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A Discussion on Oil & Gas and Geothermal Drilling Environment Differences and Their Impacts to Well Control Methods

Dorman Purba[1], Daniel W. Adityatama[2,1], Ferdino R. Fadhillah[2,1], M. Rizqi Al-Asyari[2,1], Jessica Ivana[2,1], Rasis Abi Tiyana[2,1], Triwening Larasati[2,1], Panji Gumelar[1], Ari Gunawan[1], Nurfikri Abdurrozaq Shafar[1], Andi Novita Mama Anugrah[1], Rony P. Nugraha[3,2]

[1]ENERKA Bhumi Pratama, Cibis Nine Tower, Jakarta Selatan, Indonesia

[2]Geoenergi Solusi Indonesia (GEOENERGIS), Cibis Nine Building 11th Floor, Jakarta Selatan 12560, Indonesia

[3]The University of Auckland, Department of Engineering Science, Private Bag 90210, Auckland, New Zealand

dorman.purba@enerklaz.com

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1 ABSTRACT

Drilling is one of the key activities on geothermal and petroleum projects that could face hazards such as kick and blowout. Those conditions are hazardous to the equipment and personnel on the drilling site, thus the drilling personnel should be prepared to apply any well control technique to prevent the kick becoming blowout. The current condition in the drilling industry is that the well control method for oil and gas drilling is more established compared to for geothermal practices. Even though the objective of the well control is similar between them, but the differences of the subsurface conditions, the formation fluid, and the origin of the formation pressure may render the oil and gas well control methods to be less suitable for geothermal environment, especially in Indonesia. With geothermal exploration in Indonesia is currently on the rise, there is a tendency of drilling personnel from oil and gas industry to work on geothermal project without proper knowledge of the differences and implications. The condition is aggravated by the absence of accepted national standard or training center for geothermal well control in Indonesia.

This paper describes the different aspects of petroleum and geothermal drilling, including the formations likely to be encountered, the formation condition, and the origin of the pressure encountered in oil & gas and geothermal drilling. The differences of the conditions then used as a basis to identify the limitations of widely applied oil and gas well control such as driller's method, wait and weight, and concurrent methods in geothermal drilling. The difference in the subsurface conditions is also one of the reasons why bullheading, typically the last resort of well control in oil and gas drilling, is generally more suitable for geothermal drilling in Indonesia. By understanding those differences and factors, it is expected that one can properly plan geothermal drilling campaign and avoid any accidents that may be caused by unsuitable well control method.

2 INTRODUCTION

2.1 Overview of Drilling Process and Hazards

Drilling is a complex operation that requires personnel from multidisciplinary backgrounds that may come from many companies (**Table 1**). These various backgrounds and working cultures, combined with high subsurface uncertainties could increase the challenges significantly in an exploration project, both petroleum and geothermal.

Table 1: General description of organization involved in a drilling project

Comparison	Operator	Rig contractor	Drilling service companies
Main responsibilities	The company or operator usually would assign drilling contractor to drill the well.	The contractor is responsible to provide and maintain the rig, deploy capable and certified personnel, and operate the rig.	To support the rig operation, it would be necessary to provide specialist personnel and equipment (e.g., logging, directional driller, etc.) that would be provided by the service company
Key personnel in the drilling operation	Geoscience Manager, Drilling Manager, Drilling Engineer, Drilling Superintendent, Wellsite Geologist.	Rig Manager, Rig Superintendent, Toolpusher, Driller, Derrickman.	Cementing Engineer, Directional Driller, Mud Engineer, Mud Logger, Wireline Engineer, Formation Evaluation Specialist, Coring Engineer.

General drilling process between oil/gas and geothermal well has similarities. According to PennState (2021), the general normal drilling process is shown in **Figure 1.**

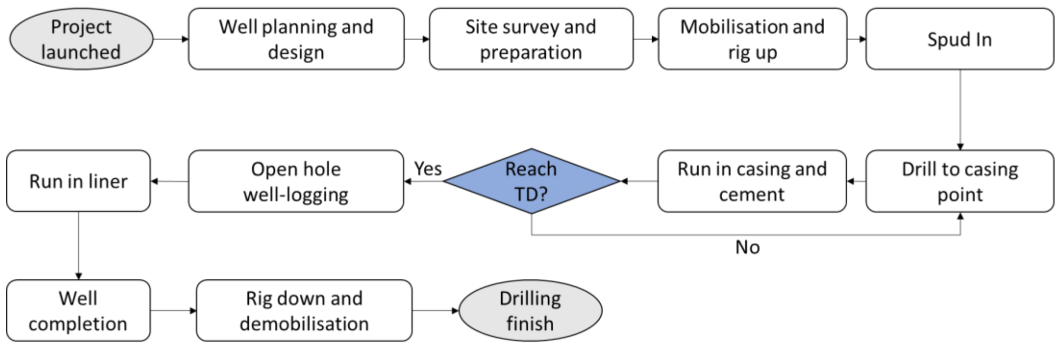

Figure 1: Simplified drilling project activities

- **Well planning** is an early step of drilling that started by proposed prospective targets by geoscience team. When the well objectives have been determined, the drilling and geoscience team will develop drilling plans into a proposal to be approved by top-level management. This stage also considers the technical aspect of well design to reach the subsurface target.
- **Site survey and preparation** are conducted after the drilling proposal is accepted by management. This step includes the preparation of drilling infrastructure such as well-pad, access road, water supply, staging area, disposal area, etc. For high relief terrains, the preparation is more challenging than flat terrain due to the topographic characteristics such as steep slopes which may create difficulties to prepare the flat area for the well pad. After the preparation, the conductor casing (18 inches to 36 inches) could be set up using an auger unit to isolate the top surface soil so the loose material would not contaminate the wellbore during the early drilling operation.
- **Mobilization and rig up** would be performed after all drilling infrastructure and permittance have been cleared. The drilling equipment would be transported from the drilling yard to the site. For land operation, the drilling equipment could be shipped to the nearest prioritized port and continue the mobilization using multiple heavy-duty trucks to well pad. After the arrival, that equipment would be placed and settled before the rig up operation.
- **Spud-in** is the start of a drilling operation. This is performed after the rig has been inspected and declared safe for operation.
- **Drill to casing point depth**. Drilling is started from the surface until reaches the planned depth for the surface casing. The surface casing is important to isolate the surface aquifer and gas, so it would be safe to continue drilling activity into the deeper formation. It is also important to use environmentally safe drilling materials to avoid environmental contamination. The drilling would use smaller bit size as depth increased. After the depth of casing is reached, the drill pipe would be tripped out to the surface.
- **Run in casing and cement** is performed after the casing depth is reached. The casing would be set up and strengthened using cement. Cement would be pumped to fill the gap between the outer side casing with the formation and isolate the casing from formation to prevent corrosion, blow out, casing shock, etc.
- **Drill to total depth.** After the first section has been completed, the drilling would be continued to the next casing setting depth. This step may face more challenging situations since the environment would be dangerous and may result in hazards as shown in **Table 4.** One of the most challenging situations is the loss of circulation that may be the result of natural conditions or induced by human error. The lost circulation would decrease the hole hydrostatic pressure that may lead to a formation influx called as kick that could escalate into blow-out condition. This would be discussed more comprehensively below (**in Possible Causes of "Kick"**). After the drilling reaches the next casing point, the hole would be secured using casing and cement. On the last section (reservoir zone), it would use the perforated liner without cement to prevent formation damage on the desired section after several data acquisition activities.
- **Perform open hole well-logging** is performed usually on reservoir sections that use logging tools with direct contact to formation. The acquired data would be used for formation evaluation for subsurface team.
- **Run in liner** would be executed after the open hole logging is performed to secure the hole using a perforated liner. The perforated liner still allows formation fluid to flow for well testing or production purposes.
- **Rig down and demobilization** will be done after all the drilling operation is completed. The rig would be disassembled and moved out for the next drilling operation.

Although the stages in a drilling project are generally similar for petroleum and geothermal, the reality is that the formation and subsurface hazards encountered are very different. As per PLN's General Plan for the Provision of Electricity (RUPTL) 2021-2030, the geothermal exploration activity (and subsequently exploration drilling) in Indonesia is forecasted to increase in the coming years. The increase in drilling activity will require a lot of personnel required for geothermal drilling. According to Umam, Purba, & Adityatama (2018), the drilling contractor and service company usually shift the same personnel for geothermal and oil/gas well, especially in Indonesia. Drilling personnel that have little to no knowledge and competencies regarding drilling in geothermal environments might make a mistake during operation that risking equipment and potentially loss of life.

Umam, Purba, & Adityatama (2018) also emphasized that awareness of well control method adaptation is important for any transferred personnel from one drilling environment to another due to the differences of nature and characteristics of lost circulation and kick. In geothermal environment in Indonesia, the kick is most likely caused by high temperature zone that cause steam kick, while in petroleum, the driller will mostly deal with flammable fluid with high explosive hazard (i.e., gas kick). Improper identification of the type of kick experienced could lead to wrong handling and may cause accident.

2.2 Research Objectives

This study objectives try to answer the following questions

1. What is the difference between oil well and geothermal drilling environment from surface and subsurface perspectives?
2. What are the causes and indication of kicks in both environments?
3. What is the limitation of oil & gas well control method for geothermal environment?

Finally, this study tries to highlight the different environment between geothermal and oil & gas drilling and their implications on well control practices. It is expected that by understanding those differences, one can acknowledge that the drilling practices and personnel from oil & gas cannot be directly utilized without proper knowledge and competencies in geothermal drilling.

2.3 Methodology

This study uses literature review to describe the differences of surface and subsurface condition and typical cause of the kick for both oil & gas well and geothermal well. These differences were then analyzed to identify the limitations of oil & gas well control method on geothermal drilling and populate the possible hazard that could happen if the crew still utilize oil well control methods on geothermal environment. A case of the recent well control incident in geothermal drilling in Indonesia were used as a case study to extract the lessons learned.

3 COMPARISON BETWEEN PETROLEUM AND GEOTHERMAL ENVIRONMENT

In order to understand the different nature and causes of the kick events in petroleum and geothermal, it is important to fully understand the differences between the subsurface systems of the two environments.

3.1 Surface Aspect

3.1.1 Environment (terrain)

Geothermal environment associated with volcanism usually would have high terrain (Nicholson, 1993). The high terrain environment will have high topography, steep slopes, and difficult access for drilling activities in high-temperature zones (usually upflow zones). Examples of high terrain environments are Indonesia, Philippines, and Chile since it is associated with magmatic arcs which are characterized by quaternary volcanism (Goff & Janik, 2000; White, Lawless, Ussher, & Smith, 2008). On the other hand, oil and gas fields are commonly found in plain areas (low terrain to offshore). This condition offers different challenges than geothermal environment.

Additionally, the most important physical feature of the geothermal environment is the presence of geothermal manifestations. The presence of manifestation could add challenges to the drilling operation especially for infrastructure preparation (Utami, 2010; Purba D. , et al., 2020). **Figure 2** shows the comparison between geothermal drilling environment and petroleum drilling environment, where the notable difference is the terrain condition (Utami, 2010; Zou, et al., 2013).

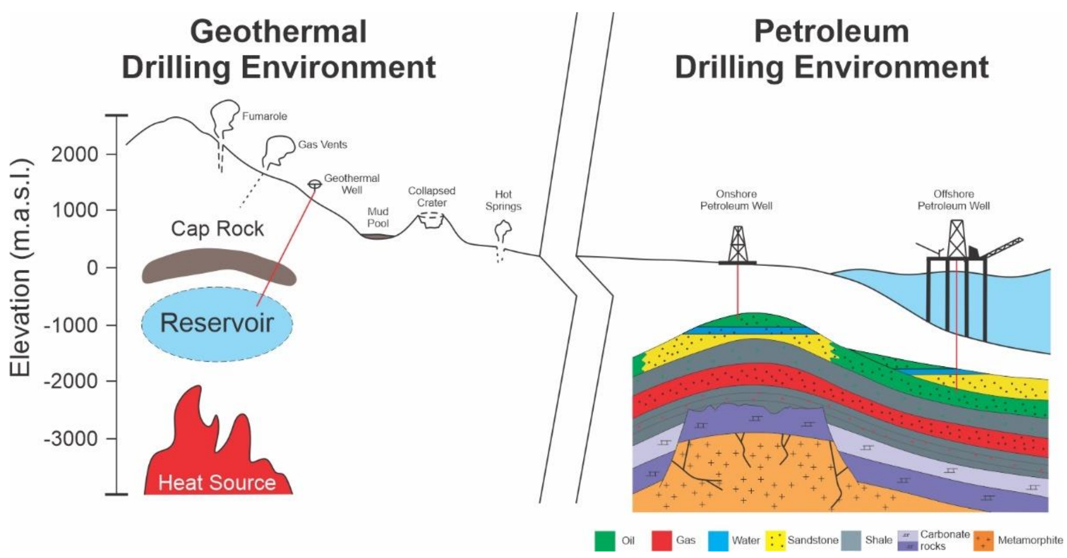

Figure 2: Simplified illustration comparing geothermal and petroleum system (adapted from Utami, 2010 and Zou et al., 2013)

Other important aspects of drilling related to the surface conditions is the availability of the water source to support drilling operations. As oil & gas drilling is not required to drill in severe loss circulation conditions (any loss circulation encountered is expected to be cured before proceed drilling), it requires significantly lower quantity of fresh water (assuming the drilling fluid is using water-based mud). Onshore oil & gas field typically lie in relatively flat area surrounded by many water sources such as creeks, springs, and even sea.

While in geothermal drilling it requires a lot of water during drilling in highly-fractured zone (Adityatama, et al., 2020; Alamsyah, et al., 2020), and typically it is difficult to get a suitable water supply (in terms of quantity and water properties such as pH, TDS, etc) due to mountainous area . Therefore, more considerations regarding water supply need to be put in place during geothermal drilling planning compared to oil & gas drilling. Table 2 shows the summary comparison between geothermal and oil/gas well surface conditions.

Table 2. Comparison of surface condition between geothermal and oil/gas well.

	Geothermal	Petroleum
Terrain	Mountainous area (high relief terrain) (i.e Indonesia, The Philippines, etc.); Plain area (low relief terrain) (i.e., New Zealand, Iceland, etc.)	Plain area (low relief terrain to offshore)
Slope	Steep condition	Flat to moderate
Surface geohazard	Landslide, volcanic eruption, gas with high temperature zone, flash flood, hydrothermal explosion, soft ground, and toxic gas	Onshore: flood Offshore: heavy weather, high tides, unconsolidated seabed
Water source for drilling	Typically difficult to obtain suitable water for drilling, both in terms of quantity / flow rate and properties (pH, TDS, etc) due to the site associated with volcanic area.	Relatively easy to get water source from river, sea, spring, etc. The water quantity requirement for oil and gas drilling also considerably less than geothermal drilling.

3.2 Subsurface Aspect Comparison

3.2.1 <u>Subsurface components</u>

The differences in the subsurface environment between geothermal and petroleum from their components are described below:

- **Source:** the source in geothermal refers to heat source from intrusion, elevated heat flow such as in extension domain, and water pressured in great burial depth (Moeck, 2014) while source in petroleum refers to rocks rich in organic matter (e.g., shale and coal) that will generate hydrocarbon after maturation (Selley & Sonnenberg, 2014).
- **Fluid migration:** commonly in geothermal, fluid came from meteoric water in surface, migrates to reservoir, then turn into hot fluid and circulate through permeable rock or creating manifestation in outflow zone. In petroleum, fluid migration was caused by expulsion from source rock to reservoir and then stop when encounter a trap or creating seepage in the surface.
- **Reservoir:** reservoir in geothermal has a function as a heat sink and stored the hot fluid. The formation of geothermal reservoirs at equal depths is hotter than sedimentary formations from most oil and gas reservoirs with temperatures from 160 °C to above 300 °C. According to Finger & Blankenship (2010), the common rock characteristics in geothermal reservoir is hot, hard, abrasive, cracked heavily and under pressure. These rocks are mainly volcanic rocks such as granite, granodiorite, quartzite, greywacke, basalt, rhyolite, and volcanic tuff since most of geothermal prospects were associated with volcanic environment. Reservoir pressure in geothermal is usually inferior or may be lower than hydrostatic pressure compared to hydrocarbon reservoirs because the stored fluid is still in liquid or steam phase. Pressure will form when the liquid phase turns into gas. In a petroleum system, reservoir is mostly sandstone and carbonates, functioned to store hydrocarbon. Hydrocarbon usually exists at a depth of 3,000 – 4,000 meters, but the depth of the oil well can be more than 6,000 meters, while the temperature in the reservoir increases as depth increased to more than 200ºC (Devold, 2013). Reservoir pressures in oil and gas drilling can be very high due to compaction effects, diagenetic effects, differential density effects and fluid migration effects (Bourgoyne & Holden, 1985). Devold (2013) explained that the pressure from the oil and gas reservoir can reach 90 Mpa.
- **Capping:** clay cap in geothermal system is the result from interaction of hot fluid and the surrounding rock. The interaction will alter the composition of rocks, creating conductive, impermeable, and low resistivity (<10 ohm-m) layer that can prevent hot fluids from escaping the reservoir (Cumming, 2009). In petroleum system, the capping mechanism is called seal. It can form as the top, bottom, or lateral seal to avoid fluids to migrate beyond the reservoir. Commonly it's a shale or evaporites (halite, anhydrite, etc.).
- **Trap:** trap component is not applicable for geothermal system. In petroleum system, trap is a geometry combination of reservoir and seal. This geometry will cause accumulation of hydrocarbon in subsurface. There are structural and stratigraphic traps, and/or combination of both. Structural traps are formed by deformation of reservoir rock, such as anticline and fault, while stratigraphic traps are formed by deposition of reservoir rock, such as reef and unconformity. Most of the trap in petroleum is structural, especially anticlines (Hyne, 1984).

3.2.2 <u>Target characteristic</u>

In terms of drilling targets, the differences that can be defined as follows:

- **Rock formation:** geothermal regions are formed due to tectonic pressure which results in wide range of faults and fractures. The presence of fractures shows great permeability, but often causes loss of circulation, which is a major problem in geothermal drilling. Fractures can also extend naturally and may also form during drilling because of the pressure on the hole and can occur throughout the wellbore. Thus, the main differences in geothermal drilling and petroleum drilling are geological complexity in the environment of geothermal reservoirs and poor geological map clarities that make exploration drilling for geothermal development wells relatively blind (Tilley, et al., 2015). In addition, poor interconnection of geothermal rocks and hard volcanic igneous rocks that may exist from the surface to total depth will affect bit selection and penetration rate (ROP). As a result, drilling equipment for oil and gas exploration will not provide the same results in geothermal exploration (Capuano, 2016).
- **Reservoir pressure:** the use of mud as drilling fluid in geothermal drilling may not be feasible due to sub-hydrostatic pressure in the reservoir. In addition, mud can cause significant damage to formations by reducing permeability if the mud is lost to productive fractures. Therefore, it is recommended to use compressed air, soda water, or mixed mud as drilling fluid for geothermal drilling (Capuano, 2016).

- **Reservoir temperature:** high temperature factors in the geothermal environment pose challenges in drilling and other geothermal operations and must be included in the design of geothermal development (Tilley, et al., 2015). High temperatures from the geothermal reservoir can also cause the temperature of the drilling fluid to rise when returning to the surface. Therefore, the quality and durability of cementing, casing, drilling equipment, materials and other equipment must be able to withstand this temperature. The difference between geothermal wells and oil wells is that geothermal drilling is characterized by high bottom hole temperature. It is usually higher than 150°C, and even higher than 300°C in hot dry rock formations (Delong, Hun, Yuwen, Wei, & Wenjian, 2014).

The comparison of subsurface conditions between geothermal and oil/gas wells is summarized in **Table 3** (modified from Umam et al., 2018).

Table 3. Summary of comparison between petroleum and geothermal subsurface system (modified from Umam et al., 2018)

Parameters	Petroleum	Geothermal
Source	Matured high organic content rock	Shallow intrusion, plutonic body, magma chamber
Fluid migration	Vertical and lateral	Vertical and lateral
Capping/sealing	Impermeable formation (shale)	Clay cap, steam cap
Trap	Stratigraphic and/or structural trap	Not applicable for geothermal system
Rock Formation	Mostly sandstone/mudstone, sedimentary layer, several areas also penetrate the basement rock (granite)	Mostly igneous and hard metamorphic rock (e.g., andesite, rhyolite, diorite, metasediment etc.)
Reservoir Pressure	High (can reach 90 MPa)	Relatively low, might be lower than hydrostatic pressure
Reservoir Temperature	May reach up to 200°C, but mostly relatively low	Mostly high temperatures (approximately 160°C to above 300°C)
Drilling Fluid	Bentonite blends	Mostly using water, aerated mud or water with air or nitrogen mixture due to severe lost circulation encountered
Drilling Bits	Typically, Polycrystalline Cutter (PDC)	Roller cone or drag bits, impregnated diamond bits
Drilling Orientation	Vertical, deviated, horizontal	Usually vertical or J-shaped, horizontal drilling is unlikely
Casing	Perforated production casing	Pre-perforated of the pre-slotted liner, large diameter casing
Cementing	Protecting the casing from hydrocarbon corrosion	Limit casing transformation/deformation due to high temperature, prevent thermal fatigue
Completion	Perforating and swabbing with NaCl saltwater	Slotted liner installation and swabbing with brine or stimulate using air

3.3 Subsurface Hazards During Drilling

Based on the comparison in Table 3, a comparison of drilling hazards can be made between the two environments (**Table 4**). The likelihood value in the table is a collective assessment of the authors based on personal experience and literature study.

Table 4. Comparison of subsurface hazards likelihood in geothermal and petroleum well

No	Subsurface hazard	Explanation	Petroleum well (likelihood)	Geothermal well (likelihood)	References
1	Loss circulation	The phenomenon where large amount of drilling fluids flow into the formation under the effect of pressure difference	2	4	(Guan, Chen, & Liao, 2021)
2	Swelling clay	Clay swelling occurs when the clay is exposed to aqueous solutions having a brine concentration below the critical salt concentration. Clay swelling can cause reduction of hole diameter, resulting in stuck drill pipe or failure in running the casing.	2	4	(Khilar & Fogler, 1983; Finger & Blankenship, 2010)
3	Acidic environment	An immediate area or enclosure with pH below 7.0 can precipitate premature cement degradation or corrosion to equipment.	1	3	(Corrosionpedia, 2018)
4	Paleosol	Paleosol is ancient soil that formed in the past landscapes. Flood debris, landslides, volcanic ash, and lava have buried most paleosol in the sedimentary record. Paleosol in some cases contain a large proportion of smectite clay. Smectite is inert, but when disturbed by drilling	2	2	(Gunderson et al., 2000; Retallack, 2014)

No	Subsurface hazard	Explanation	Petroleum well (likelihood)	Geothermal well (likelihood)	References
		especially with freshwater, it will become physically unstable.			
5	Steam cap	A vapor-dominated zone overlying a liquid-dominated zone. The steam cap presents hazardous high temperatures if not anticipated by early detection.	1	2	(Grant & Bixley, 2011)
6	Unstable formation	Sediment that is loosely arranged or unstratified (not in layers) or where particles are not cemented together (soft rock) and unstable rock layers formed by hydrothermal alteration are prone to sloughing. Sloughing can create significant washout which complicate drilling and cementing.	3	4	(OWP, 2019; Meller & Kohl, 2014)
7	Gas trap	Natural gas accumulation at abnormal pressure which exists in shallow burial depth under the seabed and does not have the value for industrial exploitation. Trapped gas is often flammable.	4	2	(Ren, Liu, Huang, & Zhang, 2019)
8	Abrasive formation	The cuttings from the rock formation, produced by the action of a drill bit, are hard, sharp-cornered, angular grains, which grind away or abrade the metal on bits and drill-stem equipment at rapid rates. The abrasiveness of formation is usually measured by quartz content. Higher quartz content represents higher abrasion risk.	2	4	(Mindat, 2021; Wheeler, 2018)
9	H_2S	Hydrogen sulfide is colorless, flammable, and extremely hazardous gas, found in both petroleum and geothermal wells. In a petroleum reservoir, H_2S is formed as a natural by-product of organic material decomposition while it is sometimes found in gas zones above a geothermal reservoir. This gas can cause corrosion and safety risks.	3	4	(OSHA, 2005; Finger & Blankenship, 2010)
10	High temperatures	High temperatures can alter drilling fluid properties and its additives.	1	4	(Finger & Blankenship, 2010)
1: less likely, 5: most likely					

As described in Table 4, geothermal drilling is more likely to encounter total loss circulation and high temperature, while the occurrence of encountering gas trap and abnormal pore pressure such as in oil & gas drilling is relatively rare. Subsurface hazards in geothermal well drilling also more likely to be associated with formation fluid chemistry and rock stability. This is also related to the difference between petroleum and geothermal system, where the target of geothermal drilling is more complex because it is targeted to a zone with high temperature and highly fractured formation. Those conditions can harm drill bits, causing lost circulation, and thus bring difficulties to the drilling process (Finger & Blankenship, 2010).

To mitigate possible geological hazards, it is important to plan a countermeasure strategy for all subsurface hazards both for petroleum and geothermal well drilling. Various subsurface fluid and rock formation conditions such as salinity, rock stability, geological structures, etc. should be considered first before installing drilling equipment in the field. In terms of drilling, casing and wellhead installation should be adapted to the subsurface condition, the drilling fluid should be kept to prevent reservoir invasion but could support well integrity, and pressure monitoring must be carried out carefully (Heijnen et al., 2015).

4 POSSIBLE CAUSES OF “KICK”

4.1 General Overview of the Causes of Kick

A kick is a situation when the formation fluid flows into the wellbore during the drilling operation. Mainly, this condition occurred due to there being no sufficient hydrostatic pressure from the wellbore against the formation pressure (Schlumberger, 2021; Watt, 2017). Kick occurrence is not only consequential to the lost time of drilling operation but also may lead to more fatal conditions known as blow out that endangered rig, crew, and environment if the kick was not identified and controlled properly. According to Abardeen Drilling School (2002), Saudi Aramco (2002), and Grace (2003), several possible causes of kick are:

4.1.1 Failure to fill the hole

This condition may reduce the capability of the wellbore to stabilize the formation due to the insufficient amount of drilling fluid on the wellbore as a source of hole hydrostatic pressure. The failure could happen when the drilling string is tripping out of the hole so there is an additional volume that must be covered by drilling fluid, but the crew is not aware to fill up the drilling fluid volume and monitor displacement during the drill string trip (Schlumberger, 1999; Saudi Aramco, 2002; Abardeen Drilling School, 2002; Grace, 2003). Moreover, the trip also must be evaluated to keep the formation in stable condition if there is an indication of a problem. Failure to fill hole condition is illustrated in **Figure 3**.

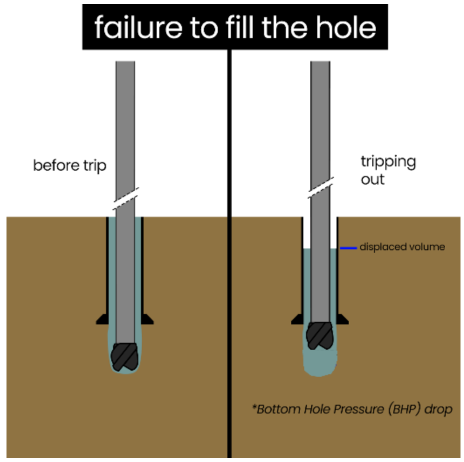

Figure 3: Illustration of failure to fill hole condition

4.1.2 Swabbing and surging

When it was pulled out of the borehole, the drill string may reduce the formation pressure on the bottom hole and create a vacuum effect that allows formation fluids to enter the wellbore which is known as swabbing (Saudi Aramco, 2002; Abardeen Drilling School, 2002). Even if it is hard to identify swabbing, the action needs to be executed immediately after swabbing is detected to prevent further decreasing of hydrostatic pressure that triggers the flow of the well. For geothermal environment, an increase of reservoir pressure may be caused by the absence of drilling fluid (i.e., cold water) during tripping out that creates steam kick which reaches the surface facility (Bayustika, 2018). According to Schlumberger (1999) and Rigtrain (2001), several factors that may induce swabbing are high-speed trip out, high viscosity mud, and tight hole clearance.

While the surging occurs during running in a borehole, the drill string with uncontrolled speed would lead to increase of the pressure to drilling fluid. The accumulation of the pressure could exceed the formation fracture pressure on the bottom hole and crack the formation, so the drilling fluid can be lost to the formation. This condition may decrease hydrostatic column and pressure, then can be followed by the kick from the formation (Aberdeen Drilling School, 2002; Grace, 2003). Swabbing and surging conditions are illustrated in **Figure 4**.

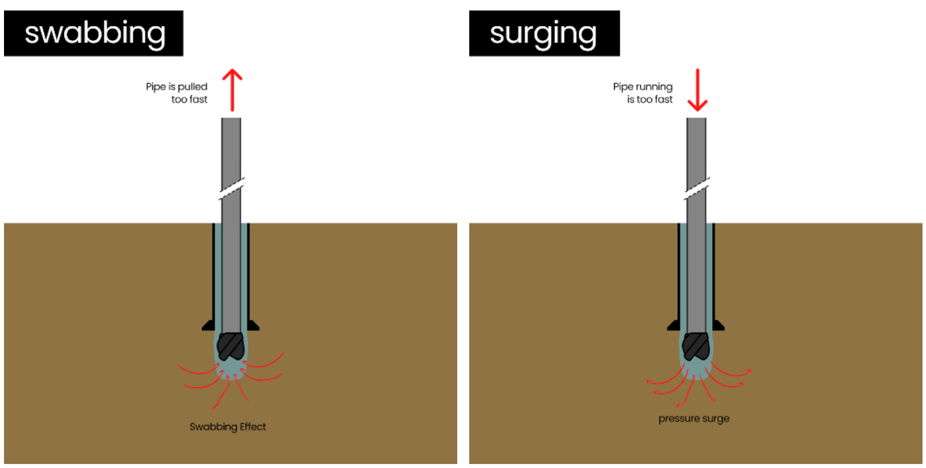

Figure 4: Illustration of swabbing (left) and surging (right) conditions

4.1.3 Lost circulation

Lost circulation naturally occurs when the drilling penetrates high permeability zone such as fault-fracture zone, dissolved carbonate, or clean sandstone formations that allow drilling fluid to infiltrate the formation too far. For geothermal environment, the fault fracture zone and highly altered rocks act as high permeability sections. It also occurs by induced conditions such as an overly high mud weight.

There are two general types of lost circulation, such as 1) partial loss circulation that still has some mud returns on the circulation and 2) total loss circulation that results in complete loss of the mud (Umam, Susilo, Purba, & Adityatama, 2016). Since the drilling fluid is lost to the formation, the hydrostatic pressure on the wellbore would be decreased and failed to balance the formation pressure. It induces the influx from the formation into the wellbore. Drilling in the geothermal reservoir section generally faces the total loss condition. During the drilling in total loss condition, water column can only cover a small portion of the hole, so the shallower feed zone that are not cooled down can produce the steam kick due to excessive temperature rise (Bayustika, 2018). Lost circulation condition is illustrated in **Figure 5**.

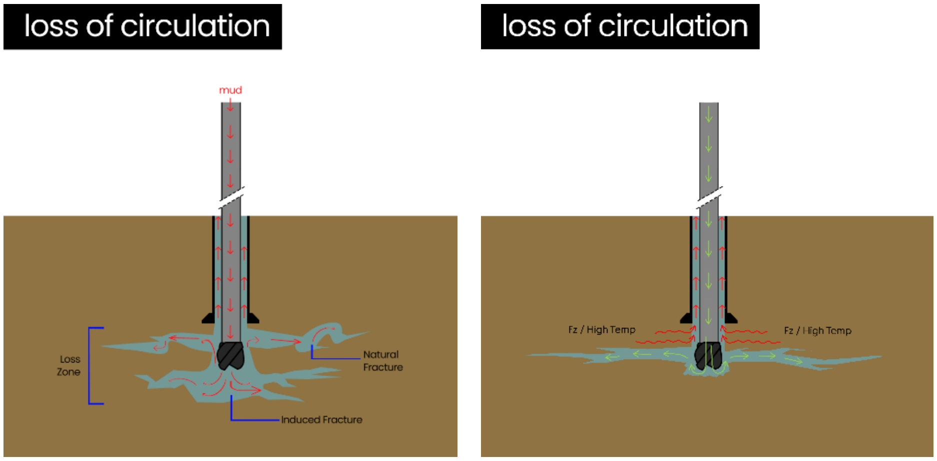

Figure 5: Illustration of lost circulation condition (left) and lost circulation with high temperature section (right).

4.1.4 Insufficient mud weight

This condition could lead to insufficient hydrostatic pressure that should be provided by the drilling fluid to support drilling operation. The change of mud weight may occur due to accidental dilution or contamination from low density fluid **(**Rigtrain, 2001; Saudi Aramco, 2002). For oil and gas, the gas cutting could have an effect to density and hydrostatic reduction that initiate the kick. While the oil and saltwater cutting also creates the reduction, it is not as significant as gas cutting since the density is greater than gas (Saudi Aramco, 2002; Abardeen Drilling School, 2002)**.** Insufficient mud weight condition is illustrated in **Figure 6**.

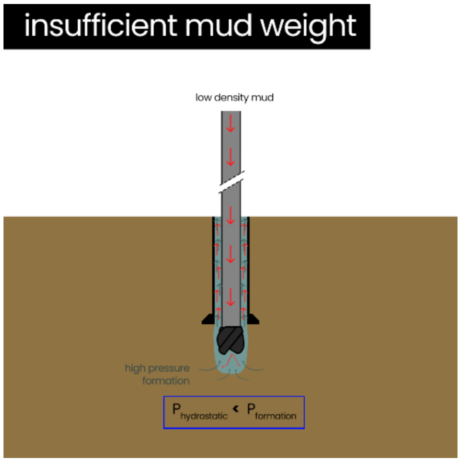

Figure 6: Illustration of insufficient mud weight condition

4.1.5 High temperature zone

Drilling at high temperatures environment poses several challenges such as the degradation of the drilling fluid properties, and in geothermal drilling case, may heat the drilling fluid into high enough temperatures that can flash when reaching surface. The drilling in high temperature zone is illustrated in **Figure 7**. Therefore, in geothermal drilling it is important to closely monitor the temperature of the drilling fluid, both the temperature-in and the temperature-out (Finger & Blankenship, 2010).

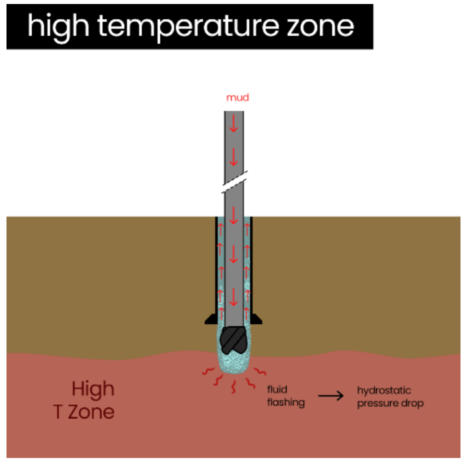

Figure 7: Illustration of high temperature zone condition

4.2 Early Identification of a Kick

4.2.1 General Kick Identification

It is important of a kick to be early detected to prevent the kick scale up into blow out. According to Saudi Aramco (2002) and Grace (2003), there are several early identifications of kick in petroleum such as:

- Increasing fluid volume, flow rate, and temperature after circulated from downhole.
  The increase of monitored outflow mud volume and rate may result in influx of the formation fluid or presence of gas on anulus if there is no added mud material. Since the increase of mud volume may also occur due to changing of mud system, any changing of mud system must be recorded and informed to driller to avoid miss-interpretation that led to unnecessary action (Saudi Aramco, 2002). In high temperatures zone, the presence of high temperatures formation fluid also would increase the mud temperature significantly (Finger & Blankenship, 2010). Those are categorized as primary indication of kick, so the driller should perform well shut in immediately after the indicators were observed (Saudi Aramco, 2002).
- Significant increase of rate of penetration (drilling breaks).
  Drilling breaks occur when the rate of penetration increasing significantly without any changing on Rotation per Minute and Weight on Bit in similar rock formation as indication of porous-permeable zone (Schlumberger, 1999; Saudi Aramco, 2002). The presence of porous and permeable zone may lead to lost circulation and induce the kick. Since many factors may lead to drilling breaks, usually the pump would be shut off immediately to observe the flow from the well to confirm the presence of kick (Saudi Aramco, 2002; Abardeen Drilling School, 2002).
- Decreasing circulating pressure.
  The presence of hydrocarbon kick would affect the mud density to became less dense than mud program which led to decreasing of circulating pressure. This event also may be induced by the washout (Saudi Aramco, 2002). The difference of both conditions was shown when the mud pump be shut downed. If the flow is continued, it means the source of the pressure came from the formation and indicates presence of kick (Saudi Aramco, 2002).
- Increasing gas reading.
  Gas reading record the presence of gas on drilling fluid where it may indicate the presence of formation influx. There are several possibilities that caused the increasing mud reading such as penetration of gas formation, temporary swabbing, and presence of porous formation (Aberdeen Drilling School, 2002). The increasing of gas reading should be monitored and correlated with other indications to avoid misinterpretation.

4.2.2 Kick in Geothermal Drilling

Geothermal well has different characteristics with the oil and gas well (Finger & Blankenship, 2010; Umam, Purba, & Adityatama, 2018). According to Finger and Blankenship (2010), the kick occurrence on geothermal well could be detected from mud flow volume. The increase of trip tank level indicates the presence of formation influx. However, the trip tank level decrease should also be carefully monitored, as the loss circulation could induce the kick as described in the previous section (**Possible Causes of "Kick"**). Furthermore, the constant monitoring of wellbore temperatures through mud temperature is critical since significant temperature increase of the drilling fluid may lead into kick in geothermal environment (Finger & Blankenship, 2010).

One example of geothermal well control incident occurred on Well "X", Java, Indonesia. The well "X" is a directional exploration well with the objective to confirm the resource presence and obtain the productivity of a high enthalpy liquid dominated geothermal field. The schematic of the Well "X" is as shown on **Figure 8**. When the drilling was continued to 17 ½" intermediate hole using 8,8 ppg KCL polymer mud, the decrease of return and increasing dynamic fluid loss was observed with output fluid temperature on pit was observed to reach very high temperature, up to 200^{o}C according to the internal report[1]. The kick was detected by the presence of steam flow during tripping out. Well control was then done by closing the annular BOP (unable to close the 5" pipe ram as the 6-1/2" drill collar was in

[1] Authors acknowledge that the temperature stated in the report is considered to be very high to be observed in the trip tank, and is unlikely to happen unless the fluid flowing in the trip tank was already in the form of steam.

place) and continuous pumping through the string and annulus while monitoring the pressure and temperature. However, the annular BOP leaked, and the blowout occurred. The blowout was controlled after the pipe ram in the BOP can be closed (after the string was lowered), the flow stopped after the wellbore was finally cooled by the continuous pumping and the casing pressure reached 0 psi. Bull heading with the kill mud (8.8 – 9.2 ppg; barite-KCL-Duovis pill)[2] followed by plugging the well with cement to further secure the well before commencing sidetrack.

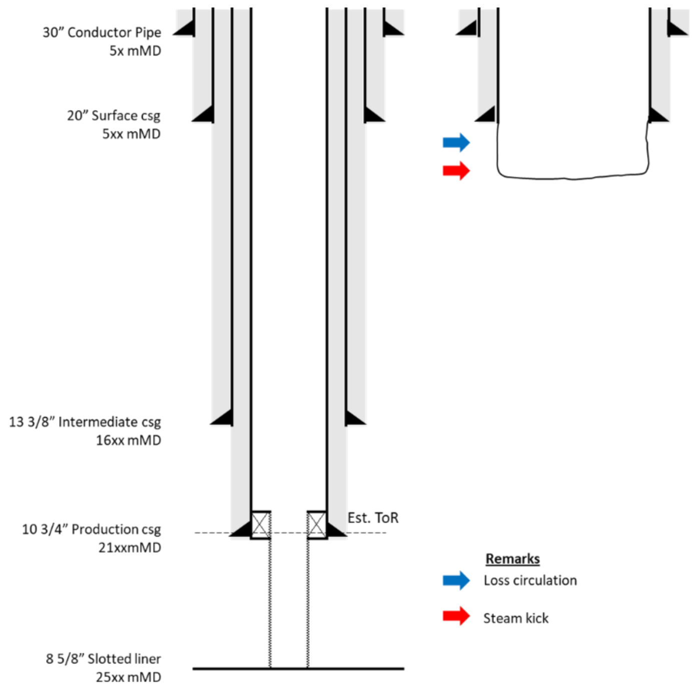

Figure 8: Left: The original schematic of well "X". Right: The well depth during drilling when the kick and blowout occurred. The red and blue arrow indicates the depth of steam kick and loss circulation respectively.

The kick (and subsequently blowout) on the case above failed to be anticipated due to there is no indication of shallow steam zone from previous wells. The increasing mud return temperature was also apparently not followed by increasing the pump rate both from string and annulus to cool down the well. If the recorded temperature of the mud return was able to reach 200 °C, then it may had been too late, as the hot drilling fluid may have flashed once reaching the surface, and further reduce the hydrostatic column in the wellbore as described by Finger & Blankenship (2010). The rubber on the annular BOP has limited working temperature that will fail if exposed to prolonged high temperature condition as in the geothermal well control event.

One of the lessons learned from the accident was to update the well control procedure to be more suitable for geothermal environments and increase the awareness for early kick detection such as increase in mud return temperatures and pit gain. The accident showed that the origin of the formation pressure in geothermal environments is different from oil and gas, and therefore may require different approaches of well control. The drilling personnel involved in the operation should be aware of those differences and thus should be able to identify for any early warning of a kick such as the sudden increase of mud return temperature and act accordingly to prevent blowout.

4.3 Well Control Method in Oil & Gas Drilling

Well control on drilling operations has objective to prevent the influx from formation (Finger & Blankenship, 2010). If the influx occurred, the well control must be performed to sweep out the influx of formation fluid and kill the well to prevent further influx from formation, so the drilling operation could be start normally (Aberdeen Drilling School, 2002). There are three main methods of well control during the drilling process such as driller methods, weight & wait methods, and concurrent methods (Rigtrain, 2001; Abardeen Drilling School, 2002). The first two method would be described below since those are the most basic and general well control methods, while the concurrent method is combination of both method (Aberdeen Drilling School, 2002).

1.Driller methods

Driller method is the simplest well control due to the simplicity of arithmetic calculations on small onshore well and highly deviated well. Generally, this method kills the well using minimal two circulations with difference in mud weight. The first circulation uses the recent mud weight with purpose to circulate the kick to surface, while the second circulation would apply heavier mud weight to kill the well (Abardeen Drilling School, 2002; Grace, 2003). If the kick does not sweep out on the first circulation, the circulation would be repeated until the kick has completely swept out of the well. **Figure 9** shows the illustration of driller method.

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[2] The purpose of bullheading with barite after the casing pressure is already zero after cooled with water was unexplained in the internal report.

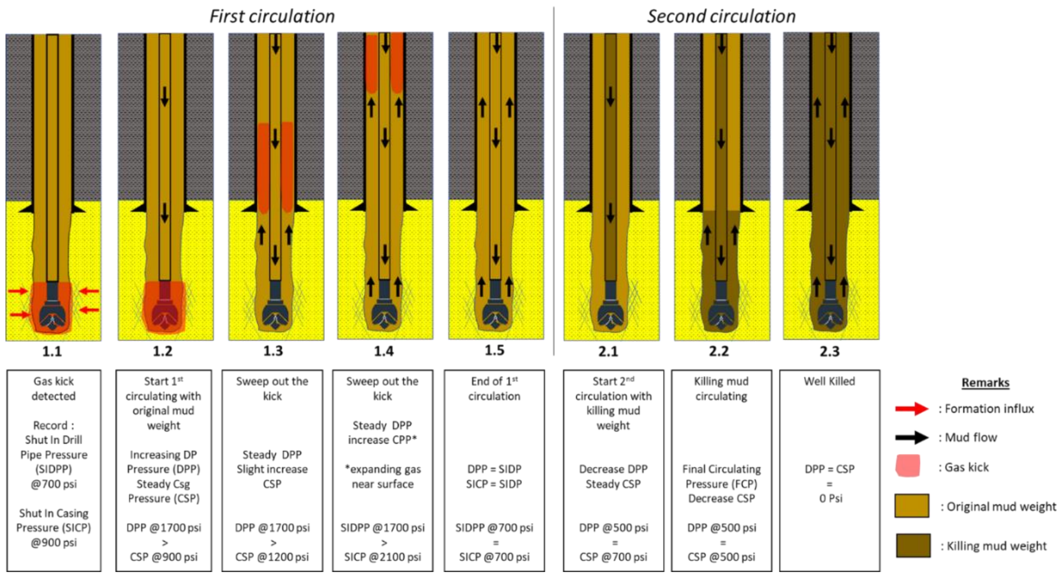

Figure 9: Driller method well control (adapted from Abardeen Drilling School, 2002; Saudi Aramco, 2002; Grace, 2003)

2.Weight and wait/engineers' methods

This method by theory uses only one full circulation to sweep the kick and kill the well with heavier mud weight. When the kick was detected, heavier mud would be prepared on mud pit and pumped to the well using kill pump rate with adjustment on the drill pipe pressure. This circulation continues until the well shut-in and surface pressure equals to zero (Grace, 2003). **Figure 10** show the weight and wait methods.

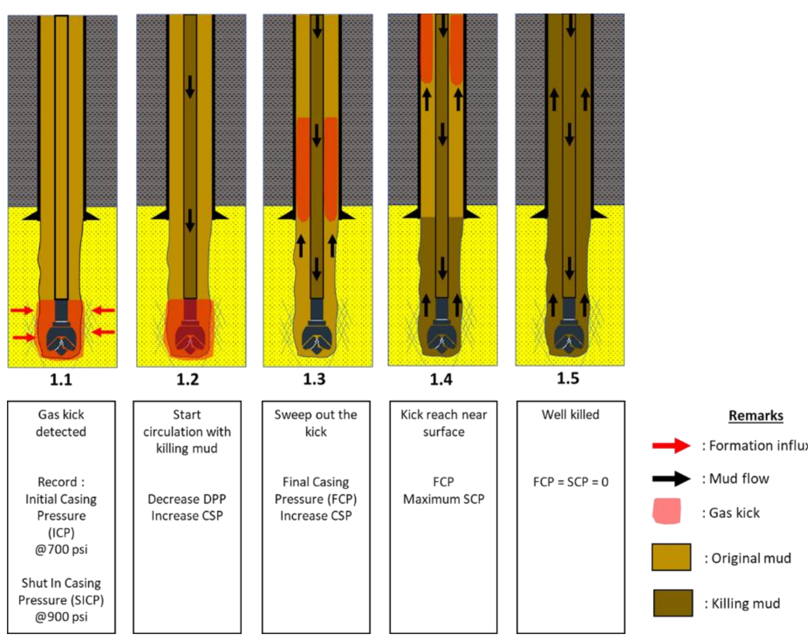

Figure 10: Wait and weight method well control (adapted from Aberdeen Drilling School, 2002; Saudi Aramco, 2002; Grace, 2003)

3. Concurrent methods

In the concurrent method, the mud will be circulated in and weighted up in stages towards the kick fluid that will be circulated out. As the kick is shut in and the pressure has been read, the mud will be pumped according to the required density. The circulated mud will reach the kick depth, then the pressure in drillpipe will be adjusted to hydrostatic pressure of the new mud weight. In addition, concurrent method need to be adjusted to the amount and type of kick fluid, capabilities and equipment on the rig, and the minimum pressure in the well (Omosebi, Osisanya, Chukwu, & Egbon, 2012).

4.4 Well Control Equipment and Material Limitation in Geothermal Drilling

In addition to the hydrostatic pressure of the fluid, the Blow Out Preventer (BOP) is the main equipment used to control the pressure in the borehole during drilling. This well control technology has been applied for a long time in the petroleum industry and has been adapted by the geothermal industry. However, there are several points that need to be considered when adapting the petroleum well control method for use in geothermal wells which can be described as follows.

4.4.1 Temperature Rating

As discussed in the previous chapter, geothermal wells tend to be exposed to higher fluid temperatures than petroleum wells. When the kick occurs, usually geothermal fluid will flow faster to the surface than the circulation speed of the drilling fluid to cool (Delong et al., 2014). This shows that the BOP equipment used in geothermal drilling must have a higher temperature property. The design of all well control equipment in geothermal drilling should be based more on the temperature factor rather than the pressure aspect.

4.4.2 Fluid Material and Availability

Most cases of well control in petroleum are associated with greater gas pressure than the hydrostatic column in the borehole. To overcome the pressure deficit at the bottom of the hole, generally the driller will increase the weight of the mud so that the formation fluid pressure (gas/oil) can be balanced or countered. The implication of this method is that the rig site team must prepare a sufficient stock of mud weighting agent material to anticipate the well control situation. The process of increasing the weight of the mud can be carried out while the well is being shut-in using BOP. The water supply requirement can be estimated based on the required kill mud volume to fill the borehole plus a margin, based on company policy.

As for geothermal drilling, the fluid pressure formed in the borehole is the product of an increase in fluid temperature so that the method used will be different from the well control principle in petroleum wells. The formation fluid (hot steam) will lose its pressure when there is a decrease in temperature. This means that the driller must have the ability to pump cold water into the wellbore to lower the fluid temperature and eventually eliminate the kick in the well. This well control method requires a continuous water supply, an adequate and reliable pump, and a sufficient BOP temperature rating.

5 DISCUSSION ON THE DIFFERENCES BETWEEN OIL & GAS AND GEOTHERMAL WELL CONTROL METHOD

After discussing the differences in the subsurface characteristics between the two environments above, an analysis of the differences in kicks can be carried out. From the well control aspect, there is a significant difference between geothermal and oil & gas, mainly on the type of formation fluid encountered. In the case of oil and gas drilling, the formation fluids that will be anticipated are generally flammable gas and tend to be in high pressure.

Downhole formation pressure in geothermal generally comes from permeable zones connected to reservoirs containing steam or hot water and is highly dependent on local temperature (Bayustika, 2018). During drilling, the process of the formation temperature increase in the borehole is inhibited by pumping or injecting cold water into the borehole continuously. Since the temperature is not increasing, the fluid pressure at the bottom of the hole also does not increase so that the drilling process can continue safely because the "steam kick" is never formed. Meanwhile, in petroleum drilling, the fluid inside the formation already has pressure that is more influenced by the overburden pressure of the rock above it, not by the temperature of the reservoir.

Well control is usually carried out by keeping the hole full of mud with enough hydrostatic pressure, which slightly exceeds the formation pressure. Whereas in geothermal drilling, the formation fluid is in the form of hot water or hot steam. When cold water is injected into the hole, there will be a decrease in temperature followed by a pressure drop until finally, the well is killed. Those differences in formation fluid characteristics make well control techniques or methods used in both drillings are different.

One major difference of the well control method is that in oil and gas drilling, the gas influx from the formation should be circulated out of the hole before killing it by introducing heavier mud into the wellbore, while in geothermal drilling the steam kick is mitigated by keeping the wellbore cool by continuously pumping cold water from the string and annulus. The mud temperature in geothermal drilling should also be carefully monitored as the drilling fluid itself can be hot enough to flash once reaching the surface and may cause chain of events that leads to blowout.

The reason of those difference is that in oil & gas drilling, the influx is typically in the form of hydrocarbon gas. The gas itself once entering the wellbore will not disappear unless if it is pushed back to the formation or circulated out of the wellbore. While in geothermal drilling, the influx is typically in the form of steam caused by the high temperature that cause water to flash. Once the cold water is introduced to the wellbore to cooldown the well, the temperature decreases and the steam condenses back to the liquid form and is not pressurized.

Currently, the well control certification that available in Indonesia and the worldwide approved by International Association of Drilling Contractors (IADC) is more suitable for petroleum drilling and considered to not fully accommodated for geothermal drilling since the principal in IADC is focusing on how to circulate the gas influx out of the wellbore.

6 SUMMARY

This paper has highlighted the differences between oil & gas and geothermal drilling environment, from the typical project structure and setting to the subsurface aspects. As drilling in oil & gas and geothermal drilling uses similar equipment (and consequently personnel), people tend to assume that all the process and practices are identical between those two distinct projects. That is not necessarily true as without proper knowledge on geothermal environment, the drilling personnel may use drilling practices in oil & gas drilling that may be unsuitable for geothermal.

The fundamental differences between the two systems lie in reservoir and fluid temperatures, rock permeability and pressure, and the heterogeneity of the rock-forming systems. Due to the different environment of the petroleum and geothermal system, the causes of the well control situation are also different. The cause of kick in the petroleum well is generally the pressurized hydrocarbon which is influenced by overburden pressure. Meanwhile, the kick that occurs in geothermal drilling is commonly the result of the pressure of the steam which is strongly influenced by temperature.

The well control in oil & gas generally focuses on circulating the hydrocarbon gas influx first before killing the well with weighted fluid, while geothermal well control typically focus on cooling down the wellbore to condense the steam back into liquid water. In geothermal, if one attempts to circulate any identified kick without cooling down the well and monitoring the mud return temperature, there is a risk that the drilling fluid will be heated enough to flash into steam when reaching surface. The well control equipment such as BOP is also developed mainly for oil & gas drilling, thus the rubber elements may not have sufficient temperature rating for prolonged exposure to steam and/or hot water. It shows that the geothermal drilling personnel cannot fully rely on the BOP to isolate the well but should focus on keeping the well cool. Therefore, in geothermal drilling, the availability of a continuous supply of cold water, the ability and reliability of the pump on the rig, and an adequate BOP temperature rating are the main factors that must be considered.

Authors observed that there are few published references regarding the geothermal well control, and this may cause problems in the future if drilling personnel from oil & gas are to be working on geothermal project without proper knowledge on geothermal environment. Authors hope this paper can trigger more discussion among drilling communities especially in Indonesia and raise awareness regarding geothermal and oil & gas drilling differences.

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