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Successful Implementation of Aerated Drilling in Improving Geothermal Drilling Performance

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ABSTRACT

Obtaining drilling fluid and cutting returns in subnormal pressure regime is still a big challenge in the drilling industry. Aerated drilling has been introduced as one of the solutions. Aerated Drilling is a technique where compressed air in combination with the drilling fluid is used to reduce the effective density of the fluid column in the wellbore. The main objective is to enhance the chance of having circulation during drilling by reducing the Equivalent Circulating Density (ECD) in the wellbore.

One of the biggest challenges in drilling a geothermal well is loss of circulation. Typically, the well targets in geothermal drilling are faults, fractures or fissures that have high permeability and are connected with the geothermal reservoir which has subnormal pressure. When these faults or fractures are intersected, losses will occur as the drilling fluid will enter the fracture zone rather than flowing to the surface. Some of the cuttings may enter the encountered fracture zone but some may stay in the annulus and accumulate. This cutting accumulation will result in torque increase that will limit the capability to drill deeper and it will also increase the risk of stuck pipe due to cutting pack off. The cuttings entering formation also become a later problem as they may reduce the permeability of the fracture and thus the production of the well.

Being able to manage circulation is very crucial as it will reduce the drilling risk, increase the drilling efficiency, enable better geological control & formation evaluation from cutting samples, and minimize formation damage.

Aerated drilling has been utilized to solve this problem. The intent is to manage the ECD that will allow a full or partial circulation despite encountering subnormal pressure zone, without neglecting the well control aspect. Understanding the ECD under various air/mud ratios and understanding the geothermal formation pressure are essential for the successful application of the technology.

This paper reviews the utilization of aerated drilling in several wells during the GPO-I 2012/2013 Salak Drilling Campaign, including the deepest geothermal well in Indonesia. The project planning, project execution, and the field results are discussed in this paper. Results show that the drilling efficiency has increased significantly in comparison to historical performance as indicated by extended bit life, longer hole section, higher ROP, and allowed deeper drilling.

1. INTRODUCTION

The nature of geothermal field is the presence of pre-existing fracture zone with high permeability at subnormal pressure. This formation pressure is even lower in a steam cap field where there is no liquid column. During the drilling, lost circulation generally will occur whenever this fracture zone is penetrated, and that will lead to further problem such as stuck pipe and reservoir damage.

Chevron GPO-I D&C Team has put continuous efforts to solve this lost circulation issue; one of them is by the utilization of aerated drilling technique. This technique has successfully enabled the team to manage or regain circulation despite subnormal pressure is penetrated. The technique has been used in several drilling campaigns previously and during Salak (Awibengkok) 2012/2013 Drilling Campaign it is being utilized more intensively. PWD sensor, air-rate surface sensor, science approach, and software are several resources being used to support the application.

Impacts are significant: a better hole cleaning that reduces the drilling risk, cutting sample availability that enable better geological control, and minimum formation damage that improves production rate

2. OVERVIEW OF AWIBENGKOK FIELD

The Awibengkok geothermal field, also known as Salak, is located 60 km south of Jakarta on the island of Java, Indonesia. 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.

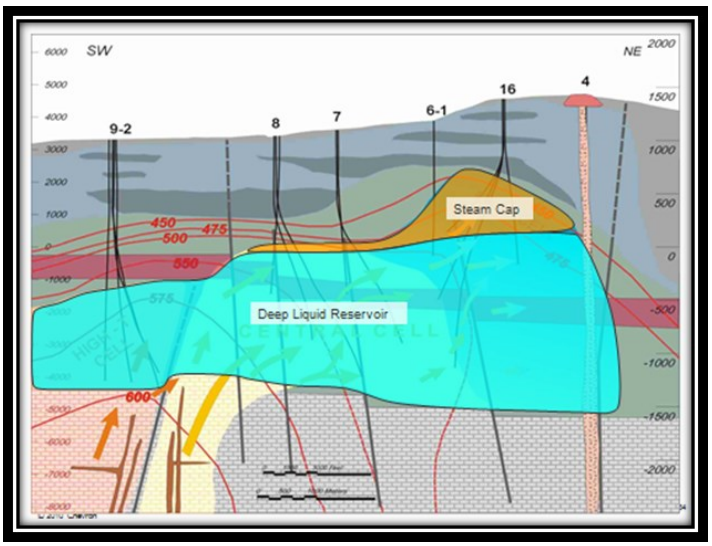


Figure 1. Salak Reservoir Conceptual Model

'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 km^2 and an installed capacity of 377MWe yield a power density of about 20MWe/km^2 despite all injection being done infield. Salak has been developed through periodic infill drilling and injection realignment to produce and maintains 377 MW production rate.

2.1 Fracture Pressure in Awibengkok

For the drilling team, understanding pore and fracture pressure in the field is the key to optimize the aerated drilling implementation. The bottom hole pressure (BHP) or ECD is to be maintained such that it will 'balance' the pore pressure (slightly overbalance) and that will allow the fluid to circulate to the surface. The ECD is also designed such that it is not so high that will fracture the formation. Pore and fracture pressures are becoming the window for ECD.

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.

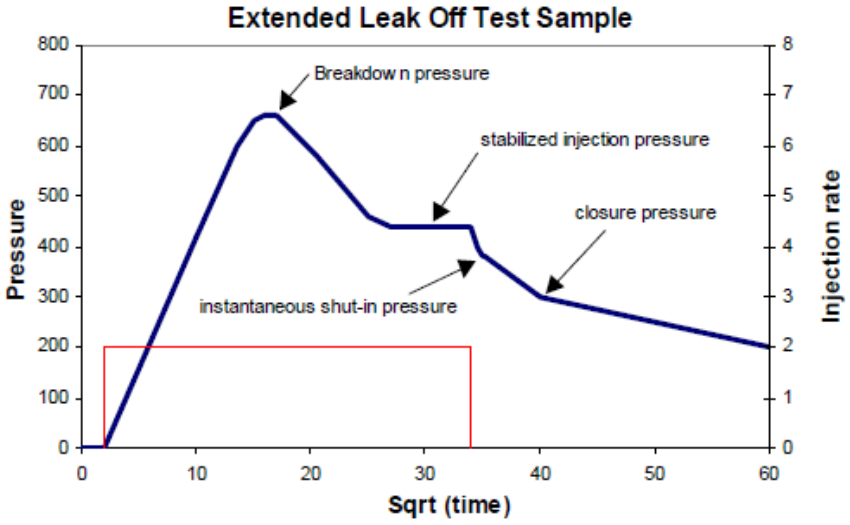


Figure 2. An example of extended leak off test. Pressure is bold dark blue line, injection rate is thin red line.

The results from all LOT in Awibengkok are in Figure 3. Based on the fit line, the gradient for minimum horizontal stress is 0.54 psi/ft.

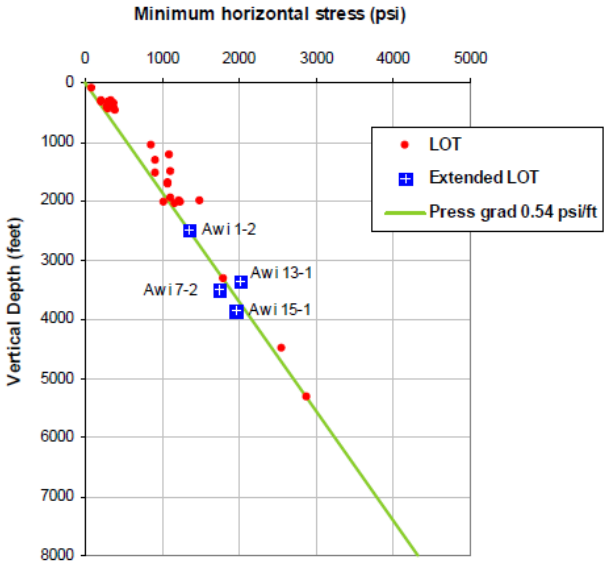


Figure 3. All leak off test data from Awibengkok wells.

2.2 Pore Pressure in Awibengkok

As for the 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 4. 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 4).

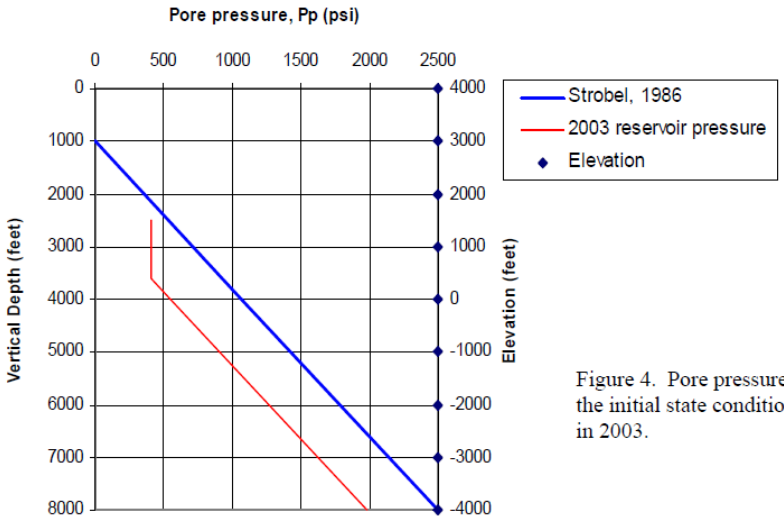


Figure 4. Pore pressure during the initial state condition and in 2003.

Figure 4. Pore pressure during the initial state condition and in 2003.

In this paper, the fracture pressure will be based on above historical study. However, pore pressure data will be based on actual PT logging survey, which provides a more updated and accurate information.

3. AERATED DRILLING TECHNIQUE

Aerated Drilling is a technique where compressed air in combination with the drilling fluid is used to reduce the effective density of the fluid column in the wellbore. The main objective is to enhance the chance of having circulation during drilling by reducing the Equivalent Circulating Density (ECD) in the wellbore (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 latter part of this period GENZL developed its DOS based Air Drilling Simulation (Hole 2006).

Further detail on aerated drilling technique will not be discussed here but instead the paper will focus on its application during the drilling campaign.

4. REVIEW OF AERATED DRILLING IN SALAK DRILLING CAMPAIGN 2012/2013

In 2012/2013 Salak Drilling Campaign, GPO-I have been utilizing Aerated Drilling technique. The campaign was regarded as a success in terms of achieving its geothermal production objective, cost saving, reducing number of incident (mainly stuck pipe incidents) and ability to reach most of its target depth. Other special achievements during the campaign were drilling the first geothermal multilateral well in Awi 2-5 ML and drilling ultra-deep well Awi 9-9 to 10,400 ft.

This paper mainly reviews the application of aerated drilling in helping the drilling campaign. Pressure profile of the wellbore (BHP) at various air injection rates in relation with the pore and fracture pressure window are evaluated. During the planning phase, software and formulas spreadsheet were used to model the pressure profile. Al-Ajmi and Guo-Ghalambor formulas, as well as UBDPro Software were used to create the model. During the execution phase, PWD (Pressure While Drilling) sensor was ran to obtain real-time ECD during the drilling. Actual results versus model are compared and evaluated. Several wells are selected as case studies in this paper.

4.1 Review on Well Awi 10-4

Well Awi 10-4 was drilled to depth 8862'MD as a Deep Brine producer. Production casing 13-3/8" was set at 4200' MD and three different sizes of production liner were set from the casing shoe down to TD. PWD was run during the 12-1/4" hole section from 4200'MD to 6900' MD. Data from PWD were obtained in real-time.

Figure 5 shows the ECD 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 logging survey. The left chart is volume of mud (GPM) and air (SCFM) pumped into the system, middle chart is pressure profile of pore-bottom hole-fracture, and right chart is percentage of mud return.

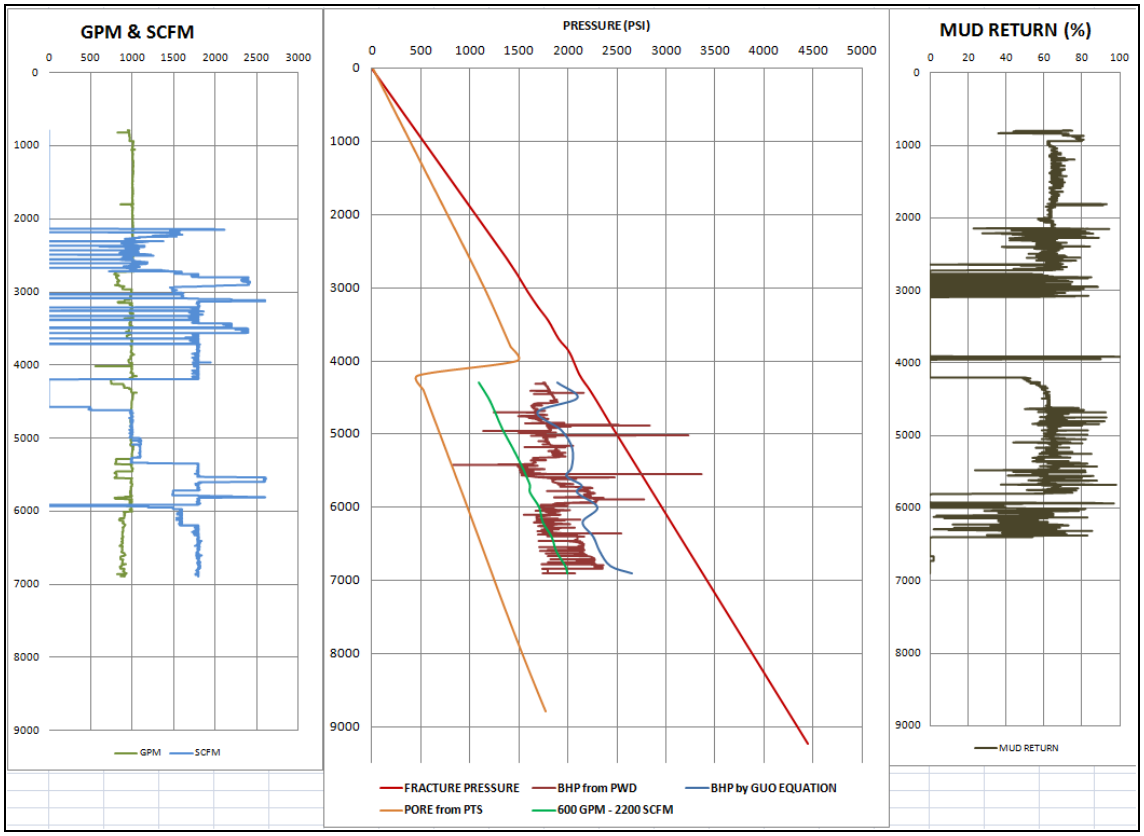


Figure 5. Drilling Parameter of Awi 10-4.

At depth 4000' MD, the well started to loss under pumping at different combination of GPM & SCFM. At 5900'MD, major fracture zone was encountered resulting in TLC. Return, however, was recovered after further drilled which was probably due to cuttings filling up the fracture zone (reducing permeability) therefore enabling fluid to be circulated. At 6300' MD, another major fracture zone was encountered and from this depth down to TD of well, no returns were recovered.

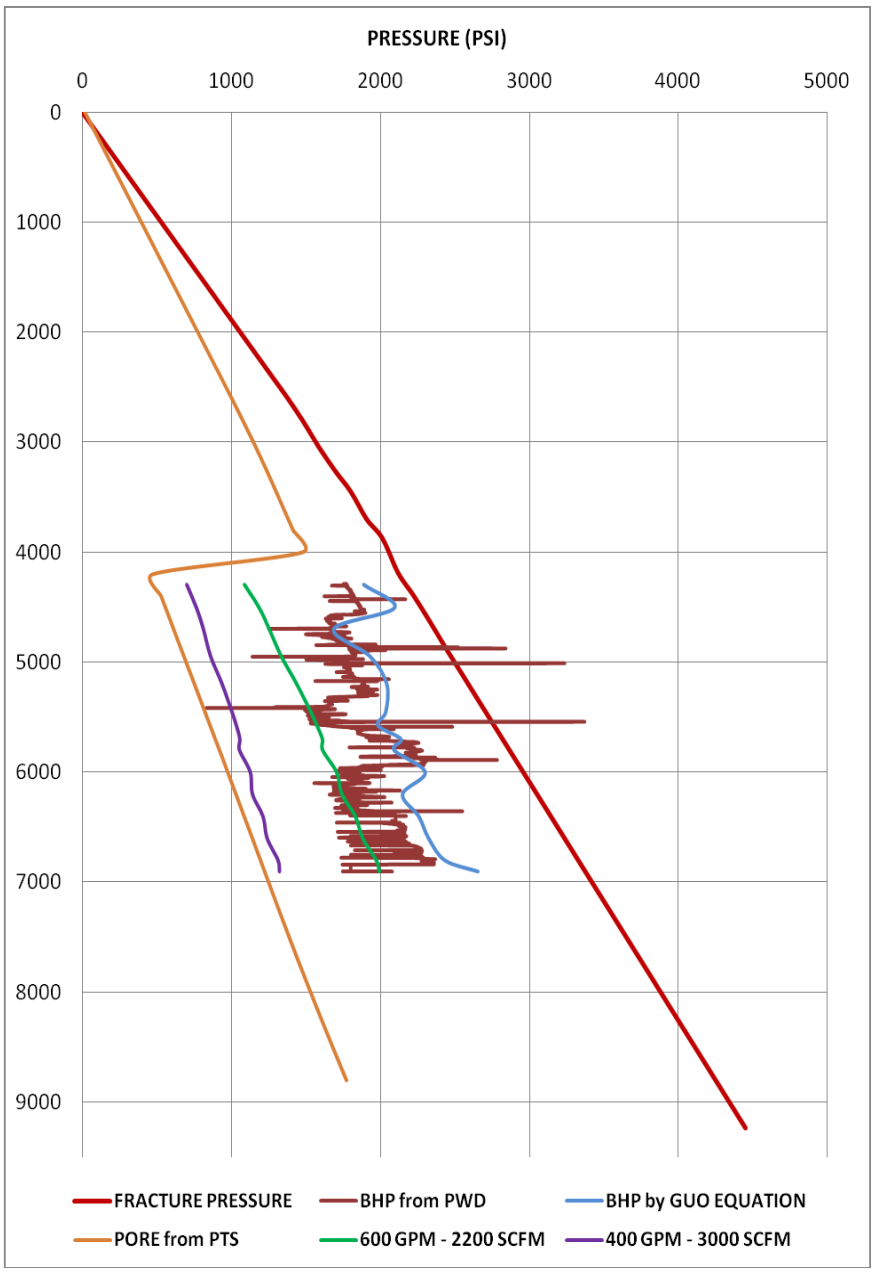


Figure 6. Pressure profile at Different Air/Mud Ratio for Awi 10-4

Figure 6 shows a zoom picture of the pressure profile. As seen below, ECD is highly overbalance against pore pressure i.e. ECD is still significantly higher than pore pressure. This is one of the reasons why there was no success in obtaining mud returns during the drilling. Theoretically, if ECD was less over-balance to formation pressure then fluid can more likely be circulated to surface.

We also compare the ECD from PWD with ECD as per calculated using Guo-Ghalambor equation, which show similar trends as seen on the figure in blue line. Proving the accuracy of this equation allows drilling team to model the ECD under different mixture of mud and air.

The green line showed in the figure is the calculated ECD using Guo-Ghalambor, with 600 GPM – 2200 SCFM. The ECD 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 ECD is nearly in balance with the formation pressure at this rate.

4.2 Review on Well Awi 10-5

In figure7, the blue line is the Formation/Pore Pressure based on PTS logging data after drilling. The red dots (4 dots) are where the feed zones are located. The light blue dotted line illustrates the BHP should the well be drilled with fresh water (8.6 ppg). The grey line show actual BHP during drilling based on PWD sensor. Green and orange line show BHP based on model/calculation using Al-Ajmi and Guo-Ghalmabor formula, respectively.

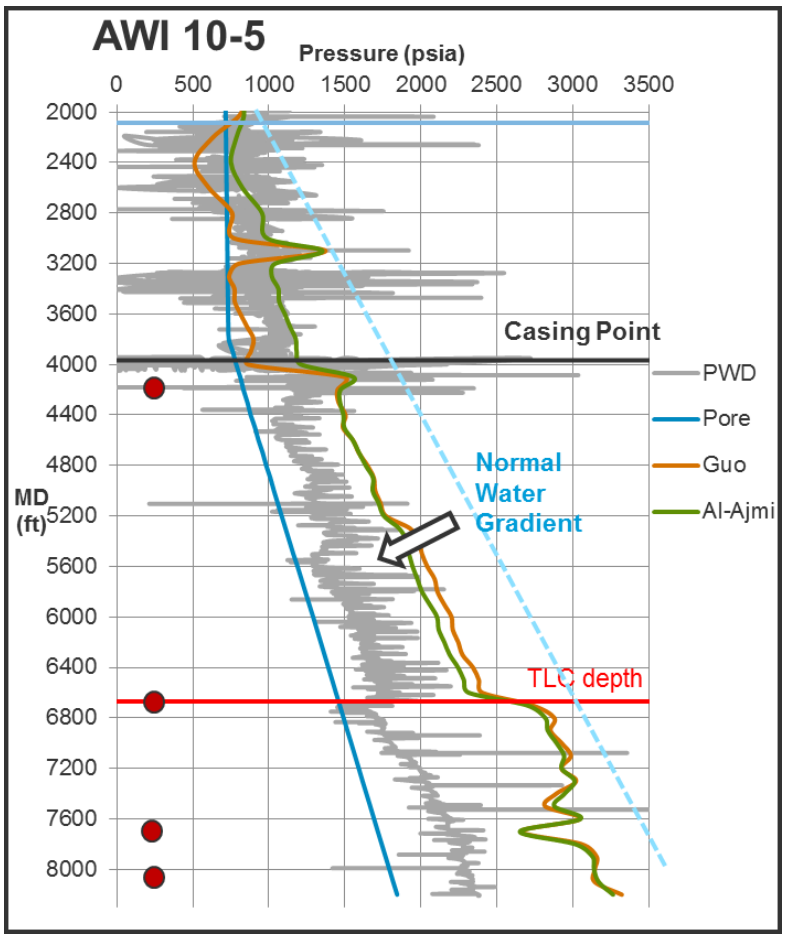


Figure 7. Drilling Parameter of Awi 10-5.

After casing point 13-3/8", first feed zone was encountered at ~4230' but the circulation was maintained due to low overbalance between BHP vs Formation Pressure. Should the well be drilled with water instead; the chance of maintaining circulation would be much lower due to higher overbalance.

However whenever 2nd feedzone at ~6670' was penetrated, TLC occured. Later PTS Injection survey showed that the 2nd feed zone has a much higher permeability (higher injectivity index). In a simple formula, rate of losses is a function of Injectivity Index and Delta Pressure :

Fluid Loss (psi) = Injectivity Index (kph/psi) x Delta Pressure (kph) (1)

That means that at same delta pressure, if the II is higher so will the rate of losses, which is exactly what we encountered in this case.

The other key point is that both calculations from Al-Ajmi and Guo-Ghalambor are showing very good trends. That means both formulas can be used to create model for planning purposes, to some degree of accuracy of course. After TLC, calculations show different value due. This mainly is due to the loss of hydrostatic column in the annulus in the actual case, which is not applicable in the formula (the formula always assumes a full column in the annulus).

Despite TLC, well was successfully drilled to its planned TD. All the new drilled cuttings from that point onward were suspected to fill the fracture zone instead of being circulated to the surface. Otherwise all those cutting would fall off to the BHA and created another problem.

Further simulations were made using Landmark Software, as shown in Figure 8. Figure on the left shows the BHP at various air mud ratio as shown in the legend. Figure on the right shows the actual air/mud ratio used during drilling. At the left figure, the brown line (900 gpm – 1500 scfm) is just to illustrate the actual BHP during drilling assuming constant air mud ratio at 1500scfm/900 gpm (in actual the ratio was fluctuated rather than constant). The purple line shows the BHP at 600 gpm – 3000 scfm. At this rate, BHP is still overbalance against pore pressure. By understanding this, the team would be able to drill at more aggressive rate (lower gpm higher scfm) while still maintaining well control assurance (stay overbalance).

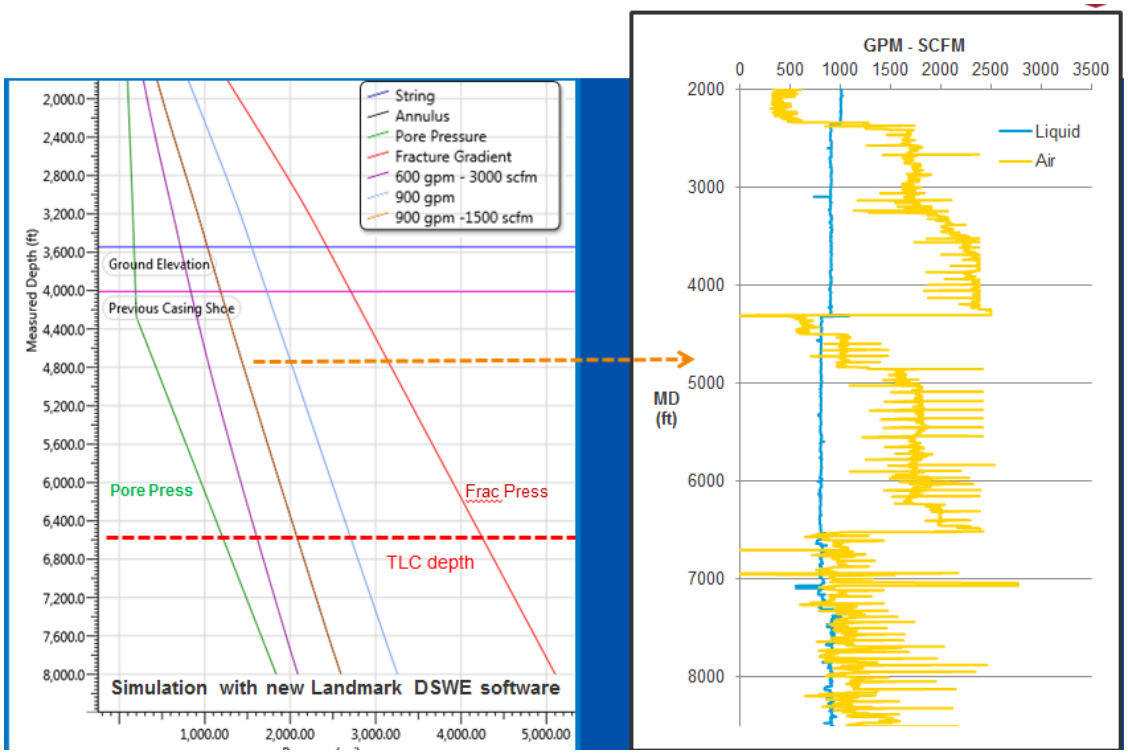


Figure 8. Simulation with Landmark DSWE Software

4.3 Review on Well Awi 9-9

Lesson learned from Awi 10-5 was then again taken to improve the planning and execution of well Awi 9-9. This well was planned to be drilled as the deepest geothermal well (TVD wise) in Indonesia.

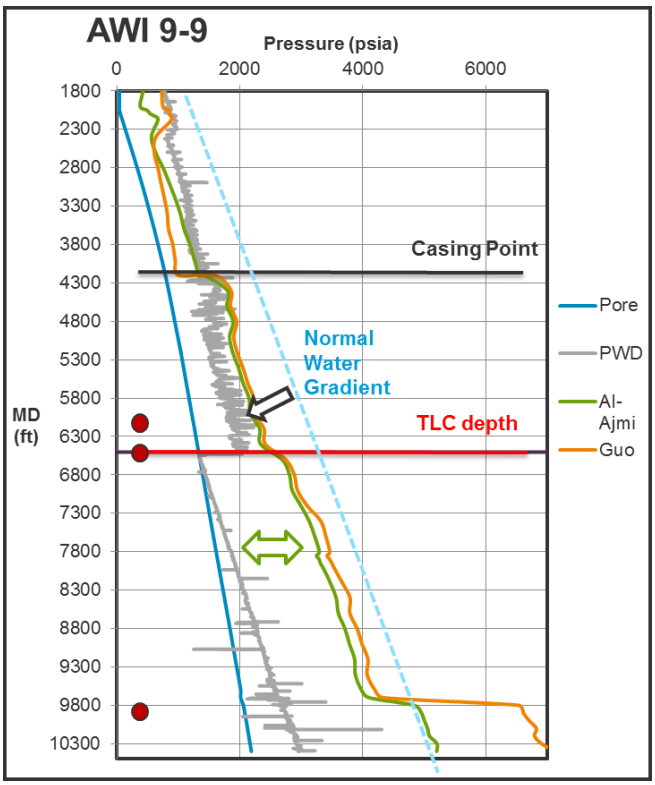


Figure 9. Drilling Parameter of Awi 9-9.

As seen in figure 9, circulation was maintained until depth of ~6400'MD. From that point onward, lost circulation occurred all the way to TD of the well. Several key points will be discussed here.

Typically, lost circulation in Salak field would occur across the reservoir section (after the Casing Point 13-3/8"). In Awi 9-9, circulation has been successfully maintained to as deep as 6400' MD. This is another improvement compared to previous practice,

where lost circulation occurred not far away after the casing point. Addition of air has helped to minimize the overbalance between wellbore ECD versus Pore Pressure.

From depth 6400' down, ECD has dropped significantly as shown by PWD data. This indicated that the mud column in the wellbore has dropped to some certain depth, probably to the level where the feed zone is. Difference of ECD before and after the drop can give a general figure of where the depth of current water column in the wellbore is. By knowing the water level in the annulus, team would know if the feed zone is covered by hydrostatic column of not. If not, then pumping down the backside should be considered in order to maintain well control.

With both Guo-Ghalambor and Al-Ajmi, until the depth of 6400' the model shows similar trend to the one actually observed, which tells us that the model is valid to a certain degree. From depth 6400', they show differences because of similar explanation; the model assumed the water column is still maintained full while in reality it has actually dropped to some level.

5. OTHER BENEFITS

There are several key information can be obtained by understanding all this pressure models during drilling, based on the simple formula as shown earlier.

Firstly for the drilling, the team would be able to somewhat predict the rate of losses.

Fluid Loss (*psi*) = Injectivity Index (*kph/psi*) x Delta Pressure (*kph*) (1)

The concept has always remained the same; it is our understanding that is getting better and better. If the Injectivity Index (II) of the well is known, delta pressure can be predicted / modelled, then the rate of losses can be predicted too. In a long-developed field like Salak field, with many wells have been drilled, the wellbore II of any upcoming wells can be predicted with a higher degree of accuracy. Pore pressure is known, BHP during drilling with air/mud can be modelled then certainly the delta pressure is known. This concept may be more difficult to apply in a new or even exploration field, but again in a developed field, this would be much more feasible to be done. By knowing in advance on what the drilling team would expect (Return/PLC/TLC), the team can manage a better plan.

Secondly for reservoir, the team would be able to estimate the II prior to drilling fluid damage. Still using the same formula, rate of losses at any given delta pressure can be translated to II of wellbore. The formula is:

Injectivity Index (kph/psi) = Delta Pressure (kph) / Fluid Loss (psi) (2)

Whenever any feed zone is encountered and TLC/PLC occurs, one should record the rate of losses and delta pressure at that moment. That will tell the II of that particular zone prior to any mud damage. The II obtained after well is completely drilled is a mud-damaged II. Knowing both II during and after drilling will tell how badly the feed zone is damaged and therefore it can give us guidance if the well is a good candidate for future work-over or not. Certainly further calculation/conversion need to be done since II is a function of fluid properties. II for drilling fluid is obviously different from II for geothermal production fluid, so further calculation/conversion still need to be done.

6. HOLLISTIC HYDRAULIC DESIGN & REVIEW

Addition of air into the drilling fluid system will certainly have an impact on other engineering aspects. While above discussion has focused mainly on the pressure aspect of the wellbore, other aspects have to be reviewed in order to generate a holistic approach. Impacts to the motor performance, bit performance, drill cutting circulations, etc are to name a few.

For this purpose, the author plans to divide those engineering aspect into two main categories i.e. controlled variables and resulting variables. Controlled variables are basically all the variable that can be adjusted/controlled directly from the surface, such as mud weight, mud flow rate, and mud rheology. Resulting variables are all the variable that are only the result from other (controlled) variables. They can also be called indirectly controlled variables. They are the ECD, cutting suspension ability, etc. More study still needs to be done on this matter.

At the end, the main goal of having a holistic hydraulic design is to fine-tune the optimum drilling parameters. At any drilling situation, there will always be trade-offs of changing any parameter. Therefore, the goal is not to achieve best parameter but rather optimum parameter at any particular situation.

CONCLUSION

Being able to manage fluid circulation in drilling a geothermal well will bring significant benefits from the point of view of drilling and reservoir engineers, and geologists. Better hole cleaning for drilling, adequate formation evaluation for earth scientist, and better geothermal production for the reservoir are the main benefits.

The main concept in managing circulation has always been the same i.e. rate of fluid loss is the product of Injectivity Index and delta pressure. Aerated drilling has been utilized mainly to manage the delta pressure and hence controlling the rate of loss. By understanding the whole pressure profile (BHP, pore and fracture pressure) with the help of available resources (software, sensors, tools), the implementation of aerated drilling as well as its results should get better and better.

In a developed field where data are available in great volume and accuracy, predicting the rate of losses prior to drilling would not be impossible as long as the II and delta pressure data are known

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