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Analysis of Drilling Problems in High-Temperature Geothermal Wells through Wellbore Temperature Simulation

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Keywords

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ABSTRACT

In high-temperature geothermal well drilling in Japan, it is sometimes reported that MWD tools get damaged because of their insufficient heat resistant temperatures of approximately 175°C to 200°C. To avoid such troubles of downhole tool failure, it is important to properly cool the inside of the wellbore by drilling fluid circulation. The objective of this study is to present an operation guideline for the prevention of downhole tool failures based on the analysis and evaluation of the effect of downhole cooling by drilling fluid circulation through a wellbore temperature simulation study.

The selected well for the simulation target was a geothermal survey well having a relatively small diameter. The necessary drilling data were extracted from the Geothermal Development Promotion Survey Report opened to the public by the New Energy and Industrial Technology Development Organization (NEDO), Japan, and numerical simulations were carried out using the modified wellbore temperature simulation program GEOTEMP2 originally developed by the Sandia National Laboratories.

Because the coring operation was carried out using a wireline coring tool for the entire depth of the well under the condition that the annular volume of the well was small compared to the case of normal rotary drilling operation. As a result of the simulation, it was found that the bottomhole temperature was as high as 200°C or more during coring, and there was a risk of damage to the downhole tools. Then, further simulation that assumed additional circulation for downhole cooling after the coring operation was carried out. The effect of cooling was insufficient even if additional circulation was performed for a considerably long time duration.

In conclusion, coring operation using wireline coring tool with a small annular volume is far from cooling the downhole compared to normal rotary drilling. Furthermore, to prevent drilling troubles caused by downhole temperature rise, it is desirable to use a rotary core bit having a sufficiently large annular volume for drilling fluid circulation.

1. Introduction

In past geothermal well drilling operations, we have sometimes encountered drilling troubles that the downhole tools were damaged caused by increases in downhole temperature. The increase in downhole temperature was estimated to be caused by the insufficient downhole cooling during tripping, fixing the surface equipment and cease of drilling operation. Among these troubles, we focused on the case that the battery in MWD tools was damaged during drilling an 8-1/2" hole section. In this trouble, it was estimated that the downhole temperature exceeded the temperature limit of the MWD tool after a long stoppage of drilling fluid circulation because of the trouble of surface equipment during tripping of the drillstring for bit replacement. So far, we are dealing with such troubles by predicting the increase in the bottomhole temperature from offset well temperature data.

To prevent such problems caused by increases in downhole temperature, the objective of this study is to present operational guidelines for drilling high temperature formations that exceed the temperature limit of MWD tools based on the analysis and evaluation of the wellbore temperature simulation. Effective downhole cooling programs by drilling fluid circulation based on the prediction of downhole temperature recovery after the circulation is stopped would make the drilling operation optimum by avoiding the over specification.

In this study, the NEDO Geothermal Development Promotion Survey Report was first reviewed to organize the details of geothermal drilling cases and to extract necessary data for simulation study using the GEOTEMP2 wellbore temperature simulator. Then, simulation study for some geothermal well drilling cases were performed according to the actual drilling conditions with some modification of computer code of GEOTEMP2. Based on the comparisons study on the effects of downhole cooling for various drilling and circulation parameters in temperature simulation, operational guidelines were proposed.

2. Wellbore Thermal Simulator

The computer code of the wellbore temperature simulator GEOTEMP2 was developed at the Sandia National Laboratory (Mondy and Duda, 1984). In performing simulation, we enabled to insert the liner casing to the well model because originally GEOTEMP2 deals only full hole casing. Full hole casing is usually run into the hole from the surface to the shoe depth, while liner casing refers to casing that is partially installed by hanging from the end of upper casing string.

3. Simulation Study

3.1 Data of Target Wells

<u>3.1.1 Well Location</u>

The purpose of the geothermal development promotion survey is to promote the development of geothermal power generation by private geothermal developers and others through NEDO's pioneering studies in promising geothermal areas where development studies have not yet been conducted because of exploration risks. The three wells selected in this study are wells N16-MS-1, N62-MS-3, and N63-MS-6, all located in Minase area of Akita Prefecture, Japan. The drillings were done in 2004, 1987, and 1988, respectively.

3.1.2 Features of Wells

One of the characteristics of the area surrounding well MS-1 was the presence of a hydrothermal layer in the shallow part of the area around 100 m depth. Also, it was a directional well with a horizontal departure of 640 m (NEDO, 2005). Because wells MS-3 and MS-6 were exploration wells and basically were cored in all hole sections with wireline tools, the flow area of drilling fluid were narrower and the flow rates were set lower compared to the normal rotary drilling operation with rotary drill bits. Well MS-3 was vertical well while well MS-6 was a directional well with a horizontal departure of 502.1 m (NEDO, 1990). Figures 1 through 3 show the casing program for each wells respectively. In addition, Tables 1 through 3 show pump rate for each drilling section.

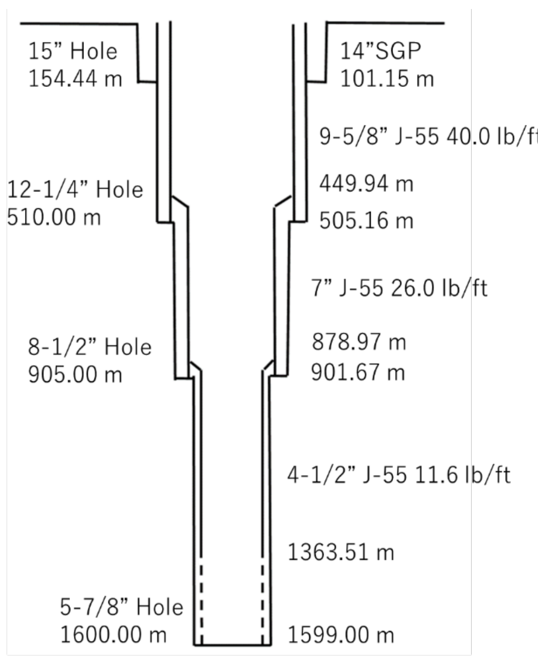

Figure 1: The casing program of well MS-1.

Table 1: Pump rate of well MS-1.

Hole Diameter	Depth Interval (m)	Pump Rate (L/min)
15"	0–154.44	1680
12-1/4"	154.44–200	1680
	200–510	1700
8-1/2"	510–905	1600
5-7/8"	905–1600	953

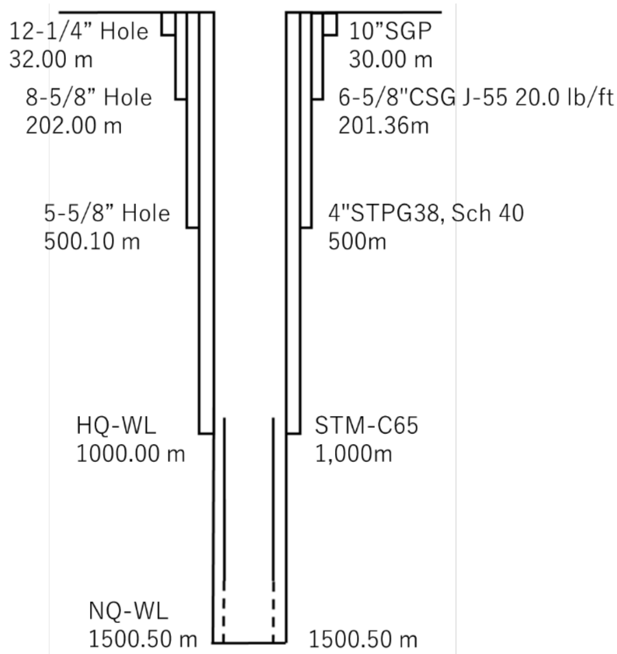

Figure 2: The casing program of well MS-3.

Table 2: Pump rate of well MS-3.

Hole Diameter	Depth Interval (m)	Pump Rate(L/min)
12-1/4"	0–32	960
HQ-WL 101 mm (Coring)	32–210	100
8-5/8" (Reaming)	32–202	960
HQ-WL 101 mm (Coring)	210–500.1	120
5-5/8" (Reaming)	202–500.1	450–500
HQ-WL 101 mm (Coring)	500.1–1000	90–120
NQ-WL 80.9 mm (Coring)	1000–1500.5	80–120

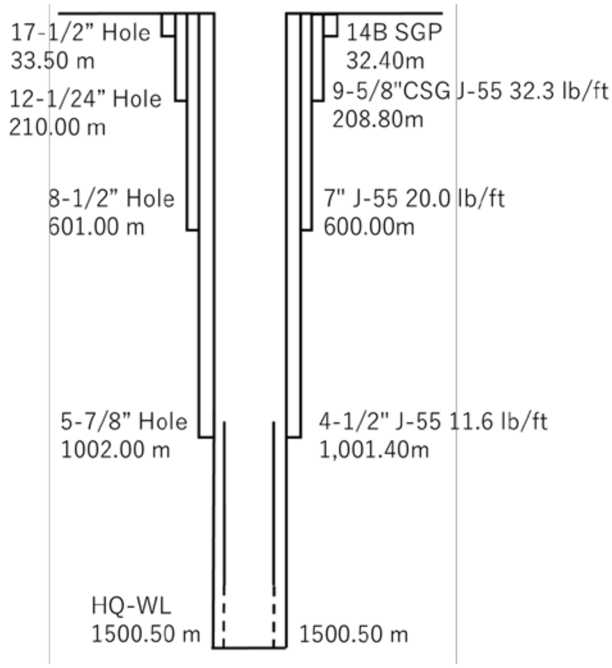

Figure 3: The casing program of well MS-6.

Table 3: Pump rate of well MS-6.

Hole Diameter	Depth Interval (m)	Pump Rate (L/min)
17-1/2"	0–33.5	550–750
12-1/4"	33.5–210	700
8-1/2"	210–601	700–1000
5-7/8"	601–1002	650–700
HQ-WL 101 mm (Coring)	1002–1500.5	100

3.1.3 Lost Circulation and Water Inflow Situation, and Result of Temperature Measurement

In well MS-1, water inflows occurred at the depths of 63.5 m, 67.7 m and 96.4 m during the first hole section, and were treated by placing cement plugs to prevent water inflow six times in total. During drilling the fourth section, there were lost circulations at 917 m, 1410 m and 1489 m, which continued until the drilling was stopped.

The temperature loggings were conducted after the ends of 510 m, 905 m and 1600 m hole sections before casing running. The temperature recovery tests were conducted after the casing pipe was run and set at 1600 m. The results of the temperature recovery test are shown in Figure 4. The temperature curve shows a large temperature increase at 66.9 m depth. This can be attributed to the influence of the hydrothermal layer at shallow depth. On the other hand, three temperature anomalies were observed at depths of 1369 m and deeper. This may be because by lost circulation.

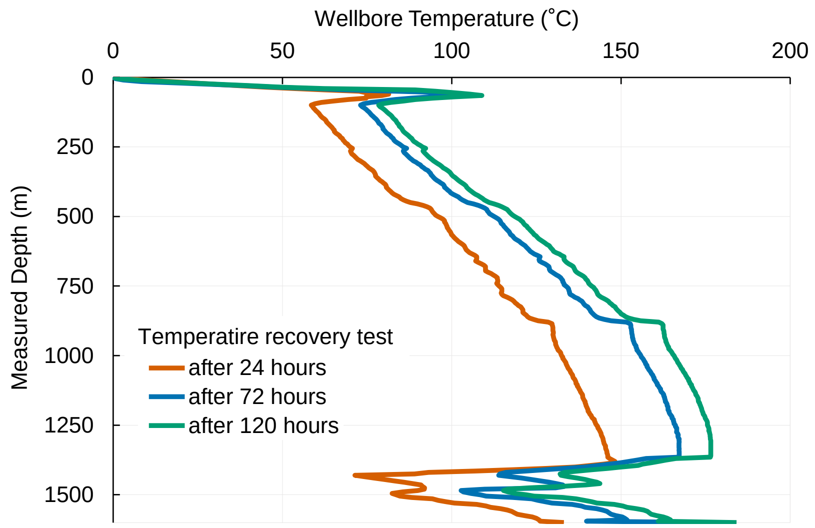

Figure 4: Temperature recovery test of well MS-1.

Lost circulation during drilling of well MS-3 was observed at depths around 709 m to 721 m and at 1050 m. From the results of the temperature recovery test shown in Figure 5, it can be seen that the temperature curve shows a linear temperature increase, but the formation temperature decreases slightly around 460 m and 1050 m depth. A slight decrease in temperature (by less than 5°C) was observed at depths of 970 m, 1040 m and 1200 m.

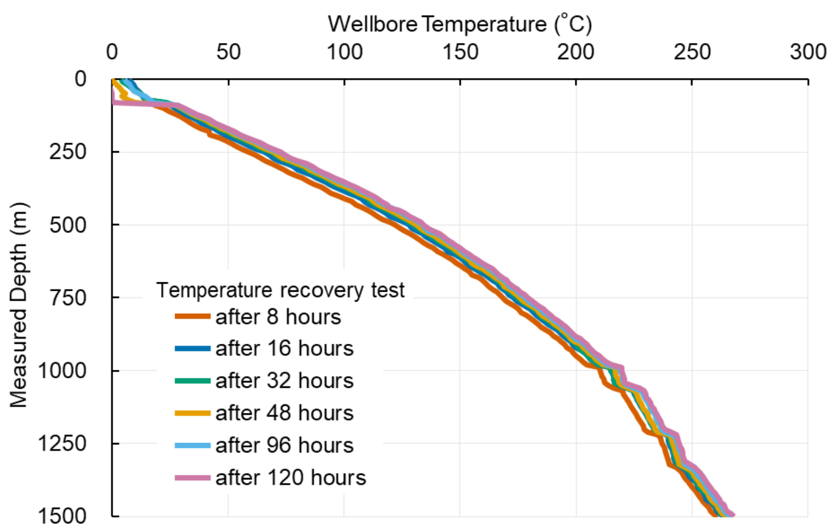

Figure 5: Temperature recovery test of well MS-3.

Well MS-6 has a kick-off point at 250 m, non-core drilling to 1000 m, and coring at depths of 1000 m and deeper. Lost circulation during drilling was observed at 20 m, 520 m, and 1483 m. From the results of the temperature recovery test shown in Figure 6, the maximum temperature is 290°C, and the temperature curve is linear.

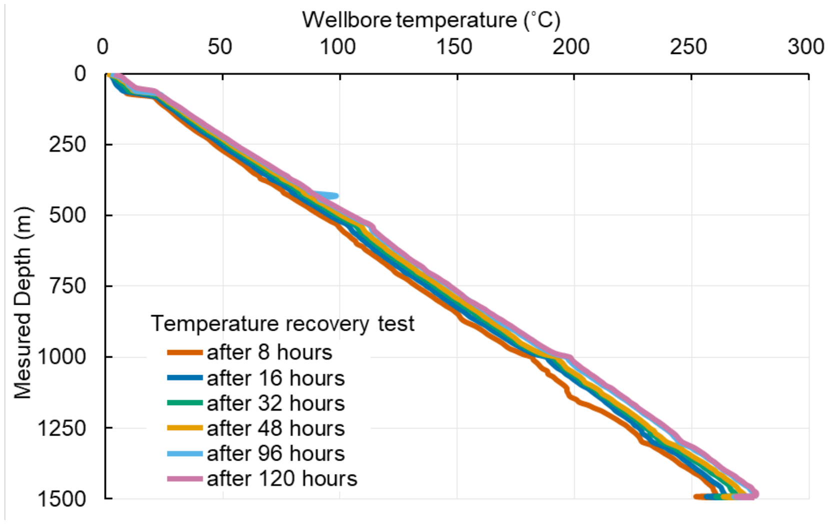

Figure 6: Temperature recovery test of well MS-6.

3.2 Research Results and Discussion

3.2.1 Simulation of Well MS-1

Figure 7 shows the results obtained from the simulation of well MS-1, which was conducted after the program was improved, with depth as the vertical axis and downhole temperature as the horizontal axis.

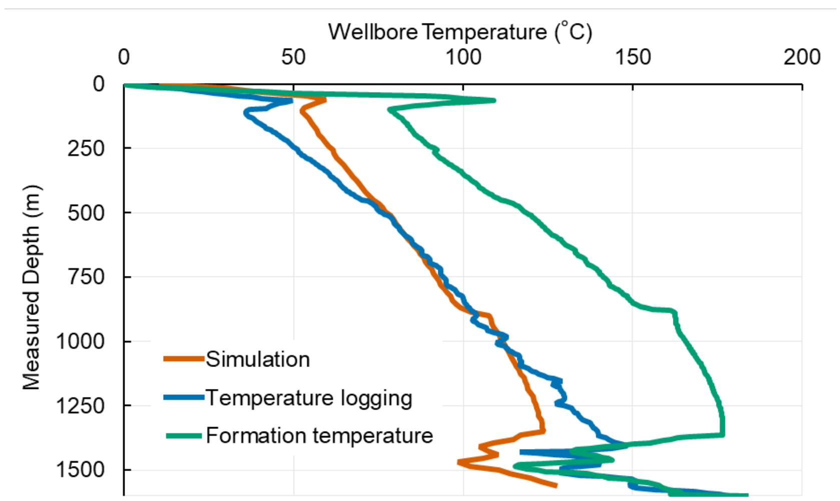

Figure 7: Simulation result of well MS-1.

From Figure 7, the post-drilling simulation roughly agrees with the measured values. However, because of the difficulty of reproducing the inflow and outflow in the current program, there is no agreement between the areas that are greatly affected by the shallow hydrothermal layer near the 100 m depth and the areas where lost circulation is said to have occurred less than 1400 m. Both measured and simulated wellbore temperatures are less than 180°C. Nevertheless, if the temperature during drilling is close to 180°C, the wellbore must be cooled for MWD operation.

3.2.2 Simulation of Well MS-3

The results obtained from the simulation of well MS-3 are shown in Figure 8. The depth is the vertical axis and the downhole temperature is the horizontal axis.

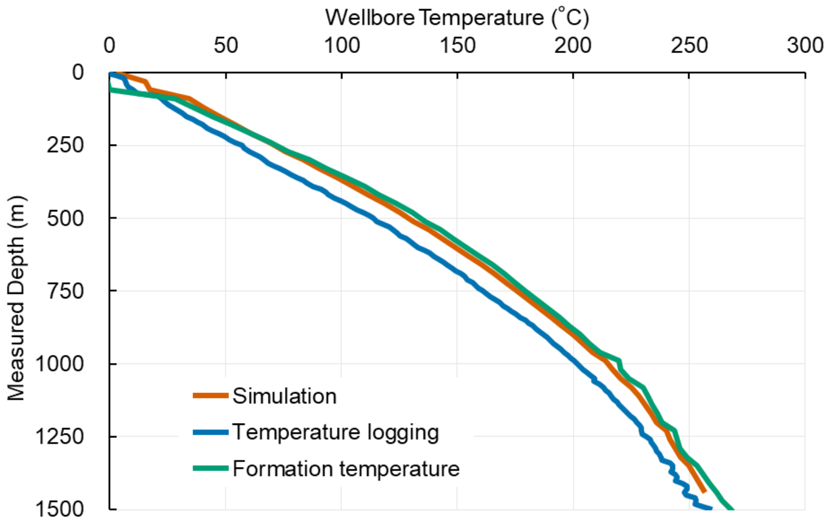

Figure 8: Simulation result of well MS-3.

Figure 8 shows that the simulation results were closer to the formation temperature than they should have been to the actual temperature of the temperature logging. This may be because of the fact that the core ring was drilled with a very small diameter and flow rate, and the effect of downhole cooling during drilling was small in the simulation. From the graph, it can be read that the temperature near the bottomhole is over 200°C, which may cause damage to the drilling tools.

3.2.3 Simulation of Well MS-6

The results obtained from the simulation of well MS-6 are shown in Figure 9. The depth is the vertical axis and the downhole temperature is the horizontal axis.

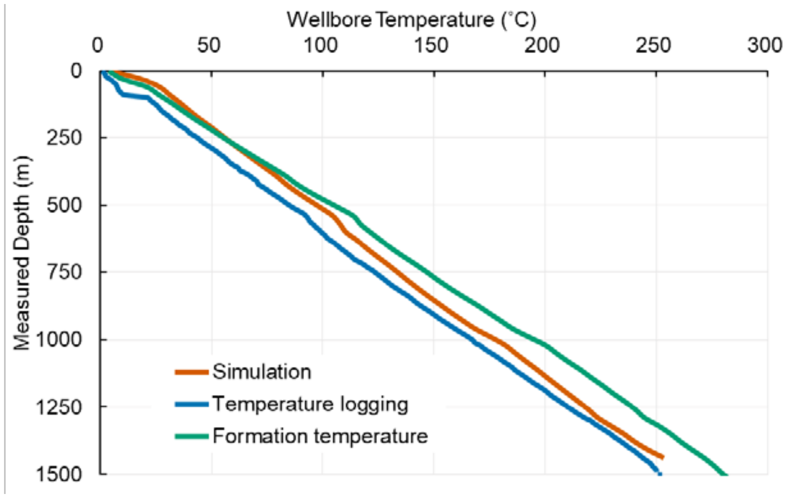

Figure 9: Simulation result of well MS-6.

As with well MS-3, the results of the simulation showed that the temperature reading approached the formation temperature when it should have been closer to the measured value. From Figure 9, it was confirmed that the downhole temperature was less than 200°C up to 1000 m, which is the section where the MWD tool would be used to drill with the Tricon bit. However, the temperature near the bottomhole is over 200°C, and there is a risk of damage to the drilling tools.

3.3 Study of Cooling Circulation

In order to reduce the downhole temperature to about 175°C, which is the maximum heat-resistant temperature of the MWD tool, a simulation of cooling circulation after coring drilling was conducted. The target wells are wells MS-3 and MS-6 where the downhole temperatures were higher than 200°C unlike well MS-1. The obtained bottom temperatures are summarized in Figure 10, with the bottom temperature as the vertical axis and the cooling circulation period as the horizontal axis.

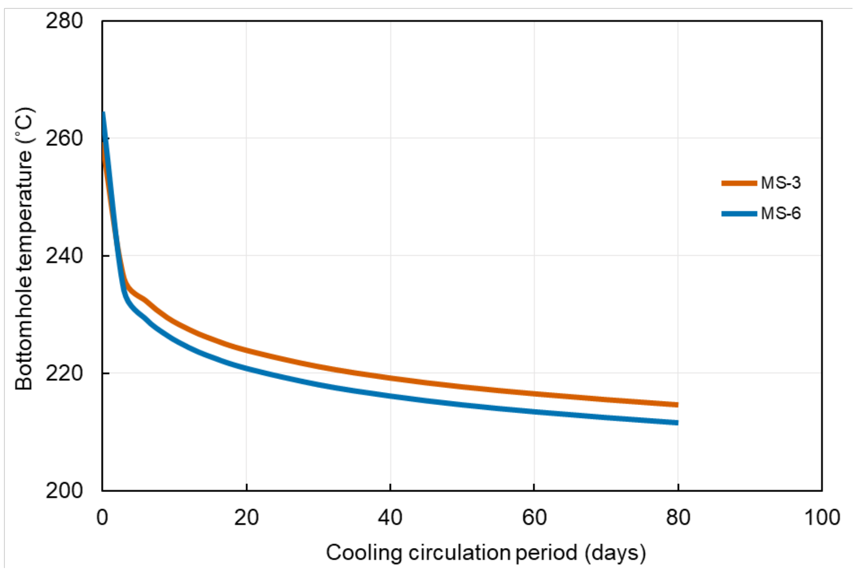

Figure 10: Changes in bottom temperature of the wellbore with a cooling circulation period.

After coring operation, the pump rate was increased to 600 L/min and the simulation was performed assuming a cooling circulation period of up to 80 days. This graph shows that even if the cooling circulation is carried out for a long time, the effect is low. This is thought to be because of the narrow annulus width. Therefore, drilling by coring was difficult to cool down the wellbore to the extent that the logging tools could be lowered.

3.4 Simulation with Different Parameters of Drilling Conditions

3.4.1 Results of Changing the Drilling Conditions of Well MS-3

In order to reduce the downhole temperature to a level where the MWD tool can be used, the conditions were changed to normal drilling instead of coring so that the diameter and pump rate of the well can be increased. The target wells are wells MS-3 and MS-6 where the downhole temperatures were higher than 200°C unlike well MS-1. The simulation results are shown in Figure 11. The green plot shows the temperature distribution of the downhole mud when the drill pipe is lowered to the bottom of the well and the incoming mud temperature is 75.2°C and circulating in the well.

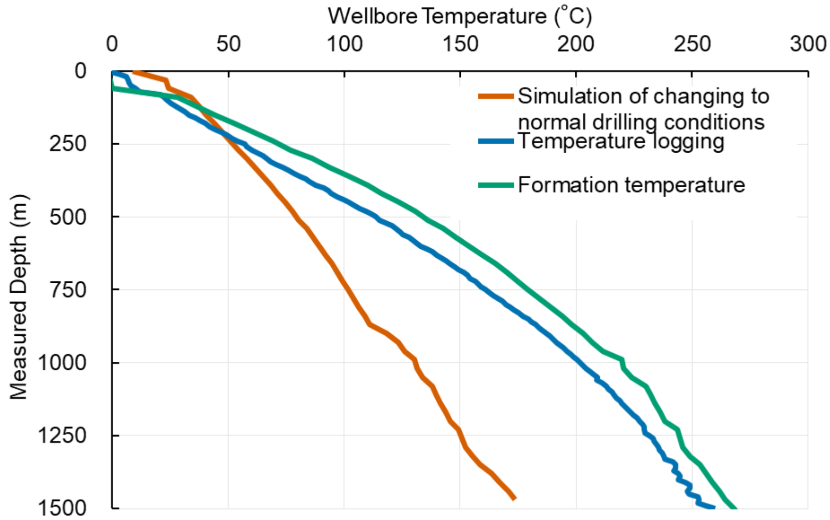

Figure 11: Simulation results for well MS-3 with different drilling conditions.

From Figure 11, it was found that the downhole temperature can be maintained less than 175°C without the time for cooling circulation under the normal drilling conditions with a large well diameter and pump rate.

3.4.2 Results of Changing the Drilling Conditions of Well MS-6

In order to reduce the downhole temperature to a level where the MWD tool can be used, the conditions were changed to normal drilling instead of coring so that the diameter and flow rate of the well can be increased. The simulation results are shown in Figure 12.

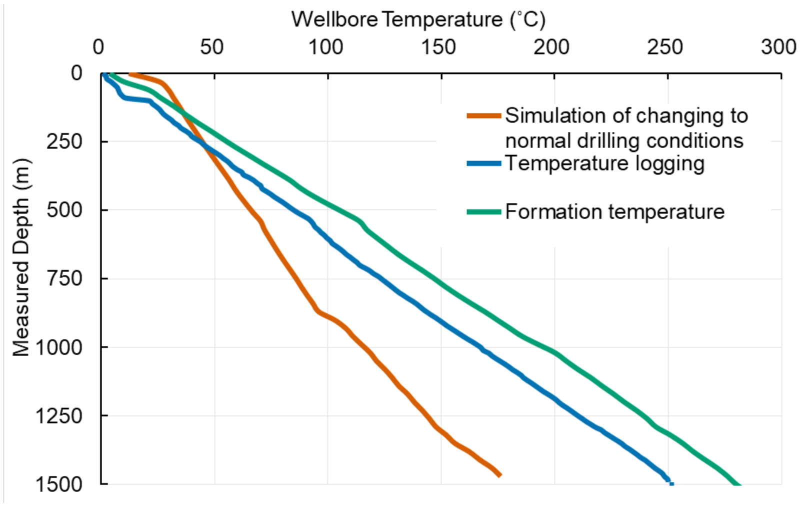

Figure 12: Simulation results for well MS-6 with different drilling conditions.

From Figure 12, it was found that the downhole temperature can be kept close to 175°C under normal drilling conditions with large well diameter and pump rate. Therefore, in order to reduce the temperature less than 175°C, an additional simulation with cooling circulation was performed. The results are shown in Figure 13.

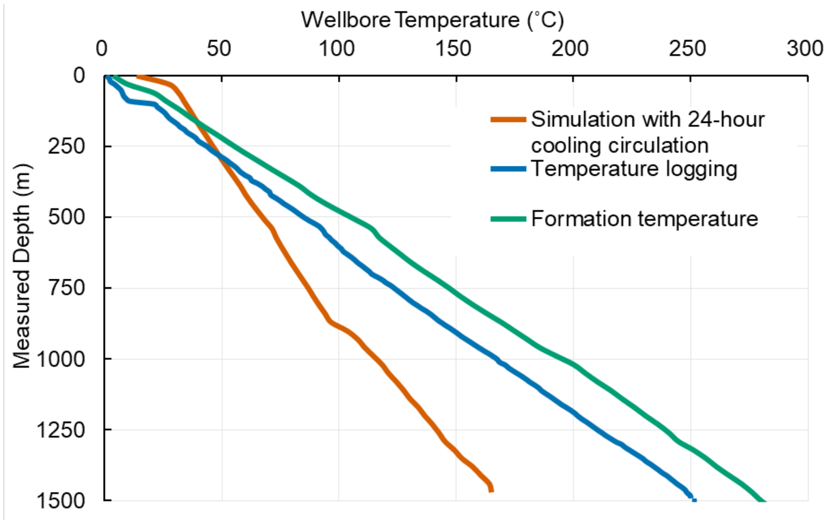

Figure 13: Simulation results of cooling circulation in well MS-6 under different drilling conditions.

From Figure 13, it was found that under normal drilling conditions with large well diameter and pump rate, a shorter period of cooling circulation was sufficient to lower the wellbore temperature to less than 175°C than when drilling by coring. As a result of the above simulation, it was found that the wellbore diameter and flow rate have significant effects on the determination of the downhole temperature. In the case of the rotary drilling of very high-temperature geothermal wells, which are different from the well geometry and type of the wells in this study, the influence of the wellbore diameter and flow rate on the downhole temperature has been found to be significant in previous studies (Saito, 1995).

4 Additional Study for Wells without Lost Circulation nor Formation Fluid Inflow

4.1 Data of Target Wells

<u>4.1.1 About the Additional Wells</u>

Of the data from the initially selected three wells, wells MS-3 and MS-6 did not show much of a cooling effect because of the small diameter of the wells and the difficulty in securing pump rates. In addition, in well MS-1, GEOTEMP2 was not able to handle the section because of the presence of inflow water and lost circulation in the shallow and deep sections. Therefore, in order to confirm the cooling effect, a general casing program and a well with as little inflow water and lost circulation as possible were additionally selected. The following are the conditions for selection.

- The final hole diameter is 5-7/8" or more.
- A well with as little spring water and lost circulation as possible.
- The temperature is relatively high.

4.1.2 Location and Characteristics of the Selected Wells

Wells N20-SY-1 in the Shimoyu area of Aomori in Japan and N13-AP-6 in the Appi area of Iwate in Japan, were selected from the Geothermal Development Promotion Survey Report. Drilling was done in 2008 and 2001, respectively.

Well SY-1 is characterized by no significant lost circulation to the bottom of the well except for lost circulation at 378 m depth. When the planned depth was reached, there was no lost circulation, so the drilling was increased. The casing program also includes a liner casing. The drilling was done by rotary drilling with a tricone bit, and the final diameter of the well was 6-1/4". The formation temperature is above 180°C. In addition, it is a directional well with a deviation of 720 meters (NEDO, 2004).

Well AP-6 is characterized by lost circulation in the shallow part of the well, but lost circulation countermeasures have been implemented. During the drilling of the final well diameter, lost circulation occurred from a depth of about 1400 m. The casing program also includes a liner casing. The drilling was done by rotary drilling with a tricone bit, and the final diameter of the well was 6-1/4". The formation temperature is above 250°C. In addition, it is a directional well with a deviation of 502 meters (NEDO, 2009).

Figures 14 and 15 show the casing program respectively. In addition, Tables 4 and 5 show pump rate per drilling depth.

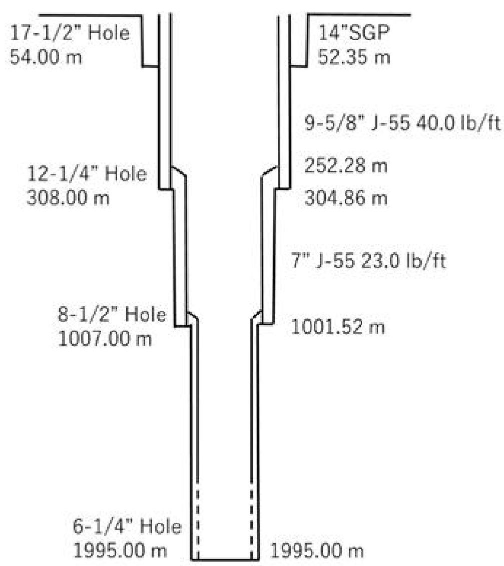

Figure 14: The casing program of well SY-1.

Table 4: Pump rate of well SY-1.

Hole Diameter	Depth Interval (m)	Pump Rate (L/min)
17-1/2"	0–54	1200
12-1/4"	54–308	2000
8-1/2"	308–1007	1600
6-1/4"	1007–1995	1100

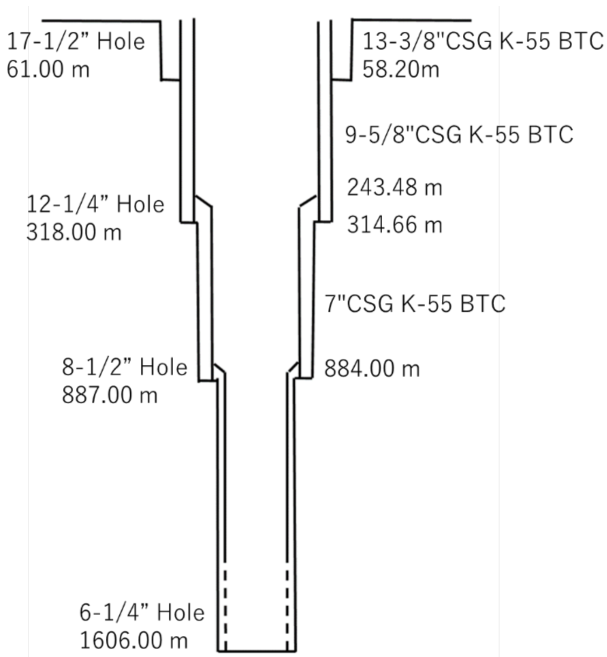

Figure 15: The casing program of well AP-6.

Table 5: Pump rate of well AP-6.

Hole Diameter	Depth Interval (m)	Pump Rate (L/min)
17-1/2"	0–61	1280
12-1/4"	61–318	1680
8-1/2"	318–887	1660
6-1/4"	887–1606	1024

4.2 Simulation Results for Additional Wells

4.2.1 Simulation Results for Well SY-1

The results obtained from the simulation of well SY-1 are shown in Figure 16 with depth as the vertical axis and downhole temperature as the horizontal axis.

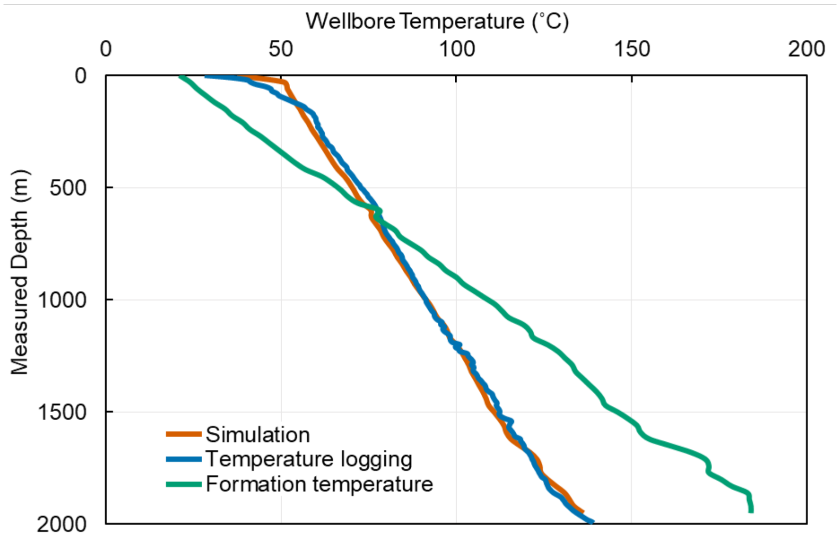

Figure 16: Simulation result of well SY-1.

From Figure 16, the post-drilling simulation agrees very well with the measured data. Both measured and simulated wellbore temperatures are less than 140°C, so there is little risk of damage to the MWD tool because of high temperatures. In consideration of the actual operation of the MWD tool, it is desirable to keep the wellbore temperature even lower.

4.2.2 Simulation Results for Well AP-6

The results obtained from the simulation of well AP-6 are shown in Figure 17. with depth as the vertical axis and downhole temperature as the horizontal axis.

From Figure 17, it was confirmed from the post-drilling simulation that the wellbore temperature can be cooled down to about 150°C by drilling at a pump rate of more than 1000 L/min, even when the formation temperature exceeds 250°C.

The data from well AP-6 did not include post-drilling temperature logging, so it was not possible to compare simulated and measured data. Instead of the actual temperature logging data, the distillation point thermometer data during the tilt azimuth measurement during drilling is plotted in orange. The temperature of the distillation point is lower than that of the post-drilling temperature logging because it is measured in real time during drilling. Figure 17 also shows a lower wellbore temperature than the post-drilling simulation.

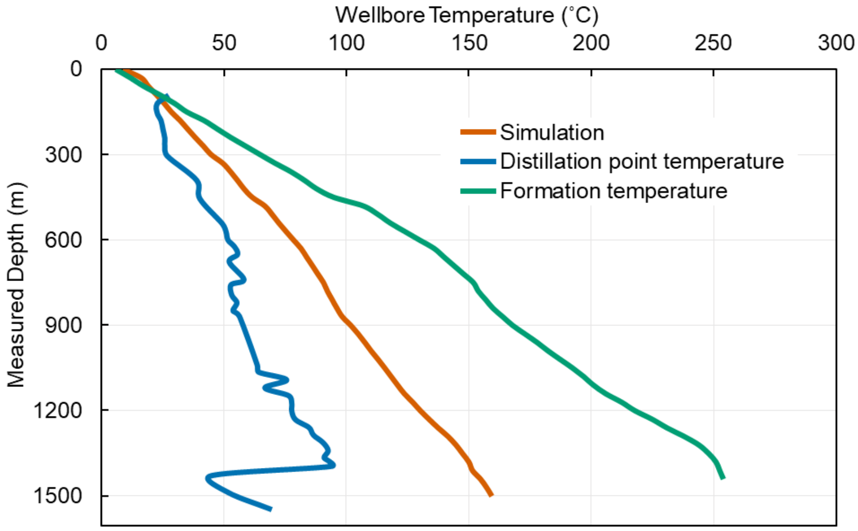

Figure 17: Simulation result of well AP-6.

The temperature in the wellbore is estimated to be about 150°C based on the simulation results. The temperature in the wellbore needs to be kept lower to ensure that the MWD tool avoids damage because of high temperature.

4.3 Temperature Recovery Study

4.3.1 Results of Temperature Recovery Simulation in Well SY-1

When tripping for bit replacement, etc., the wellbore is left in a static state with the circulation stopped. If the formation is to be descended again, the degree to which the temperature in the wellbore has recovered is a very important factor.

Simulations were performed on the temperature recovery in the wellbore after 24, 48, and 72 hours of stopping circulation. The changes in the bottom temperature obtained are summarized in Figure 18, with the bottom temperature as the vertical axis and the temperature recovery time as the horizontal axis.

From the graph, it was found that when the circulation was stopped after the drilling was completed, the temperature gradually increased and approached the formation temperature. Because of the GEOTEMP2 program, one step of the elapsed time is a minimum of 24 hours. If the interval from the shutdown of circulation to the end of the 24-hour period can be calculated in smaller time steps, the temperature at the bottom of the well after the tripping can be simulated.

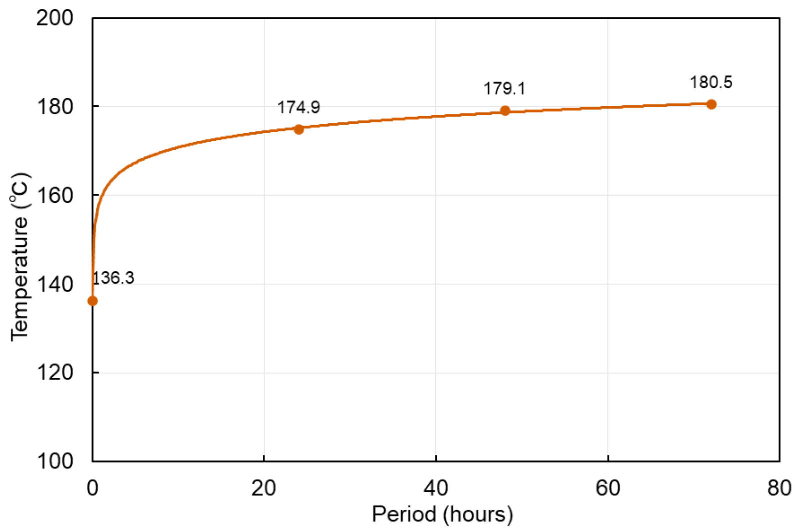

Figure 18: Simulation of temperature recovery at the bottomhole in well SY-1.

4.3.2 Results of Temperature Recovery Simulation in Well AP-6

Simulations were performed on the temperature recovery in the wellbore after 24, 48, and 72 hours of stopping circulation. The changes in the bottom temperature obtained are summarized in Figure 19, with the bottom temperature as the vertical axis and the temperature recovery time as the horizontal axis.

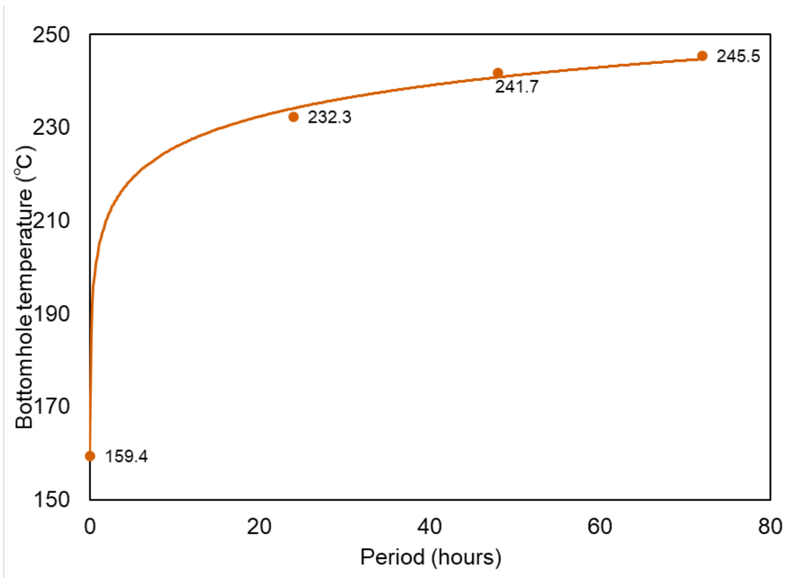

Figure 19: Simulation of temperature recovery at the bottomhole in well AP-6.

The graph shows that, as in well SY-1, when circulation was stopped after the completion of drilling, the temperature gradually increased and approached the formation temperature. Because of the GEOTEMP2 program, one step of the elapsed time is a minimum of 24 hours. If the interval from the shutdown of circulation to the end of the 24-hour period can be calculated in smaller time steps, the temperature at the bottom of the well after the tripping can be simulated.

4.4 Results of Case Specific Simulations for Well AP-6 (Temperature Recovery and Cooling Circulation)

After the circulation was stopped for 24 hours and 48 hours, the simulation was performed with cooling circulation in each case. The simulation results obtained are summarized in Figure 20 with depth as the vertical axis and wellbore temperature as the horizontal axis.

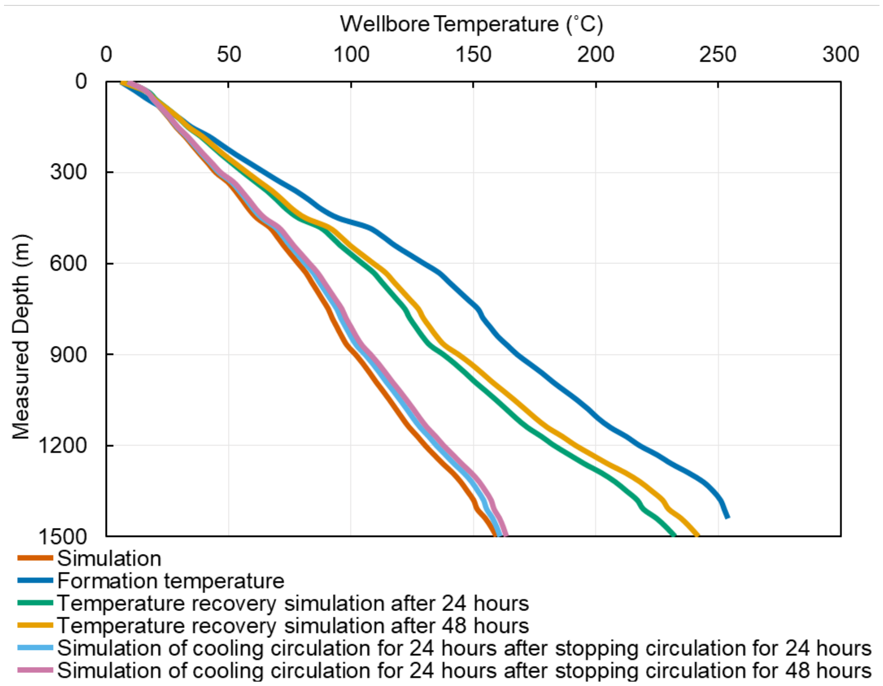

Figure 20: Simulation results of temperature recovery and cooling circulation for well AP-6.

After the circulation was stopped for 24 hours, the temperature in the wellbore increased to about 240°C, but the temperature then decreased to about 150°C after 24 hours of cooling circulation. The same applies for 48 hours. Even if the circulation was stopped for 48 hours, it was found that 24 hours of cooling circulation could cool the wellbore to the wellbore temperature before the circulation was stopped.

5. Conclusions

The findings from this study are summarized as follows:

- For wells MS-3 and MS-6, in contrast to well MS-1, the simulation results indicated that the temperature near the bottom of the well was higher than 200°C, which could lead to downhole tool failures. It was also confirmed that the effect of cooling circulation was quite low.

- For wells MS-3 and MS-6, simulation results under normal drilling conditions with large hole diameters and larger pump rates showed that the downhole temperature could be lowered to less than 175°C more easily than in the case of coring.
- From the above, it was found that the coring operations with small hole diameters are more difficult to cool the wellbore temperature than drilling with tricone bits. Therefore, to prevent drilling problems caused by temperature rise in coring, it is desirable to use PDC or roller cone type core bits and make the hole sufficiently large diameter for drilling.
- As per the findings of the simulation results in Shimoyu and Appi areas, wells SY-1 and AP-6, which were rotary drilled with the tricone bits, showed lower wellbore temperatures after the completion of drilling than wells MS-3 and MS-6 in Minase area.
- The overall simulation results show that the well diameter and pump rate have significant effects on downhole cooling with drilling fluid circulation.

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