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AERATED DRILLING TO IMPROVE GPO-I DRILLING PERFORMANCE

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ABSTRACT

Aerated Drilling is a technique where compressed air is introduced into the drilling fluid circulating system to reduce the effective density of the fluid column in the wellbore annulus with final goal to allow drilling fluid and cutting circulated back to the surface.

Obtaining cutting return to the surface is very important and beneficial for all function within the subsurface team i.e. drilling, earth science, and reservoir engineering. For drilling, a better hole cleaning will reduce the risk of stuck pipe and minimize drilling torque that allow to drill deeper well. Improved ROP and longer bit life are the other side benefit. For earth science, availability of cutting sample will help on formation evaluation and better geological control. For reservoir, less cutting entering feed zone will minimize formation damage which eventually results in a better production.

The paper reviews the practice of using aerated mud in improving the Drilling Performance in GPO-I 2012/2013 Salak Drilling Campaign. The actual Bottom Hole Pressure (BHP) from PWD is compared to its fracture pressure and formation pressure. Understanding the important role of Pore Pressure, Fracture Pressure, and ECD in aerated drilling is however still a proving a challenge. The intent is to balance the annular and formation pressures to avoid over-gain via under-pressure that can cause a blow out, but minimal overbalance to avoid loss circulation. Proper drilling planning and optimum execution are the key factors that lead to a successful aerated drilling.

INTRODUCTION TO AWIBENGKOK FIELD

The Awibengkok geothermal field, also known as Salak, is located 60 km south of Jakarta on the island of Java, Indonesia (**Fig. 1**). The reservoir is the largest producer of geothermal power in Indonesia (Ibrahim et al., 2005). The Awibengkok (Salak) geothermal system is a liquid-dominated. The commercial Awibengkok reservoir is a moderate-to-high temperature (464-600˚F) fracture-controlled reservoir with benign chemistry and low-to-moderate non-condensable gas content. The geothermal system is hosted mainly by andesitic-to-rhyodacitic rocks, and floored by Miocene marine sedimentary rocks cut by igneous intrusions. A proven reservoir area of 18 km2 and an installed capacity of 377MWe yields a power density of about 20MWe/km2 despite all injection being done infield. Salak has been develop for through periodic infill drilling and injection realignment to produce and maintains 377 MW production.

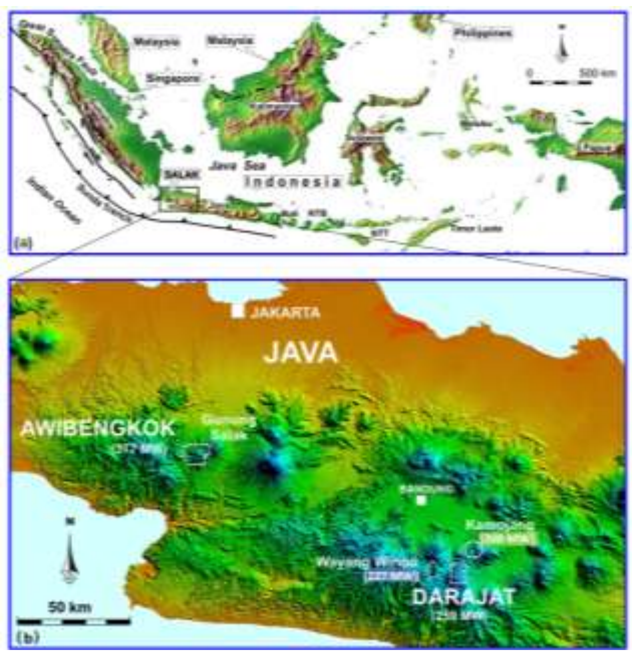

__Figure. 1.__ Location map. (a) Image of Indonesia and (b) location of West Java Awibengkok and Darajat contract areas and other producing geothermal fields

HISTORY OF AERATED DRILLING (HOLE, 2006)

Injecting compressed air into the mud circulating system to combat circulation losses while drilling for oil was first carried out by Phillips Petroleum in Utah, USA in 1941. During the early 1970's, air or 'Dust Drilling' was introduced at the Geysers geothermal field in California, USA.

Aerated drilling of geothermal wells was initially developed by Geothermal Energy New Zealand Ltd. (GENZL) during the period 1978 to 1982 while involved in drilling projects at the Olkaria Geothermal field in Kenya, and at the Kakkonda field in Honshu, Japan; and during the later part of this period GENZL developed its DOS based Air Drilling Simulation.

Subsequent aerated geothermal drilling operations occurred at the following geothermal fields as listed below:

1982 – 1987:

- North East Olkaria – Kenya.
- Aluto-Langano – Ethiopia.

1987 – 1992:

- Nigorikawa, Hokaido – Japan.
- Sumikawa, Honshu – Japan.
- Darajat – Indonesia.
- Olkaria II and Eburru – Kenya.
- Los Humeros – Mexico.

1992 – 1997:

- Los Humeros – Mexico.
- Tres Virgenes – Mexico.
- Wayang Windu, Patuha and Salak, – Java, Indonesia.
- Ulumbu – Flores, Indonesia.

1997 – Present:

- Olkaria III – Kenya.
- Los Azufres – Mexico.
- Salak - Indonesia
- Ohaaki, Mokai, Rotokawa, Putauaki, Wairakei,
- and Tauhara – New Zealand
- Trölladygja – Iceland
- Hellisheidi – Iceland.

In Chevron GPO D&C, aerated drilling has been introduced since 2004 and still an ongoing practice till date.

GEOTHERMAL DRILLING PROBLEMS (KESUMA, 2008)

Geothermal well drilling operations have to cope with high temperature. In high-temperature geothermal fields, the formation temperature is usually in the range 200-350 deg C. Drilling mud characteristics and rheological properties will be affected by the high temperature. With increasing temperature of drilling fluids, viscosity will decrease. This condition will result in cuttings or chips not being effectively removed from the hole, instead accumulating at the bottom, increasing the risk of pipe sticking (Nur et al., 2005).

Usually, the targets of wells in geothermal drilling are faults, fractures or fissures that have high permeability and are connected with the geothermal reservoir. When drilling is in progress, drilling fluid pressure higher than formation pressure will cause a loss of circulation when these fractures are intersected. Loss of circulation in drilling operations causes poor cleaning of cuttings from boreholes that can cause pipe sticking.

When total loss of circulation occurs, drilling fluids and cuttings are pushed into the formation. It may become a problem later because the cuttings and mud cake can reduce the porosity and permeability and may reduce the production of the well. To have a total loss of circulation in the productive part of the well is highly desirable, as it indicates that the well will be a productive one. However, the loss causes some drilling problems, especially with borehole cleaning. The use of aerated drilling fluid aids in borehole cleaning, and keeps fractures open for later production.

AERATED PROCESS (HOLE, 2006)

To maintain drilling fluid circulation while drilling permeable formations, the hydraulic (hydrostatic and hydrodynamic) pressure in the hole must be 'balanced' with the formation pressure. Typically geothermal systems are significantly 'under-pressured' with respect to a hydrostatic column of water to the surface. To balance the pressure in the hole with the formation pressure, the density of the fluid in the hole must be reduced.

The primary objective of drilling a geothermal well is to encounter permeability, and therefore productivity (or injectivity); and because in most geothermal systems permeability is not limited to just the reservoir formations but is also prevalent in overlying formations. It is therefore inevitable that communication between the 'formation' and the fluid in the hole will occur.

Figure 2 depicts typical pressures within a well with a range of drilling fluids with respect to a column of boiling water. The effective drilling fluid density can be varied in the approximate specific gravity range of

1.1 for un-aerated mud to 0.1 for air, by varying the ratio of air to liquid.

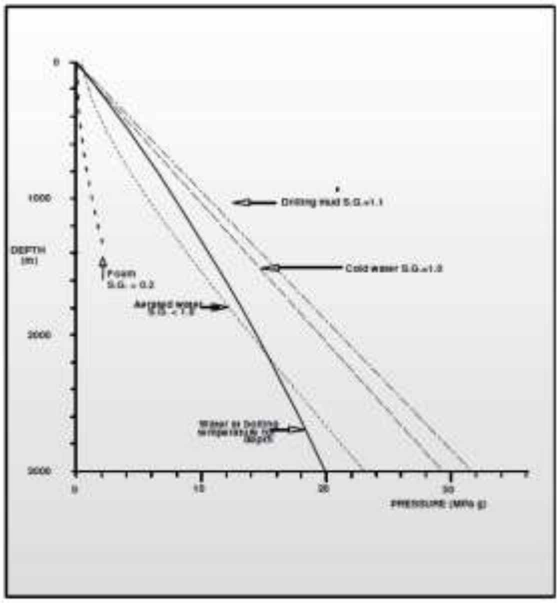

Figure 2. *Typical Downhole Pressure of Several Type of Drilling Fluids*.

To ‘balance’ the down hole circulating fluid pressure with under-pressured formation conditions, the density of the circulating fluid is reduced with the addition of air. The ratio of liquid to air, and the throttling of the circulating fluid outlet to produce a backpressure in the annulus are the variables which can be altered to provide the required pressure balance.

However, the addition of air into the drilling circulation system introduces a compressible component. The volume occupied by a unit mass of air at a particular depth in the hole is dependent on the fluid pressure at that depth. In other words the volume of a bubble of air at the bottom of the hole will be a small fraction of the volume occupied by the same bubble of air at the top of the hole. The density of the fluid column varies with depth and for simplicity purposes is described as a ‘liquid volume fraction’ (LVF). LVF 1.0 being 100% liquid while 0.0 being 100%.

AEREATD DRILLING EQUIPMENT (HOLE, 2006)

Although the equipment required to undertake aerated drilling operations varies with the type of fluid system selected, equipment common to all systems includes:

Primary Compressors

These can be divided into two distinct types: positive displacement and dynamic. The positive displacement type is generally selected for air drilling operations and is compact and portable. The most important characteristic of this type of compressor is that any variation of pressure from the unit’s optimum design, exit pressure does appreciably alter the volumetric rate of flow through the machine.
Pressure increases at the discharge can be balanced by an increase in input power to produce a relatively constant volumetric output, which ensures stable conditions under a variety of drilling conditions. Positive displacement units can be further subdivided into reciprocating and rotary models. Although drilling operations originally utilized the positive displacement type; technological advances have made the rotary units even more compact and less susceptible to changes in discharge pressure, which makes them more efficient when used at the high altitudes at which many geothermal fields are located. Primary compressors typically have discharge pressures up to approximately 25 bar.

Booster Compressors
Boosters are positive displacement compressors that take the discharge from primary compressors and compress the air to a higher pressure (up to 200 bar). Field booster units are, in general, exit pressure (and temperature) limited. This is dependent on the inlet pressure and volumetric flowrate the booster is required to handle. As the volumetric air flowrate to the booster increases for a given booster pressure output; the booster becomes limited by its horsepower capability and similarly with an increase in output pressure.

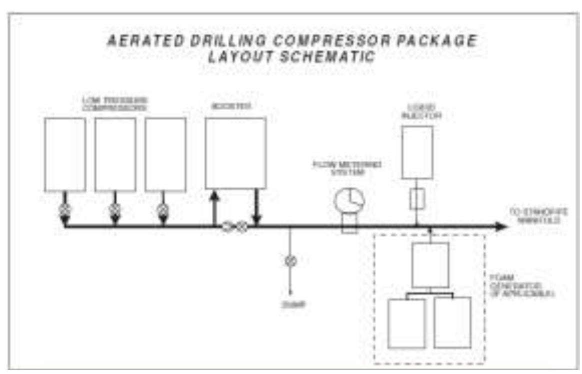

Figure 3. *Typical Aerated Drilling Equipment Schematic*.

Both primary and booster compressors should have after cooling units to reduce the temperature of their discharges. The air from the primary must be cooled to reduce the power requirements of the booster and the booster discharge must be cooled before entering the standpipe to prevent packing and equipment damage. Intercoolers are also installed between stages in multi stage units.

Fluid Injection Pumps
When undertaking mist or foam drilling operations, small triplex pumps are used to inject water (and foaming chemicals) into the air supply pipework at a controlled rate. These pumps generally have capacities up to 300 lpm and have coupled metering pumps for the injection of foaming agents. The compressor and booster units are usually independently diesel powered, skid mounted, and often silenced, each unit occupying a footprint of approximately 3 metres x 6 metres. A schematic layout of this equipment is indicated in Figure 8 below.

AERATED VS NORMAL MUD

Kesuma (2006) in his paper wrote a very good summary about the comparison between using aerated versus non-aerated mud for drilling. Below is the summary (Kesuma, 2006):

Table 1. Comparison of Aerated vs Normal Mud

	Aerated drilling	Mud drilling
Formation damage	Aerated drilling reduces the probability of formation damage because the borehole pressure is less than the formation pressure; drilling fluids and cuttings do not go into the formation. Cuttings pushed into the formation can block and reduce porosity and permeability.	Can cause formation damage when mud cake forms in the production zone and drilling fluids and cuttings go into the formation when total loss of circulation occurs, blocking permeability.
Rate of penetration	Drilling with underbalanced drilling increases the rate of penetration because of improved bit performance and reduces the regrinding of cuttings. Penetration rates, experienced in the basaltic lavas encountered in Icelandic geothermal field, have been as much as three times the penetration rates experienced in the same formations drilled conventionally (Hole, 2006).	Rate of penetration lower than when using underbalanced drilling.
Controlling hole pressure	Aerated drilling fluid has lighter density thus leads to lower annular pressure than formation pressure. It is flexible in controlling formation pressure as pressure in annulus can be maintained by reducing the pressure at the throttle valve at the flow line and air and liquid ratio.	Drilling mud has higher density than aerated drilling fluid. Hydrostatic pressure depends on the density of the mud.
Loss of circulation	Aerated drilling has a lower density than water that can work against circulation loss. When using aerated drilling fluids, even formation pressure is low, but it still has the possibility to deliver cuttings to the surface. A hydraulic gradient towards the wellbore, using under-balanced drilling will reduce the invasion of fluids and fine grained cuttings into the production zone (Bjelm, 2006).	When a total loss of circulation happens, drilling with mud is changed into blind drilling (drilling only with water). The water still enters the formation and the cuttings are not delivered to surface, which can increase the probability of pipe sticking due to poor cleaning of the borehole.
Annular velocity	Aerated drilling needs higher annular velocity to raise the cuttings.	Lower annular velocity.
Volume of water requirement	It needs less water due to the reuse of water and less water loss to formation.	Needs more water when drilling in geothermal fields.
Drilling fluid materials	Water, air, foaming agent, corrosion agent, and other chemical solutions.	Water, bentonite, and many additives to preserve the quality of mud; depends on bottom hole conditions.
Extended equipment	Needs additional equipment than for conventional drilling: air compressors and booster to compress air, mist pump, separator etc.	Mud tank, hopper, mud pump.
Cost	Daily compressors, booster rent costs and fuel.	Cost of drilling mud.
Operation	Needs a skilled person to operate aerated drill. There are differences in jointed or disjointed drill string operations because of the high pressure of aerated drilling and the need to maintain the pressure. Check valve is needed to put in a drill string.	Check valve is put at the bottom of the drill string; operation as conventional drilling.
Corrosion	Causes somewhat higher drill pipe corrosion.	Less drill pipe corrosion.

Above table provide general insight although there will always be pros and cons between them.

PORE & FRACTURE PRESSURE IN AWIBENGKOK

Understanding pore and fracture pressure in the field that being drilled is the key in optimizing aerated to obtain return. The bottom hole pressure (BHP) as well as annulus pressure is designed such that it will 'balance' the pore pressure and will allow the fluid to circulate to surface. The BHP is also designed such that it is not too high that will fracture the formation. Pore and fracture pressure information for Awibengkok field can be obtained from previous Unocal study (Sugiaman, 2003).

As for the fracture pressure, the minimum horizontal stress gradient (fracture gradient) in Awibengkok is between 0.5 and 0.6 psi/ft, based on extended leak off tests or LOT (Swanson, 1996a,b,c; Pinnacle Technologies, 1996a). From the LOT, the minimum horizontal stress is determined from closure pressure.

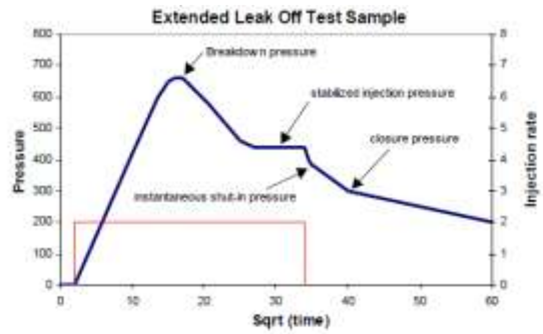

Figure 4*. An example of extended leak off test. Pressure is bold dark blue line, injection rate is thin red line.*

Extended leak off test have been done for four wells in Awibengkok and the result can be seen in the following table:

	Awi 1-2	Awi 7-2	Awi 13-1	Awi 15-1
Test Date	10/6/95	8/5/95	6/11/95	2/8/96
Casing shoe depth (ft TVD from cellar)	2466	3479	3328	3822
Closure pressure (psi)	1330	1740	1990	1935
Closure pressure gradient (psi/ft)	0.54	0.5	0.6	0.51

The result from all LOT in Awibengkok can be seen in Figure 5 below. Based on the fit line, the gradient for minimum horizontal stress is 0.54 psi/ft.

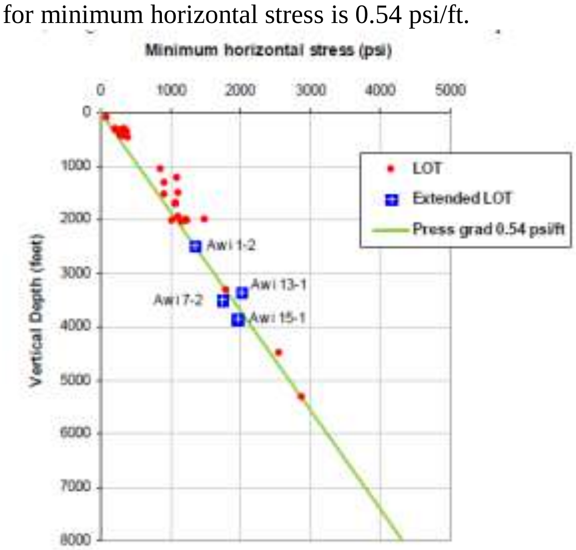

Figure 5*. All leak off test data from Awibengkok wells.*

As for pore pressure, Strobel (1996) interpreted the reservoir fluid pressure gradient during initial state condition to be from 0.355 to 0.359 psi/ft. The piezometric level for this liquid gradient was around 3000 feet above sea level. In Awi 2-1, this level is equal to 998'TVD (Figure 4). Based on down hole pressure monitoring in Awi 3-1, the reservoir pressure has dropped 520 psi by April 2003.

Assuming that the same pressure drop has occurred in Awi 2-1, the current reservoir pressure at Awi 2-1 is represented as the red line in Figure 6. A steam cap has developed in the shallowest part of the reservoir as a result of the reservoir pressure drop. The interpreted steam-liquid interface depth varies throughout the reservoir. In Awi 2-1, the steam-liquid interface is approximately at 400' msl or 3600'TVD (Figure 6).

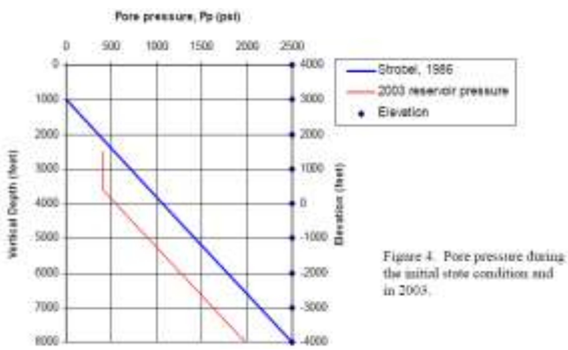

Figure 6. *Pore pressure during the initial state condition and in 2003.*

In this paper, the fracture pressure will be based on above historical study, while Pore pressure data is obtained from PT survey during shut-in, which provides a more update information.

AERATED DRILLING FOR SALAK DRILLING CAMPAIGN 2012/2013

In 2012/2013 Salak Drilling Campaign, GPO-I has been implementing Aerated Drilling during the campaign (field Awibengkok) and it has enable the successful drilling of the Awi 9-8 OH well to 10,500 ft MD - the deepest well in Salak Field to date. Furthermore, the confidence gained is allowing us to proceed with the planning and drilling an ultra deep well to 14,500 ft in the near future.

This paper reviews the BHP from PWD in relation with its pore and fracture pressure window. Furthermore, BHP data from PWD is compared to manual calculation using Guo-Ghalambor equation. UBDPro software is also utilized to simulate the annulus pressure and cutting transportation. Well Awi 10-4 is selected as study cases well for its data completeness.

Well Awi 10-4 was drilled to 8862'MD as Deep Brine producer. Production casing 13-3/8" was set at 4200' MD and three different size of production liner are set from the casing shoe down to TD. PWD was run in the 12-1/4" hole section from 4200'MD to 6900' MD. Below is the BHP obtained from PWD in correlation with the fracture and formation pressure. Fracture pressure is 0.53 psi/ft and pore pressure is based on shut-in pressure from PT tools. The left chart is volume of mud (GPM) and air (SCFM) pumped into the system, middle chart is pressure profile for pore-bottomhole-fracture, and right chart is percentage of mud return.

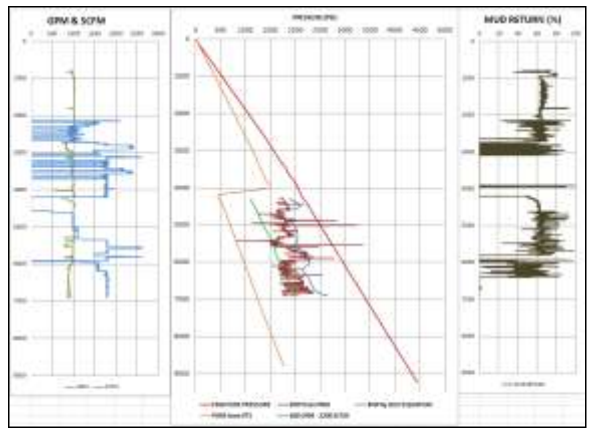

Figure 7. *Drilling Parameter for Awi 10-4.*

From depth 4000' MD, the well started experiencing loss while still pumping at different combination of GPM & SCFM. At 5900'MD, major fracture zone was encountered resulting in total loss. Return was recovered after further drilled which probably due to cutting filling up the fracture zone and enable fluid to be circulated. At 6300' MD, another major fracture zone was again encountered and from this depth down to TD of well, no returns recovered.

Figure 8 below shows a zoom picture of pressure profile. As seen below, BHP is 'not balance' to the pore pressure i.e. BHP is still significantly higher than pore pressure. This could explain why no success in obtaining mud returns during the drilling. Theoretically, only if BHP was balance to formation pressure that fluid can be circulated to surface.

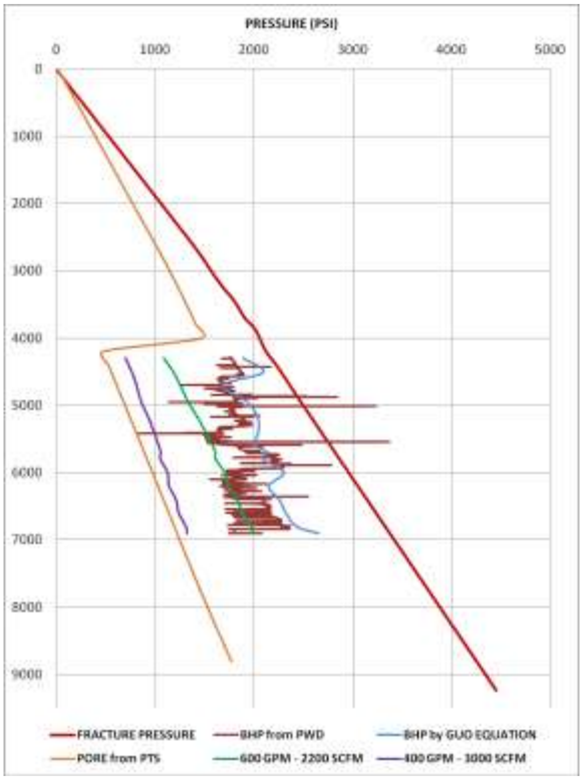

Figure 8. *Pressure profile for Awi 10-4*

We also compare the BHP from PWD with BHP as per calculated using Guo-Ghalambor equation, which show similar trends. Proving the accuracy of this equation allows drilling team to predict expected BHP under different mixture of mud and air using this equation.

The green line showed in the figure is the calculated BHP using Guo-Ghalambor, with 600 GPM – 2200 SCFM. The BHP is close to Pore Pressure at 400 GPM – 3000 SCFM as shown by purple line in the figure. Hypothetically, the possibility of getting mud return at this combination (400 GPM -3000 SCFM) is higher as the BHP is nearly balance to the formation pressure at this rate.

Further effort can be done to balance the BHP to pore pressure i.e. by further maximizing SCFM and minimizing GPM. However, there are some limitations that also need to be addressed. Surface equipment limitation, space limitation for air drilling equipment, and mud motor minimum required flows are some of them.

There are also several factors that may contribute to the inability to obtain return. Degradation in the fluid carrying capacity and the practice of pumping down the backside during losses are some contributing factor. These require a further study too.

CONCLUSION

Obtaining cutting return is beneficial for all function in the Geothermal asset development team. Better hole cleaning for drilling, formation evaluation for earth scientist, and better production for reservoir are those key benefits.

Study on Awi 10-4 showed that the final BHP after injecting air into the fluid system is not low enough to balance the formation pressure. Therefore after fracture zone was encountered, no returns gained from that intersected fracture zone down to TD of the well. Combination for 400 GPM – 3000 SCFM will lower down the BHP close to pore pressure and at this rate the chance of getting fluid return is higher. However, a more comprehensive evaluation is needed to address some of the limitation within the overall system to pump at this rate.

Another valuable study is to evaluate the improvement in production on the wells drilled with aerated drilling.

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