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Innovative Drilling Technology for Supercritical Geothermal Resources Development

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ABSTRACT

Supercritical geothermal system originated in Japan Trench subduction zone has the potential to generate a terawatt-scale of energy in Japan. For development of the supercritical geothermal system, technologies to efficiently drill into the deep ductile formation with temperature over 400°C and to complete wells with sufficient integrity are indispensable. A concept of well stimulation method to create fracture clouds that uses rock failure phenomena induced by the thermal-shock or thermal-stress generated by a decompression, boiling and consequently a rapid cooling of the completion fluid in the wellbore has been previously presented. In the current research project, the authors are extending the concept to develop a new innovative drilling method that uses thermal-shock failure phenomena artificially induced at the bottomhole. An industrial-government-academia joint study project is now in progress which consists of the following five subtasks: (1) development of a new drilling tool that can generate a thermal-shock failure of rock induced by depressurization, boiling and cooling at the bottomhole, (2) experimental and simulation studies on the mechanism of thermal-shock failure of high temperature rock, (3) development of wellbore hydrothermal simulation technology applicable under supercritical formation condition, (4) development of a new concept casing packer, and (5) study on acid- and corrosion-resistant materials against supercritical environment.

1. INTRODUCTION

Utilization of high enthalpy supercritical geothermal resources where the formation temperature exceeds 400°C has been discussed pursuing more efficient and larger capacity geothermal power generation. In 1995, the hottest geothermal exploration well of the day, Kakkonda WD-1a, was drilled in Japan. The estimated maximum formation temperature at the depth of 3729 m exceeded 500°C. After the 2000s, the first well for the Iceland Deep Drilling Project (IDDP) was drilled in Krafla geothermal field, Iceland. Although the drilling was unintentionally terminated at 2.1 km depth, the well was completed and tested in which production of 330°C superheated steam corresponding to some 20 MW of electric power was obtained. The second IDDP well was just drilled and completed in January 2017 at Reykjanes where the bottomhole temperature measured was 427°C. Subsequent researches including well stimulation and flow test is scheduled until the end of 2018 (IDDP, 2017).

After the Great East Japan Earthquake and Fukushima Nuclear Power Disaster in March 2011, Japanese researchers proposed to investigate a new concept for engineered geothermal system (EGS), “Japan Beyond-Brittle Project (JBBP)” where the reservoirs were created in ductile basement formations. The proposed project was aming to overcome the known defects in the conventional EGS and expecting the following advantages (Asanuma et al., 2012; Muraoka et al., 2014; Tsuchiya et al., 2015); (a) simpler design and contol the reservoir, (b) nearly full recovery of injected water, (c) sustainable energy production, (d) possibility of large-scale EGS in widely distributed ductile zones at relatively shallow depth in tectonic belt, (e) site-independent universal design/development/control methodologies, (f) suppression of induced/triggered eqarthquakes. In the concept of JBBP, well stimulation or hydraulic fracturing might be essential because it was considered that the brittle-ductile transition (BDT) drastically reduced formation permeability. As shown in Figure 1, supercritical geothermal system estimated to contain slab-derived geothermal fluid originated in Japan Trench subduction zone has the potential to generate a terawatt-scale of energy in Japan. Recent studies also have revealed that high enthalpy supercritical fluids are trapped at 500°C to 550°C temperature formations and that potentially exploitable geothermal resouces may exist even in the nominally ductile crust (Tsuchiya et al., 2016; Watanabe et al., 2017). However, no human beings have ever experienced the resource developments in such a harsh and hostile environment.

For development of the supercritical geothermal system, technologies to efficiently drill into the deep ductile formation with temperature over 400°C and to complete wells with sufficient integrity are indispensable. Furthermore, some breakthrough in drilling technology has been expected. In the 1960s, concepts of novel drilling systems were already being presented to replace conventional rotary drilling bits (Maurer, 1966). Whereas conventional drill bits have a mechanical rock breaking mechanism, these new concept drill bits use thermal spalling, melting, electric, laser, microwave, or nuclear energy. However, these novel drilling systems were never implemented commercially because high power generation necessary for these drilling systems requires large and heavy equipment that is difficult to install in downhole tools. Among these innovative drilling systems, research and development on laser drilling have been renewd since 2000 in some institutes such as the Colorado School of Mines and the Argonne National Laboratory (Parker et al., 2003), and the Japan Oil, Gas and Metals National Corporation (Kobayashi et al., 2009). A prototype of laser and PDC-hybrid bits was also presented with funding from the US Department of Energy (Ezzedine et al., 2015). Other recent ongoing studies on novel or innovative drilling technologies include hydrothermal spalling (Potter et al., 2010; Kant et al., 2016), plasma (Kocis et al., 2013), laser jet (Jamali et al., 2016), flame jet (Meier and von Rohr, 2016), and electric impulse (Lehr et al., 2016), conducted mostly in Europe.

A concept of new well stimulation method to create fracture clouds that uses rock failure phenomena induced by the thermal-shock or thermal-stress generated by a decompression, boiling and consequently a rapid cooling of the completion fluid in the wellbore has been previously presented (Tsuchiya et al., 2012). In this research, the authors are extending the concept to developing a new innovative drilling method that also uses thermal-shock failure phenomena artificially induced at the bottomhole.

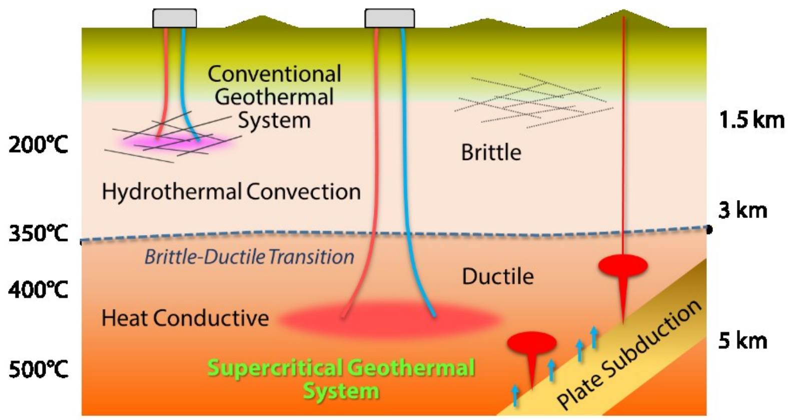

Figure 1: A concept of supercritical geothermal resources development.

2. ASSUMED DRILLING TARGET FOR SUPERCRITICAL GEOTHERMAL DEVELOPMENT

In this study, it is assumed that the temperature profile follows the boiling-point depth (BPD) curve at shallower depths than critical point of water as shown in Figure 2. The depth corresponding to the critical point of formation fluid is approximately 3500 m. Under supercritical conditions at temperature above 374°C and depth greater than 3500 m, constant geothermal gradient (e.g. 20°C/100m) is assumed. It is also assumed that formation pressure follows the hydrostatic condition and that the density of supercritical fluid is constant. The assumed density of supercritical formation fluid is 500 kg/m^3 at maximum and 100 kg/m^3 at minimum similar to the previous study (Hefu, 2000). If the formation fluid is estimated as brine, the critical point shifts to higher pressure and temperature, thus the depth corresponding to critical point may be deeper than 3500 m. If there exist abnormal pressure zones in the brittle shallower formations, the critical point depth may be shallower than 3500 m.

Based on the above assumption of pressure and temperature profile for supercritical geothermal well drilling, a possible drilling program scenario may be as follows:

(1) 21-in. hole and 18 5/8-in. casing at 1000 m

(2) 17 1/2-in. hole and 13 3/8-in. casing at 2400 m

(3) 12 1/4-in. hole and 9 5/8-in. casing at 3500 m (critical point)

(4) 8 1/2-in. hole to 5000 m (supercritical zone) and optional 7-in. production anchor

Conventional drilling method and equipment, e.g. normal rotary drilling system probably with insert type roller cone bits, can be used to drill and set casings until critical point depth,. In ductile supercritical formations with over 350°C temperature, most of conventional drilling equipment such as roller cone bits, drilling fluids, cement and cementing equipment, directional tools, MWD/LWD tools, and completion tools, cannot be safely used because of their relatively low temperature limitations (Naganawa, 2015). Therefore, high temperature drillings completed so far such as Kakkonda WD-1a and IDDP wells, used continuous and effective drilling circulation method to maintain the downhole temperature sufficiently low so that the downhole equipment and materials can thermally resist.

Another issue in high temperature drilling in geothermal field is related to low rate of penetration and short bit life. Particularly in supercritical ductile formations whose temperature can be up to 600°C, innovative drilling method and tools that are not rely on the conventional mechanical rock failure mechanism provided by bit tooth/rock interaction may be a possible solution.

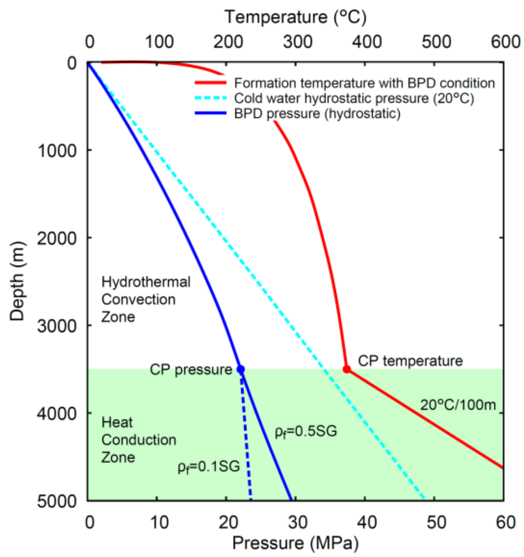

Figure 2: Assumed temperature and pressure conditions for supercritical geothermal drilling.

3. EXPERIMENTAL STUDY ON THERMAL SHOCK FAILURE OF ROCKS

Authors' research group has experimentally investigated the behaviors of hydrothermal rock failure (Hirano et al., 2002; Hirano e al., 2015). Based on the experimental results, the group have proposed the concept of decompression drilling (Tsuchiya et al., 2012). Figure 3 is one of the recent experimental works on hydrothermal rock failure where a granite core sample with small borehole in it was set in a water saturated high pressure cell and inside the cell was initially heated and pressurized to the supercritical condition. Then, the valve 2 in the figure was opened to rapidly depressurize the cell to atmospheric condition and the changes in pressure and temperature were measured.

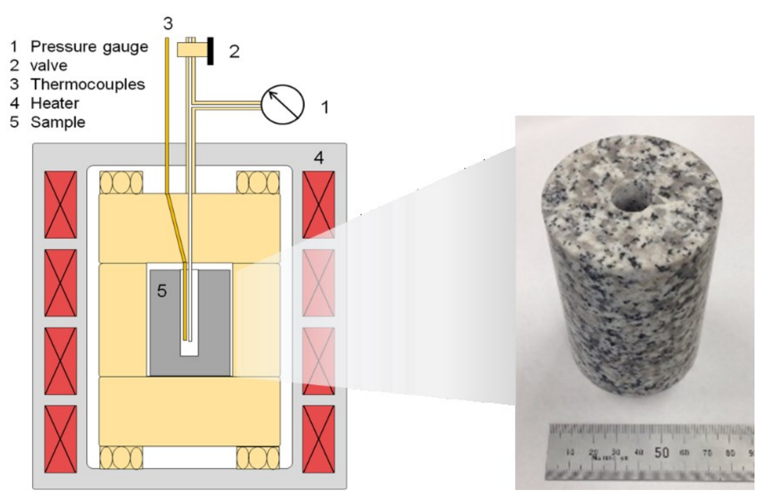

Figure 3: Hydrothermal rock failure experiment using granite core simulating borehole.

Figure 4 shows a result of the experiment where the rapid pressure change in the cell from approximately 42 MPa to atmospheric pressure caused a rapid temperature reduction by approximately 130°C (from 610°C to 480°C in this experiment) due to the latent heat of vaporization of water. The comparison of X-ray CT images for the cross sections of the core before and after the experiment is also shown in the figure. A considerable number of thermal-stress microfractures were observed to generate by rapid depressurization and subsequent temperature reduction. The experimental results including those obtained under other conditions demonstrate that formation rock in deep borehole under high pressure and high temperature condition can be fractured or weakened in strength if the drilling or completion fluid can be effectively depressurized.

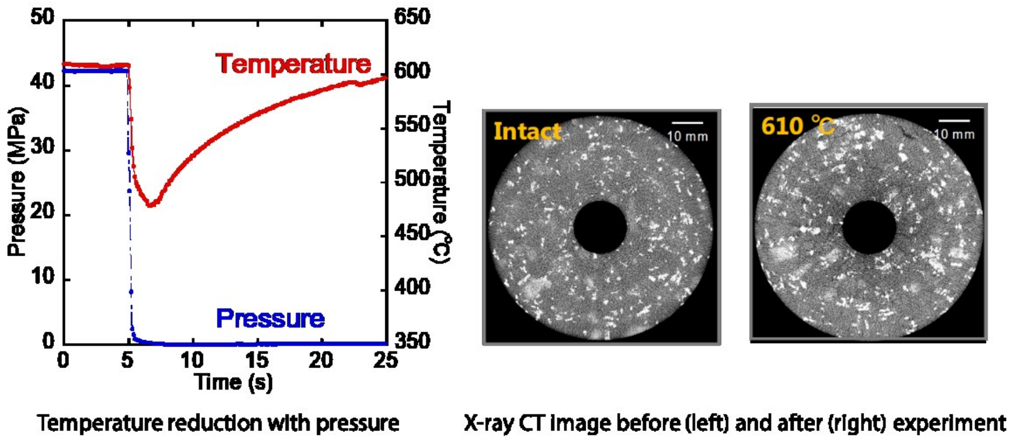

Figure 4: Hydrothermal rock failure experiment using granite core simulating borehole.

4. THERMAL-SHOCK ENHANCED DRILL BIT

An idea of application of thermal shock or thermal stress failure of rocks to drilling of hard formations was already published over 60 years ago (Blood, 1951). The proposed system provided a drilling mechanism designed to alternately heat and cool hard formations in oil well drilling operations so as to cause fracture of the hard formations. The downhole drilling equipment was a fishtail bit with drilling fluid circulation nozzles, passageways/nozzles for combustible gases (e.g. oxygen and acetylene) and ignition mechanism to alternately cool and heat the bottomhole. The system, however, requires special and probably expensive drill pipes to introduce combustible gases to the downhole and additional mechanism to prevent the risk of downhole fire. From the view points of the total energy efficiency and drilling cost, the proposed thermal shock drilling system has only a few advantages.

According to our experimental results as mentioned above, if the drilling fluid in a wellbore could be locally depressurized and boiled at the bottomhole, the drilling fluid and the surrounding high temperature formation may be cooled due to the latent heat of vaporization. And if the depressurization and temperature reduction could be relatively rapid, a difference of thermal stresses would be generated in the vicinity of borehole wall. The resultant thermal shock may induce fracturing of formation and reduce the apparent strength of rock. Thus, the drillability of hard rocks encountered in drilling ductile, supercritical geothermal formation can be possibly improved. Based on the hypothesis, the authors propose utilization of the "venturi effect" to achieve a local depressurization in the bottomhole. As the principle is illustrated in Figure 5, the venturi effect can generate a pressure reduction at the choke section of flow path. The pressure reduction by the venturi effect Δp can be calculated by Eq. (1), where ρ is the fluid density, Q is the volumetric flow rate, A_1 is the cross sectional area of the flow path, A_2 is the cross sectional area of the choke section, and C is discharge coefficient considering of energy loss, generally ranges from 0.96 to 0.99.

$$Q = CA_1\sqrt{\frac{2}{\rho}\cdot\frac{\Delta p}{\left(\frac{A_1}{A_2}\right)^2-1}} \qquad \therefore \Delta p = \frac{\rho Q^2}{2C^2 A_1^2}\left[\left(\frac{A_1}{A_2}\right)^2-1\right] \tag{1}$$

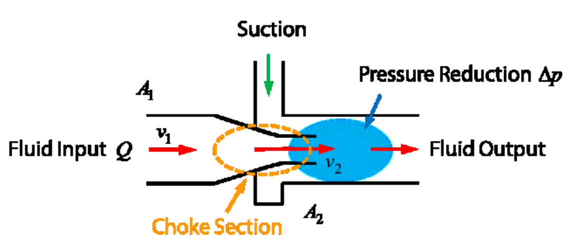

Figure 5: Principle of venturi effect.

The venturi effect is commercially utilized in downhole tools such as vacuum type fishing tools and jet pumps for artificial oil production. The proposed tool is a venturi mechanism and PDC hybrid bit, namely “thermal-shock enhanced drill bit” as shown in Figure 6 (Naganawa et al., 2017). The “drilling mode” that uses conventional PDC bit drilling mechanism and the “depressurizing mode” that uses venturi depressurizing mechanism to reduce the rock strength can be alternately switched by operating the sliding sleeve to open and close the port valves.

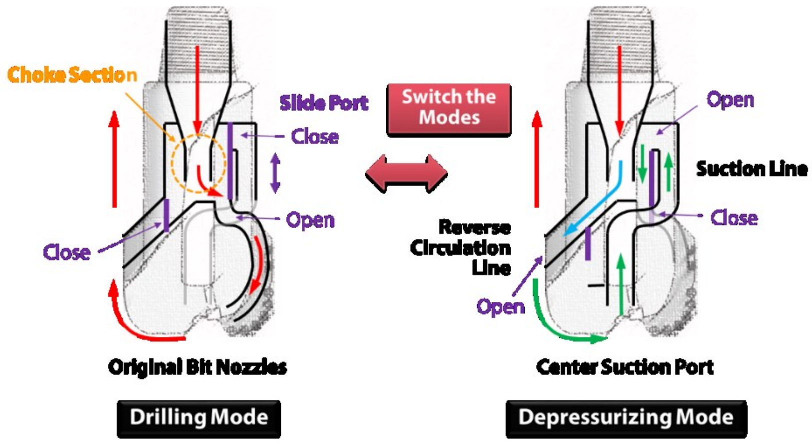

Figure 6: A concept of thermal-shock enhanced drill bit (Naganawa et al. 2017).

A problem to be solved is whether a sufficient pressure reduction can be obtained or not below the bit. Here, we assume that the inner diameter of inside flow path of the thermal-enhanced bit is 0.1 m, the ratio of the cross sectional areas of the choke section and original flow path is 1/36, the fluid density is 1050 kg/m^3, and the fluid flow rate is 2 m^3/min, then the pressure reduction can be obtained as approximately 13 MPa from Eq. (1). The target reduction in bottomhole pressure to boil and vaporize the drilling fluid is estimated approximately 20 MPa at minimum as illustrated in Figure 7. Optimization of design of the bit, and configuration and mechanism of flow paths in the future study could be expected to improve the pressure reduction.

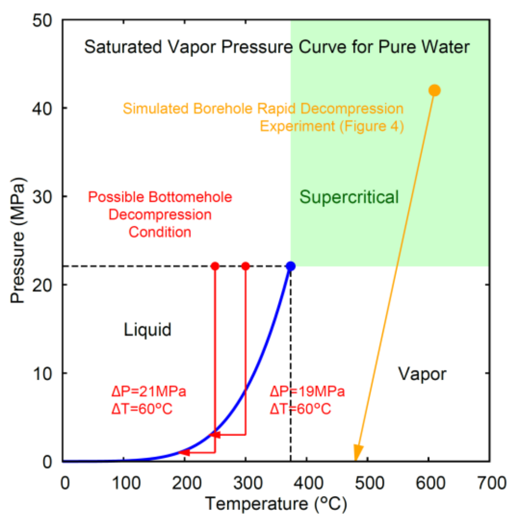

Figure 7: Possible bottomhole conditions for depressurization, boiling and cooling of drilling fluid.

5. OVERALL DRILLING SYSTEM AND PERIPHERAL TECHNOLOGIES DEVELOPMENT

From the view point of borehole stability, pressure fluctuation in the wellbore annulus induced by the successive depressurization just below the drill bit is generally unfavorable and should be avoid. To mitigate the potential risk of borehole instability induced by applying the thermal-shock enhanced drilling, the authors also propose to combine the method with "casing with drilling" (CWD). As shown in Figure 8, extreme high temperature and hard rock in supercritical formation zone is drilled by a BHA retrievable type CWD system with the thermal-shock enhanced bit. After drilled to the section TD, drilling fluid circulation is stopped and the BHA was retrieved out of the hole, at which the casing string is already ran into the hole. Because the normal Portland cement or silicate cement for geothermal wells are known to be significantly degraded at temperature range over 400°C. Therefore, instead of conventional cementing, the authors' research group is also investigating a new casing setting method using a newly developing packer in which the increase or recovery in wellbore temperature after stopping drilling fluid circulation can automatically activate packer element to expand (Shimada et al., 2015).

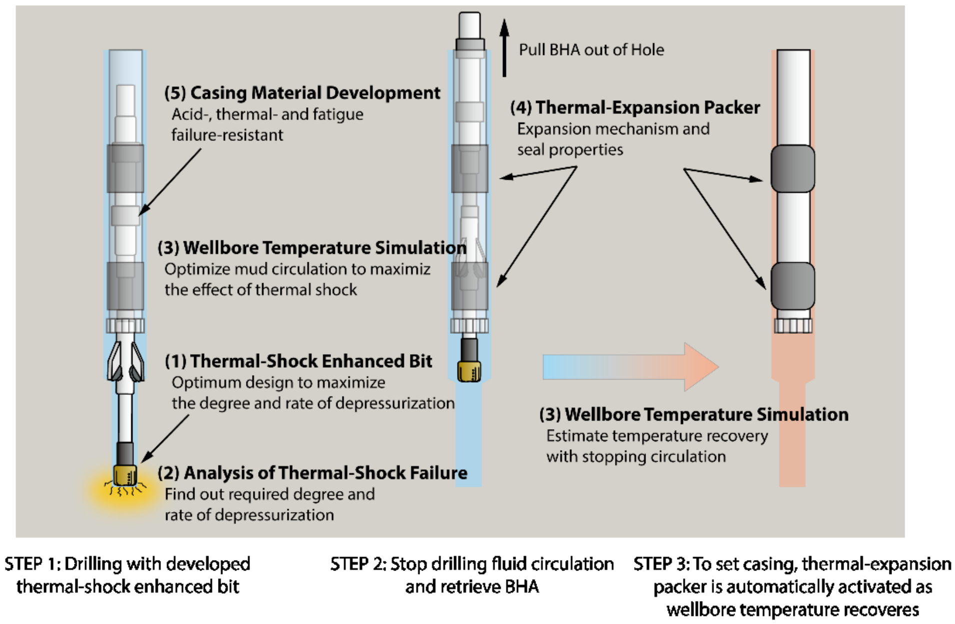

Figure 8: A possible proposed drilling method using thermal-shock enhanced bit to mitigate borehole instability induced by pressure fluctuation.

6. SUMMARY

The development of thermal-shock enhanced drilling system is now in progress as a two-year industrial-government-academia joint leading-research project among Japanese geothermal development companies, universities and a national institute. The project consists of the following five subtasks:

(1) CFD simulation-based development of a new drilling tool "thermal-shock enhanced drill bit" that can generate a sufficient thermal-shock failure of rock induced by depressurization, boiling and cooling at the bottomhole

(2) Experimental and simulation studies on the mechanism of hydraulically induced thermal-shock failure of high temperature rocks

(3) Development of wellbore hydrothermal simulation technology that is applicable to supercritical formation condition to optimize the design of the developing bit and packer

(4) Experimental evaluation of the mechanism of a thermally activated new concept casing packer

(5) Study on acid-, corrosion-, and fatigue failure-resistant materials against supercritical environment, particularly of casing pipes.

We are aiming to complete the feasibility study on the thermal-shock enhanced drilling system and to draw the future R&D road map in this two-year project to extend the development to the following national project.

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