standing time. Below 2,215m depth the pump output was decreased for the 8 1/2 inch hole compared to the 12 114 inch hole. Curve D shows that the temperature increased in spite of pumping cooler mud for the 8 1/2 inch hole. Well temperature decreased drastically while drilling with partial or total lost circulation below 2,764m.

4.1.2 Well–22

Well–22 temperature data are shown in Figure 6 to indicate MWD temperature data in the 8 1/2 inch hole which were not recorded in the Well–20. Formation temperature was not recorded for this well, but the fact that pre–tertiary and neo–granite depths are shallower than the Well–20, formation temperature is estimated to be slightly higher than Well–20 in the deeper section. Mud temperature in and out, MWD temperature and one hour standing time temperature recorded with the thermometer arc shown in Figure 6. From these data, bottom hole circulation temperature (BHCT) in the 121/4 inch hole shows almost the same temperature as the returned mud temperature; but BHCT in the 8 1/2 inch hole shows much higher temperature than the returned mud. And the temperature distribution curve of BHCT in the 8 1/2 inch hole is parallel to curve D. One of the reasons for the BHCT increment in the 8 1/2 inch hole is reduction of mud circulation volume to 96 kl/h whereas 150 kl/h was pumped for the 12 1/4 inch hole. Well temperature decreased drastically after lost circulation was encountered at 2,618m.

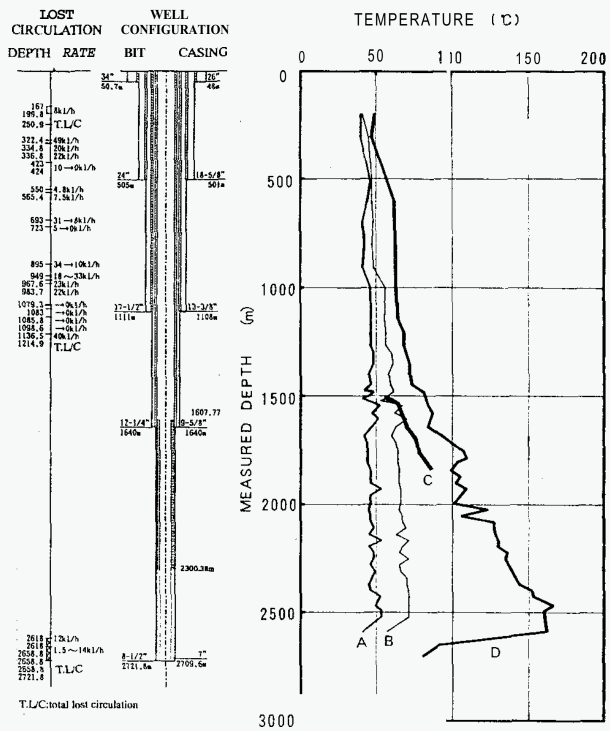

Figure 6. Lost circulation zones, well configuration and temperature distribution curves of Well–22.

A,B:Drilling fluid temperature measured at suction tank(A) & flow line(B). C:Bottom hole circulation temperature measured with MWD(SLIM–1). D:The temperature inside the NDC about 15m above the bit within 1 hour after circulation ceased. Recorded with thermometers.

Table 1. Downhole motor performance summary of Well–20.

Downhole motor					Drilled interval (m)		Meters drilled (m)	Hours run (h.m)	ROP (m/h)	Mud temp. (°C)		Hours in hole (h.m)	Reason to POOH	Downhole motor condition after POOH
Hole size	Run no.	Maker code	Tool no.	Tool OD	From	To				In	Out			
171/2"	1	A	1	9 5/8"	860.2	880.4	20.2	13.40	1.48	45	58	25.00	R.S.D	
121/4"	2	B	1	8"	1561.5	1588.2	26.7	8.10	3.27	49	68	23.00	C.BHAs	
	3	B	1	8"	1531.0	1548.5	17.5	25.30	0.68	47	63	41.30	WOC	
	4	A	2	7 3/4"	1556.0	1569.4	13.4	23.30	0.57	48	61	37.00	WOC	
	5	A	2	7 3/4"	1530.0	1539.9	9.9	24.20	0.41	42	62	36.00	Ck.bit	
	6	A	2	7 3/4"	1539.9	1542.7	2.8	10.20	0.27	46	58	26.00	L/C	
	7	A	3	7 3/4"	1542.7	1549.0	6.3	12.10	0.52	54	65	29.30	Ck.bit	
	8	A	3	7 3/4"	1549.0	1565.5	16.5	20.50	0.79	50	62	30.00	R.S.D	
	9	A	3	7 3/4"	1575.0	16035	28.5	15.50	1.80	50	68	23.30	R.S.D	
	10	A	4	7 3/4"	1810.0	1838.4	28.4	22.00	1.29	54	74	36.00	R.S.D	
	11	A	5	7 3/4"	2107.5	2129.0	21.5	17.20	1.24	56	83	39.30	R.S.D	
	12	A	5	7 3/4"	2191.6	2198.5	6.9	5.20	1.29	60	82	21.10	pp.W.U	S.R.C.O
	13	C	1	9 5/8"	2198.5	2211.2	12.7	5.30	2.30	64	82	22.40	D.F.I	
8 1/2"	14	A	6	6 1/4"	2245.0	2245.0	0.0	---	---	48	86	23.50	Sk. BHA	
	15	A	6	6 1/4"	2245.0	2245.0	0.0	---	---	--	--	23.50	pp.W.U	S.R.C.O

R.S.D:reached schedule depth, C.BHAs:change BHA, WOC:wait on cement, Ck.bit:check bit, pp.W.U:pump pressure went up, D.F.I:drag force increased, Sk.BHA:stuck BHA, S.R.C.O:stator rubber came off

5. DOWNHOLE MOTOR AND MWD PERFORMANCES

5.1 Well–20

The trajectory correction runs with downhole motors were performed one time for the 17 1/2 inch hole, 12 times for the 12 1/4 inch hole and twice for the 8 1/2 inch hole for the Well–20. Bent sub tool face orientations were done with magnetic single shots for the first two correction runs, but failed to set tool face orientations properly because reaction torque could not be estimated while pumping mud. Usually steering tools have been used to set the tool face orientation in the deeper section of the hole, but the retrievable MWD which has temperature limitation of 150 deg.C was deployed for this well after the second correction run. Eight downhole motors were supplied by three manufactures and used for this well (Table 1). The thrust bearings of all downhole motors used for depths shallower than 1,810m wore out after about 20 to 50 hours operating time; however, the stator rubbers were still in good condition. Whereas the stator rubber of two downhole motors used below 2,100m unbonded and broke up. The round trip times of the bottom hole assemblies were 6 to 8 hours at 1,000 and 2,200m. The trip–in temperature in the hole was estimated from curves D and E (Fig. 7). An 150 deg.C or higher bottom hole temperature was estimated after downhole motor run No.11. This high temperature might have caused the stator rubber failures. The stator rubber did survive for downhole motor run No.13. This was perhaps due to a shorter running time and the fact that the pump flow rate was higher for the larger diameter downhole motor size compared to the other runs. The downhole motor runs in the 8 1/2 inch hole did not drill at all and the rubber stators failed. Therefore, the 8 1/2 inch hole section was drilled just with rotary BHAs.

A retrievable MWD was used not only with downhole motor assemblies but for five rotary drilling and one multiple magnetic trajectory survey. About 300 hours of operation were recorded for 27 runs and a total downtime of MWD was about 13 hours, which is less than 5 % of all the operation time (Table 2). In the 8 1/2 inch section MWD could not operate but this was because the hole temperature was over 150 deg.C which was out of this MWD temperature specifications. From this operation, it is concluded that retrievable MWD can be used for the very high temperature well if the hole can be cooled below 150 deg.C. It was also determined that the main failure of MWD was battery parts.

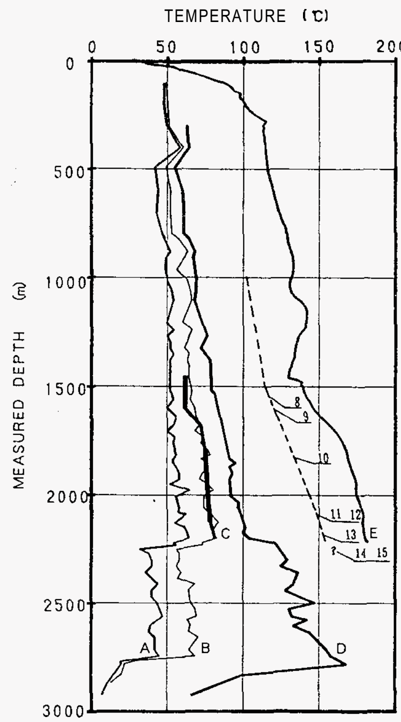

Figure 7. Estimate downhole trip–in temperature and downhole motor performance.

Curves A through E are *same* as shown in Fig. 5. Estimete downhole trip–in temperature curve was made taking into consideration of round trip time each depth and curves D and E of which standing time about one hour and 12 hours. Numbers 8 through 15 show the downhole run numbers. Stator rubbers were broken up after runs 12 and 15.

Table 2. MWD(SLIM–1) motor performance summary of Well–20

Hole size	MWD Run no.	PDM run no.	Drilled interval (m) From	To	SLIM–1 Hours run (h.h)	BHCT (°C)	Results	Down time (h.h)	Remarks
12 1/4"	1	3	1531.0	-----	2.7	65	good	0	
	2	3	-----	1548.5	27.0	62	good	0	
	3	4	1556.0	1569.4	26.0	64	good	0	
	4	5	1530.0	1539.9	18.0	64	No G.	0.75	Battery wire parted
	5	6	1539.9	-----	13.0	65	good	0	
	6	6	-----	-----	2.0	65	No G.	6	Battery wire parted
	7	6	-----	1542.7	13.0	64	good	0	
	8	7	1538.0	1549.0	0.0	--	No G.	1.5	Battery wire parted
	9	8	1549.0	2222.2	10.0	65	No G.	0	Battery fuse blow
	10	8	2222.4	-----	3.5	65	No G.	1.5	Battery fuse blow
	11	8	-----	1565.5	7.5	65	good	0	
	12	9	1575.0	1603.5	24.0	65	good	0	
	13	RT	1603.5	1616.0	18.5	68	good	0	
	14	RT	1616.0	1624.0	14.5	77	good	0	
	15	MS	1536.0	1611.0	1.5	77	good	0	
	16	RT	1685.5	-----	35.0	78	good	0	
	17	RT	-----	-----	17.0	82	good	0	
	18	RT	-----	1803.0	7.0	79	good	0	
	19	10	1810.4	1838.4	34.0	82	good	0	
	20	11	2107.5	-----	6.0	82	No G.	3	Wire insulation failed
	21	11	-----	-----	0.0	--	No G.	0	Tool free fell to bottom
	22	11	-----	2129.0	20.0	82	good	0	
	23	12	2191.6	2198.5	8.0	82	good	0	
	24	13	2198.5	2211.2	10.3	82	good	0	
8 1/2"	25	14	2245.0	-----	0.3	166	No G.	1.5	BHCT above temp. limit.
	26	14	2245.0	-----	1.5	150	No G.	1.5	Same as above
	27	15	2245.0	-----	0.3	166	No G.	1.5	Same as above

PDM:positive displacement motor, RT:rotary drilling, MS:multiple trajectory survey

Table 3. Downhole motor performance summary of Well–22.

Hole size	Run no.	Maker code	Tool no.	Tool OD	Drilled interval (m) From	Drilled interval (m) To	Meters drilled (m)	Hours run (h.m)	ROP (m/h)	Mud temp. (°C) In	Mud temp. (°C) Out	Hours in hole (h.m)	Reason to POOH	Downhole motor condition after POOH
12 1/4"	1	A	1	7 3/4"	1469.2	1499.5	30.3	20.20	1.49	42	61	36.00	L.ROP	
	2	A	2	7 3/4"	1499.5	1527.0	27.5	13.30	2.03	44	63	25.50	N.G.O	
	3	A	3	7 3/4"	1527.0	1528.9	1.9	1.50	1.03	42	71	8.30	N.G.O	
	4	A	3	7 3/4"	1528.9	1545.7	16.8	10.40	1.57	49	64	20.30	pp.W.D	DS. B
	5	C	1	8"	1500.0	1505.9	5.9	24.40	0.24	45	57	32.30	Ck.bit	
	6	C	1	8"	1505.9	1515.4	9.5	48.10	0.20	42	58	60.00	Ck.bit	
	7	C	1	8"	1515.4	1520.7	5.3	26.30	0.20	45	56	35.10	Ck.bit	
	8	C	1	8"	1520.7	1528.0	7.3	27.00	0.27	42	54	32.50	Ck.bit	
	9	A	3	7 3/4"	1528.0	1538.1	10.1	17.00	0.59	41	58	26.10	Ck.bit	
	10	A	4	7 3/4"	1538.1	1554.5	16.4	14.20	1.14	45	60	22.50	Ck.bit	
	11	C	2	8"	1554.5	1594.0	39.5	28.50	1.37	48	63	38.30	Ck.bit	
8 1/2"	12	C	3	6 3/4"	1650.0	1695.7	45.7	10.40	4.29	42	63	24.30	pp.W.U	
	13	C	3	6 3/4"	1695.7	1758.1	62.4	17.50	3.50	44	63	29.30	pp.W.U	
	14	C	3	6 3/4"	1761.0	1835.7	74.7	21.30	3.47	44	64	36.00	Ck.bit	

L.ROP:low ROP, N.G.O:no good tool face orientation, pp.W.D:pump pressure went down, Ck.bit:check bit, pp.W.U.:pump pressure went up, DS.B:broken drive shaft

5.2 Well–22

Eight downhole motors were supplied by two manufacturers and a total of 14 downhole motor runs was needed for trajectory correction for Well–22. The thrust bearings wore out after only one run for some downhole motors, but no stator rubbers failed even when used in the 8 1/2 inch section (Table 3). This was because the downhole motors were used in the shallower section of the 8 112 inch hole compared with Well–20 where the formation temperature was lower, and the round trip times were less.

A total of 18 MWD runs was performed for both downhole motor BHAs and a rotary BHA. Only 1.5 hours of down time was recorded due to battery failure.

6. CONCLUSIONS

1. Even for formation temperatures greater than 350 deg.C drilling fluids can be cooled with a proper cooling system and the bottom hole circulation temperatures *can* be kept to about 80 deg.C in the 12 1/4 inch hole.

2. The BHCT is very strongly dependent on hole diameter and pumped volume of mud. And the BHCT increases for 8 112 inch hole compared to 12 114 inch hole.

3. The stator of the downhole motors failed at about 150 deg.C trip–in temperature for these operations.

4. Due to the development of the high temperature retrievable MWD, such MWD tool can be used in very high temperature geothermal wells.

5. When comparing the performance of MWD tools and downhole motors, even though the temperature limitations of the tools are the same, it must be recognized that running conditions arc very different. That is, MWD tools can be run in the hole rapidly after the well is cooled. Whereas downhole motors must be run on the drill string. Therefore, downhole motors reach their temperature limits earlier in the drilling operations. The top drive system, with which mud circulation *can* be started immediately after a drill pipe stand is connected during running BHA in the hole, will be of great help to extend downhole motor life in high temperature wells.

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