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GEOTHERMAL DRILLING FLUIDS

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ABSTRACT

Geothermal well drilling is a vital part of a geothermal project after extensive surface scientific exploration and research have been done. Drilling is one of the most expensive activities of a geothermal project. In the drilling project, the circulation system takes up a part of the well cost. Making the selection of the geothermal well drilling fluid is vital to the success of the project. It is, therefore, important to select a drilling fluid that will provide the best results in terms of cost, safety, reaching the desired depth and the output of the well. Drilling fluids are required to remove cuttings from the well, cool and lubricate the bit and the drill string, and control the pressures during drilling. Various drilling fluids are selected in accordance to reservoir pressure, temperature and the drilling technique being utilized. Geothermal drilling fluids commonly used include water based mud, water only, aerated mud or water and foam.

This report discusses the classifications of geothermal drilling fluids, their functions and properties, drilling fluid equipment and loss of circulation policy. The paper also discusses the environmental issues that come into play when using these fluids and a case history analysis of two wells, one from Iceland and another from Kenya.

1. INTRODUCTION

Drilling fluids are any fluids which are circulated through a well in order to remove cuttings from a wellbore. The fluid is pumped down the drill string, through the nozzles of the bit, and returns back up the annulus between the drill string and the wellbore walls, carrying the cuttings produced by the bit action to the surface. The main function is to clean the hole while drilling but the drilling fluid also serves to cool the bit, provide power to the mud motor and measuring-while-drilling (MWD) tool, support the walls of the hole and control the well pressure (prevent the well from flowing). An alternative method is called reverse circulation, where the flow of the fluid is reversed from the previously mentioned one (Finger and Blankenship, 2010).

Geothermal drilling fluids can be air, a liquid or a mixture of both. Air is highly compressible and its volume is dependent on the pressure and temperature. On the other hand, liquids are only slightly compressible, and their volume is only slightly dependent upon temperature (Finger and Blankenship, 2010).

Large borehole volumes and frequent lost circulation means that the drilling fluid consumption can be high and thus expensive, especially when drilling mud is used. The pressure drop of the fluid as it flows through the drilling string and up the annulus results in high pumping pressures. The high pumping pressures combined with the large flow rate means that geothermal drilling fluids have a significant impact on fuel cost; hence, a balance should be reached between cost and effectiveness of the drilling fluid.

2. LITERATURE REVIEW

There are many papers on the subject of drilling fluids, but they are primarily oriented towards petroleum drilling. There are some papers on geothermal drilling fluids, but biased towards drilling mud and the modifications and treatments done to it for use in drilling high temperature reservoirs. Some of the more specific papers are highlighted in the following paragraphs.

Hagen Hole in 2008 highlighted drilling fluids commonly used for the drilling of geothermal wells, and the advantages and disadvantages of each (Hole, 2008). He also briefly discussed slip velocity and the results expected from different wells when particular fluids were used in drilling the production zone.

In 2006, Hagen Hole in his United Nations University Geothermal Training Program (UNU-GTP) lecture notes on geothermal drilling and direct uses, described aerated drilling for geothermal wells. He pointed out that aerated drilling can be used to solve some of the drilling problems in reservoirs with a low water table. He further noted that aerated drilling allows full circulation, hence better hole cleaning and a better chance of reaching the target depth. He also reported on improved productivity of wells drilled with aerated fluids in the open-hole section due to less formation damage. Samples can be collected at the surface for geological analysis.

In a paper by Ísleifur Jónsson in 1975, the use of water for geothermal drilling was described for the first time. The well cleaning was adequate and there was less formation damage compared to drilling with mud, one of the benefits in addition to the low cost of water. In the paper, Jonsson detailed examples from Icelandic drilling projects on the use of water and its benefits.

This report will compare the various drilling fluids used for geothermal drilling and how each impacts the effectiveness and power consumption of the rig.

3. TYPES OF DRILLING FLUIDS

Currently, there are four main types of drilling fluids in use for geothermal drilling. These are: water based mud (bentonite and polymers), water only, aerated mud or water, and air and foam. The geothermal drilling industry has evolved from the oil and gas drilling industry and, therefore, most of the equipment and materials are sourced from the oil and gas industry. The drilling fluids used in the geothermal industry are similar to the drilling fluids used in the oil industry but do not have to be treated with chemical additives to the same extent. Because most of geothermal drilling is in hard rock and there are no over-pressure problems requiring heavy mud, a rather “simple” mud can be used. Because of the heat that the drilling fluid picks up down-hole, a cooling tower is required to keep the mud from becoming too hot.

3.1 Water based mud

Fresh water is used as a base fluid in geothermal drilling mud. Geothermal brine produced from other wells is sometimes used as a base fluid. Active and inert solids are added to the mud to achieve a certain desired property, primarily to increase its viscosity and thus its carrying capacity for the rock cuttings. Active solids, clays (bentonite) and polymers, are added to the water to produce a colloidal suspension. They determine the viscosity of the mud and are known as viscosifiers. Inert solids are those added to the mud either by drilling (formation particles) or by using barite (barium sulphate) as a weighting material. These solids increase the density of the mud without significantly affecting the viscosity. High density mud is, however, seldom required for geothermal drilling. The up-hole velocity required to carry the cuttings varies as a function of the size and density of the cuttings and the viscosity and density of the mud. The up-hole velocities range from 0.2 to 0.7 m/s (U.S. Army Corps of Engineers, 2001).

a) Bentonite mud

Bentonite is the most commonly used drilling fluid additive and consists of finely ground sodium bentonite clay. When mixed with water, the resulting slurry has a viscosity greater than water, possesses the ability to suspend relatively coarse and heavy particles, and tends to form a thin cake with very low permeability on the walls of the borehole. Because of these attributes, bentonite drilling mud is superior to water as a drilling fluid for drilling large diameter holes, larger than a 12 ¼” bit. (U.S. Army Corps of Engineers, 2001). Generally, most geothermal wells have been drilled using a simple mixture of water and bentonite clay, possibly with polymer additives. These muds require little or no chemical treatment beyond pH control and some dispersant. In geothermal drilling, bentonite mud is generally of two forms: spud mud and natural mud (IADC, 1992).

Spud mud is prepared with water and the appropriate concentration of bentonite and or premium clays. Generally, spud mud is not treated chemically; however, lime, cement, or caustic soda is added occasionally to increase viscosity and give the mud a fluff to seal possible loss zones in unconsolidated surface formations and to clean holes of cuttings. Spud mud is used in drilling the surface hole. The mud tolerance for drilled solids and contaminants is very limited (IADC, 1992).

Natural mud is prepared by the addition of a mixture of bentonite and water; the required concentration of high-yield bentonite clay is only 5-7% by weight of water. Further, the mud utilizes native drilled solids incorporated into mud for viscosity, weight and water loss control. Natural mud is simple to make and control, and is used where no unexpected conditions occur. The mud stabilizes and, hence, its properties are in a range to control the hole conditions. Caustic soda is the main additive to maintain high pH of 9.5 to 10.5. Generally, natural mud is used in the drilling of the top hole to the point where there is loss of circulation (sometimes referred as the mud up point) or to conventional depths.

b) Polymer mud

Both natural (guar gum) and water soluble synthetic organic polymers produce drilling muds with desirable properties. Although the cost of most polymer additives is greater than the cost of bentonite, the lubricating quality of many polymer muds is excellent and can noticeably reduce bit and drill-string wear. As compared to bentonite mud, polymer mud often contains lower solid content. Although polymer mud may lack the gel strength which is required to suspend particles or to form a satisfactory filter cake as compared to bentonite mud, polymer mud can be pumped at much higher viscosities. Consequently, the water loss due to poorer filter cake properties is partially mitigated by reduced seepage of the very viscous mud into the formation (U.S. Army Corps of Engineers, 2001). High-viscosity polymer “pills” (a batch of a few cubic meters) are used a lot for geothermal drilling to clean the hole and keep the cuttings suspended while adding a drill pipe, when there is a total loss of circulation and water is the drilling fluid (Thórhallsson, 2011).

c) Mixture of bentonite and polymer mud
It is sometimes advantageous to prepare drilling mud composed of both bentonite and polymer with water. The low solid viscosity properties of organic polymers when combined with the filtration properties of a bentonite mud yields a mud with excellent characteristics for many applications. When the combination mud is prepared, the bentonite should be added to the water before the polymer is added (U.S. Army Corps of Engineers, 2001). This type of mud is also used to clean the drill hole of cuttings while drilling blind with water.

3.1.1 Advantages of using mud

- Drilling mud is a better lubricant than the other drilling fluids. Drilling mud cuts down on the friction, lowering the heat of drilling and reducing the risk of friction-related complications.
- Mud is a better cleaner than the other drilling fluids. Mud is viscous and therefore can lift cuttings adequately at a lower annular velocity.
- Mud forms wall cake on the walls of the borehole and hence eliminates seepage out of the borehole, thus reducing the problem of loss of circulation. Because of this, smaller volumes of the drilling fluid are consumed. The cake formed has also the effect of considerably improving the stability of the borehole. The property of lower water loss is important when drilling clay rich formations.
- There is a reduced risk of a stuck drill string: mud has lower slip velocities compared to water. When pumping through the drill string is stopped (e.g. to make a connection), any cuttings suspended in the annulus will take a longer time to settle to the bottom of the well, hence reducing the risk of stuck drill string.

3.1.2 Disadvantages of using mud

- Drilling mud is difficult to dispose of at the end of drilling. The mud cannot simply be tipped on the site.
- Bentonite drilling mud must be properly mixed, using appropriate equipment, in order to ensure that it is of the correct consistency and does not contain unmixed dry bentonite lumps, capable of clogging the borehole or the drill- string.
- Drilling mud can cause formation damage. In conventional mud drilling, mud is forced into the formation in the process called invasion, which frequently leads to formation damage. Acid stimulation is sometimes used to aid in mud removal at the end of drilling.
- When drilling using mud, the rate of penetration is lower compared to other drilling fluids, for example aerated drilling.
- Loss of circulation. Large amounts of mud can be lost before a proper mud cake forms, or the loss can continue indefinitely. Drilling mud is expensive and therefore a large loss of drilling mud increases the well's cost.
- There is a possibility of differential sticking when drilling using mud. Differential sticking is when the drill pipe is pressed against the wellbore wall so that part of its circumference will see only reservoir pressure, while the rest will continue to be pushed by wellbore pressure. As a result, the pipe becomes stuck to the wall, and can require high force and power to remove it, which may prove impossible.

3.2 Water

Water is generally a cost-effective and efficient drilling fluid which has been used in drilling operations. Water or aerated water is the preferred drilling fluid for the open hole section of the well.

While drilling using water, a rising velocity of 0.5-1 m/s should be maintained in the annulus; this is to ensure that the cuttings are carried to the surface (Thórhallsson, 2011). The drilling fluid returns through the regular mud cleaning system or is directed into a cooling/settling pond where the cuttings settle at the bottom of the pond and the water is allowed to cool. The water can then be recycled back by pumping it into the tanks. Brine from nearby wells can also be used for drilling.

Water as a drilling fluid is used to continue drilling past an unsealable loss zone and for the final production section of a geothermal well. When drilling into a permeable 'under pressured' zone, the drilling fluid circulation is lost and the drilling fluid flows into the formation rather than returning to the surface. The traditional method of dealing with this situation was to continue drilling 'blind' with water, the pumped water being totally lost to the formation with the cuttings being washed into the formation as well (Hole, 2008). Drilling blind increases the risk of getting stuck and so drilling is often cut short after some 400 m of drilling. This is not really a problem as a total loss of circulation indicates good permeability and a productive well. To reach deeper, either aerated water would have to be used or polymer pills.

3.2.1 Advantages of using water

- Reduced cost: drilling with water alone is cheaper compared to drilling using water based mud, especially when lost circulation is experienced. Drilling blind with water is cheaper compared to drilling with aerated fluids where more equipment, personnel and increased risks and costs are involved.
- Improved bit life: when drilling blind on a fractured geothermal formation, water is not re-circulated back to the surface but is lost to the formation. This significantly lowers the down-hole temperature and extends drill bit life.
- Because the maximum down-hole temperature while drilling with cold water rarely exceeds 100°C, conventional down-hole motors and even MWD equipment can be used until the total depth is reached.
- Reduced likelihood of a kick: When drilling with water a large quantity of water is lost to the formation resulting in cooling of the reservoir around the well bore during drilling. The cooling results in less likelihood of a kick.
- Improved penetration rates: when drilling blind with water or drilling with aerated water, lower bottom-hole circulating pressures are developed, resulting in improved penetration rates.
- Improved productivity of the well as compared to drilling using mud: Because mud and thick wall cake are not squeezed into permeable zones, there is reduced formation sealing; possibly, increased well productivity is achieved when water is used in drilling the production zone.
- Reduced risk of differential sticking: Because a wall cake is not developed, differential sticking does not occur.

3.2.2 Disadvantages of using water

- A large volume of water is required: A continuous large flow rate (about 3600 litres per minute for drilling a 12 ¼" hole and 1800 litres per minute for an 8 ½" hole) supply of water to the drilling rig is required, especially during blind drilling. This could be a big challenge especially for drilling projects which are far from good water sources.
- Increased risk of stuck drill string: Water has higher slip velocities compared to mud, hence requiring increased annular fluid velocities. When pumping to the drill string is stopped (e.g. to make a connection), any cuttings suspended in the annulus or accumulated in the permeable zones and cavities will start settling immediately, which increases the risk of a stuck drill string.

- No geological data: Cuttings are not returned to the surface, but washed into the permeable zones; therefore, no samples can be collected for geological analysis.
- Reduced permeability: The loss of cuttings into the permeable zones may reduce permeability (not as much as mud); this may lead to lower production.
- Long well recovery periods: Loss of large volumes of cold water to the formation can cause long recovery periods after drilling is completed before the well can be discharged.

3.3 Air and foam drilling

Compressed air is pumped down the drill-string and is a very effective drilling fluid for drilling in dry formations in arid climates, in competent consolidated rock, or in frozen ground. Down the hole hummers (DTH) are frequently used for such drilling and in geothermal drilling for the 26” surface hole, as in Iceland. To drill large holes, detergent or drilling soap (foaming agent) is added to aid in removal of the cuttings by the foam created. Foam ranges from a mist (mixture of air, foaming agent and an injection of water) to a stiff foam (consisting of a mixture of bentonite slurry and/or organic polymer, water, air and foaming agent). The foam mist is generally adequate to suppress dust, combat small water inflow, and remove sticky clay, wet sand, and fine gravel in holes with few hole problems. Stiffer foam is required as the hole diameter and depth increase, gravel or cuttings become larger, water inflows become significant, or unstable hole conditions are encountered (Ball, 2001).

3.3.1 Advantages of air and foam drilling

- In general, foam cleans the bit more efficiently, which extends its life, probably as a result of less grinding of the cuttings.
- Foam drilling is usually faster than mud drilling due in part to the increased weight on the drill bit.
- There is no differential sticking associated with mud drilling.
- Minimum well damage or erosion since low annular velocities can be used.
- No loss of circulation when the drilling is in porous or fractured formation; the expense of lost circulation of drilling muds is eliminated.
- Very low water consumption. Air is the main constituent in foam drilling.

3.3.2 Disadvantages of air and foam drilling

- Complex mixture: Foam, especially stiff foam, is a complex mixture and requires great expertise in the mixing to achieve the desired properties such as viscosity.
- There is a likelihood of soft formations collapsing onto the drill string resulting in a stuck string, since foam does not provide the hydrostatic support to the well to prevent it from collapsing.
- It is hard to collect a geological sample (cuttings) for analysis during foam drilling.
- If left unchecked, foam can be an environmental disaster; foam can blanket the whole rig site.
- Foam mist is a bad coolant and will not cool the bit and the drill string.
- Foam mist is not a good lubricant and does not lubricate the drill string.
- Foam, especially stiff foam, is costly because it cannot be collected and recycled and also because it requires additional equipment.

3.4 Aerated fluid

This is mainly called ‘aerated drilling’, and it involves the injection of compressed air (sometimes with a foaming agent, like drilling detergent/soap) to the normal drilling fluid circulating system (drilling mud or water) to reduce the density of the fluid column in the wellbore such that the hydrostatic pressure within the wellbore annulus is slightly less or balanced with the formation pressure in the permeable ‘loss zones’ of a geothermal well. Aerated drilling fluids have been used and are continually used in different parts of the world to drill geothermal wells. The main application is to drill the open hole section with this method as it prevents formation damage since the cuttings do not clog the veins where there are losses; due to better hole cleaning it allows the drilling to reach the target depth (Hole, 2006). Aerated drilling also has been applied in geothermal fields where the reservoir pressure is low (low water table), e.g. in Kenya.

When drilling into a permeable under pressurized geothermal system, fluid circulation is always lost. Initially, the method of dealing with this situation was to continue drilling ‘blind’ with water, but the cuttings rarely totally disappeared into the formation, hence the high risk of ending up with a stuck drill string. This is where aerated drilling has been employed to overcome this problem. The primary objective of utilising aerated fluids is the ability to maintain drilling fluid circulation back to the surface and, therefore, the cleaning cuttings from the hole as drilling proceeds. The continuous removal of cuttings from the hole significantly reduces the risk of the drill string getting stuck. Aeration of the drilling fluid reduces the density of the fluid column and thus the hydraulic pressure exerted on the hole walls and the formation. In geothermal drilling the base fluid during aerated drilling is mainly water but aerating drilling mud is also possible (Hole, 2006).

Initially, the technique was utilised only in the smaller diameter production hole section of a well. In some fields, such as Olkaria in Kenya, permeability is prevalent in the formations located above the production zone where the static water level is low (about 400 m deep). Significant amounts of lost time can be incurred in attempting to plug and re-drill such zones (Thórhallsson, 2011). Utilising aerated fluids to drill these zones has proven to be a highly successful solution (Ball, 2001).

3.4.1 Advantages of using aerated fluids and foam

- Transportation of the cuttings to the surface: The primary objective of utilising aerated drilling fluids is the maintenance of drilling fluid circulation, which results in continued return of drill cuttings back to the surface. This enables the collection and the analysis of the cuttings as the well is drilled.
- Reduction of drilling materials used: A significant reduction in the consumption of bentonite and treating chemicals, cement plugging materials, and bentonite and polymer ‘sweep’ materials can result from the use of aerated drilling fluid. In addition, a major reduction in the quantity of water consumed occurs because aeration of the fluid allows almost complete circulation and re-use of drilling water.
- Reduction of the risks of a stuck drill string: The most common reason for a stuck drill-string is inadequate hole cleaning during blind drilling with water. Aerated drilling prevents the accumulation of cuttings in the annulus and allows for circulation to be maintained even when new loss zones are encountered, hence reducing the risk of getting stuck and the time consuming fishing operation.
- Aerated drilled geothermal wells recover faster: Aeration of the drilling fluid limits the fluid loss to the reservoir around the well, allowing it to recover faster as compared to blind drilled geothermal wells.
- Improved well productivity: Wells drilled with aerated fluids show less skin damage than those drilled ‘blind’ with water. In general terms, wells with the production zone drilled with aerated

fluids demonstrate better productivity than those drilled blind with water, and significantly better productivity than those drilled with bentonite mud in the production zone (Hole, 2006).

3.4.2 Disadvantages of using aerated fluids and foam

- Increase of the cost of the well: The rental of or purchase of aerated drilling equipment, the additional fuel consumed plus specialized operators imposes an additional operational daily cost on the drilling.
- Increase in non-productive time: Aerated drilling requires the utilisation of additional no-return valves to be placed in the drill string to limit the amount lost to air as exhaust during the addition of a new drill pipe. Prior to any inner string surveys, these floats must be removed from the drill string; this requirement imposes additional tripping time. The valve, depending on type, can also be in the way of attempts to locate where a drill string may have gotten stuck and precludes back-off or cutting the drill string by explosives.
- The location of productive intervals is more difficult to assess during aerated drilling than while drilling with mud or water, as losses or gains do not show up as clearly as during normal drilling.
- Potential dangers: Drilling with aerated fluids requires the drilling crew to deal with compressed air and with pressurised high temperature returned fluids at times. These factors are potentially dangerous to the drilling crew and require additional training, awareness and alertness. During aerated drilling within a geothermal reservoir system, the potential for the well to ‘kick’ is significantly higher than when being drilled with large volumes of cold water which are then ‘lost’ to the formation’.
- Reduced bit life: Aerated drilling prevents the loss of drilling fluid to the formation and thus reduces the cooling of the formation and near well bore formation fluids. At times hot reservoir water will enter the well. The drill bits and bottom-hole assemblies used are, therefore, exposed to higher temperature fluids, reducing bearing and seal life and bit life.

4. FUNCTIONS OF DRILLING FLUIDS

4.1 Clean the hole of cuttings

The main function of geothermal drilling fluids is to transport cuttings from the well bore as the drilling operation progresses. Several factors influence the removal and transportation of the cuttings resulting from the milling action of the bit.

The velocity at which the fluid travels up the annulus is an important cleaning factor. The fluid annular velocity must be greater than the slip velocity of the cuttings for the cuttings to be transported up the well bore. The density of the fluid in the well bore has a buoyancy effect on the cuttings; therefore, an increase in the density of the fluid increases the capacity of the fluid to carry the cuttings. The viscosity of the fluid also affects the carrying capacity of the fluid, because it controls the settling rate of the cuttings in the fluid. Low viscosity results in a higher settling rate. The size, shape, and weight of the cuttings also affect the settling rate and, hence, its transportation (Hole, 2008). For water the settling rate is around 0.5 m/s; therefore, the “rule of thumb” is for the circulation rate (l/s) to achieve a minimum annular velocity of 0.7-1.0 m/s. For drilling with an 8 ½" bit, the water circulation rate is maintained at about 30-40 l/s and for 12 ¼" 50-60 l/s (Thórhallsson, 2011).

4.2 Cool and clean the bit

The transportation of the cuttings from the base of the bit is necessary in order to avoid regrinding the cuttings which would result in low rates of penetration. Furthermore, geothermal wells are hot; some of the heat is generated by the milling action and must be carried away for efficient cooling of the bit and the bottom-hole assembly. This is important considering that bits have seals that are destroyed with high temperatures; thus, high temperatures will significantly affect the life of the tri-cone bits (Finger and Blankenship, 2010). The drilling fluid therefore has a function of cooling the bit and other down hole tools such as mud motors and measurement-while-drilling tools (MWD) that are used in the drilling operations of directional wells.

4.3 Lubricate the drill string

Drilling fluid also has a function of lubricating the drill string. This can be a significant factor in deviated wells, where the drill string is in contact with the wall of the well (Finger and Blankenship, 2010). The lubricating ability of the drilling fluid ensures that the drill string does not wear out too fast and that the torque limit of the drill pipes is not exceeded.

4.4 Maintain the stability of the borehole

A good drilling fluid will be able to maintain the stability of the borehole by controlling the swelling and sloughing formations, thus lessening the risk of a stuck drill string. It is important that the fluid hold the cuttings in suspension when circulation is stopped, so that they do not fall back and pack around the bit and part of the bottom hole assembly (Finger and Blankenship, 2010).

4.5 Allow collection of geological information

The drilling fluid transports the cuttings to the surface and then releases them. The fluid allows the collection of cutting samples for geological analysis in order to ascertain the type of formation being drilled. The drilling fluid should, therefore, promote the cutting integrity for the purpose of analysis. Drilling fluid is in constant contact with the wellbore formation, revealing substantial information about the formations being drilled as well as being a conduit for data collected down-hole by down-hole tools (Lake, 2006).

4.6 Control formation pressure

Drilling fluid is the first line of defence against a blow-out or loss of well control caused by formation pressures or internal well flow. The proper restraint of formation pressures depends upon the density or weight of the drilling fluid. A normal pressure gradient is the pressure exerted by a column of formation water. Normally the weight of water plus the solids picked up from drilling would balance the formation pressures; however, at times abnormal pressures are encountered and require the addition of denser material, such as barite, to increase the hydrostatic head of the drilling fluid. The hydrostatic head counters the formation pressure in order to avoid a bow out while drilling. Care should be taken so as not to increase the hydrostatic head too much because that could result in fracturing the formation, resulting in loss of drilling fluid and a lowered hydrostatic pressure (Lake, 2006; Finger and Blankenship, 2010).

4.7 Protect the drilled formation from damage

Drilling fluid used to drill the production zone should be able to protect the production zone from damage. Mud forms a protective filter cake on the wall of the drilled formation which is good for the zones that will be cased but not good for the production zones. Mud should therefore not be used to drill the production zones (Thórhallsson, 2011).

4.8 Support partial weight of the drill-string or casing

With increasing depth, the weight supported by the rig mast becomes increasingly important. Since a force equal to the weight of the mud displaced buoys up both the drill pipe and casing, an increase in drilling fluid density necessarily results in a considerable reduction in the total weight which the surface equipment must support. Equally, if the casing is not completely filled up during running, some of the hook load is alleviated. Geothermal drilling mud typically does not contain material to increase its density; it is typically only 1,05 g/cm^3 or only 5% more than that of cold water (Baker Hughes, 2006).

4.9 Transmit hydraulic power

The drilling fluid is the medium for transmitting available hydraulic horsepower at the surface to the bit and also to drive the downhole motors. In general, this means that circulating rates should be such that utilization of optimum power is used to clean the face of the hole ahead of the bit (Finger and Blankenship, 2010).

5. GEOTHERMAL DRILLING FLUID PROPERTIES AND REPORTING

A fluid can be either a gas or a liquid. Gases are highly compressible and their volume depends on pressure and temperature. Liquids are only slightly compressible, and their volume only slightly dependent on temperature (Baker Hughes INTEQ, 1995).

Drilling fluid properties determine the behaviour of the drilling fluid in and out of the well-bore. Although tests are available to measure each of these properties, simple field tests for viscosity and density can help to understand the behaviour of the fluid and generate a daily drilling fluid report, sometimes called the mud report. The report contains the mud or fluid additives inventory, costs and the measured fluid properties. The properties of the drilling fluid are known by conducting certain tests on the fluid. Some of the tests will be discussed under the specific property below. Knowing the properties and the changes taking place helps in predicting the situation of the well (Baker Hughes INTEQ, 1995).

5.1 Viscosity

The measure of resistance of a fluid to flow or to deform by either shear or tensile stress is called viscosity. The thicker a fluid is, the higher its viscosity. The size, shape, and the number of suspended particles, the forces existing between particles and the fluid, and the viscosity of the base fluid (water) are the factors that affect the viscosity of the drilling fluid. At the well site the viscosity of the drilling fluid is estimated by the use of the Marsh funnel. The funnel viscosity is the time in seconds for 1 quart (0.946 dm^3) or 1 liter of drilling fluid to pass through the Marsh funnel, expressed as seconds per quart (sec/qt) or seconds per liter (sec/l). The usual range of Marsh funnel viscosities for good effective bentonite mud is 32 to 38 sec/qt; for polymer muds, funnel viscosities of 40 to 80 sec/qt are reasonable. The funnel viscosity of fresh water is 28 sec/qt (30 sec/l) at 20°C (U.S. Army Corps of Engineers, 2001).

It is important that the viscosity of the drilling fluid is maintained to provide the required hole stability and water loss control. Less viscous fluid has a good impact in cleaning the bit and optimizing the drilling rate, but more viscous fluid is good in cleaning out coarse gravel from the hole (U.S. Army Corps of Engineers, 2001). Marsh funnel viscosity readings should be taken routinely and recorded on the drilling fluid logs.

5.2 Density

Density is defined as mass per unit volume and is measured in kilograms per cubic meter (kg/m^3). The desired density of mud is usually less than 1,080 kg/m^3 and is determined using a mud balance. The density of pure water is 1,000 kg/m^3 at 4°C. The density of the drilling fluid (mud) should be routinely determined and recorded, since an increase in its density could show that the mud is not being cleaned efficiently and the cuttings are being recirculated. The density of a bentonite mud can be decreased by adding water or increased by adding additives with high specific gravity such as barite (U.S. Army Corps of Engineers, 2001).

5.3 Gel strength

Gel strength is a measure of the ability of a drilling fluid to hold particles in suspension after the flow ceases. All bonds between particles are broken while bentonite mud is flowing but when the flow ceases there is an attraction between clay particles (positively charged clay platelets are attracted to the negatively charged clay platelets). This coming together and bonding is termed flocculation and it is the structure responsible for suspending cuttings when the flow ceases. A drawback to this property is that cuttings do not readily settle out of the drilling mud in the mud pit and may be recirculated. Polymer drilling fluids essentially have little or no gel strength (U.S. Army Corps of Engineers, 2001).

Gel strength is measured with the viscometer by stirring the mud at high speeds for about 15 seconds and then turning the viscometer off or putting it into neutral (low gear if it's a lab model) and waiting the desired period (i.e., 10 seconds or 10 minutes). If the viscometer is a simple field model, the “gel strength” knob is turned counter clockwise slowly and steadily. The maximum dial deflection before the gel breaks is then recorded (Baker Hughes, 2006).

5.4 Filtration

This is a measure of how well the fluid forms an impermeable layer (“mud cake” or “filter cake”) on the borehole wall to prevent leakage into the formation’s natural permeable zones. The ability of a fluid to deposit mud solids on the wall of the borehole to limit fluid loss to the formation is referred to as filtration. Drilling fluid would infiltrate into the formation due to hydrostatic pressure which could be greater in the borehole than in the formation. This is minimised by the deposition of the drilling mud solids on the borehole wall as the drilling fluid flows in the annulus, significantly reducing further fluid loss. The solids deposited are referred to as a filter cake and an ideal filter cake is thin with little intrusion into the formation. A good, well-conditioned bentonite drilling mud will deposit a thin filter cake. Polymer muds have low solids and do not form a filter cake but reduce fluid loss because they have a high affinity for water and form swollen gels which tend to plug the formation pores in the borehole wall (U.S. Army Corps of Engineers, 2001).

Mud filtration tests are done by the use of a filter press. The test consists of monitoring the rate at which fluid is forced from a filter press under specific conditions of time, temperature and pressure, then measuring the thickness of the residue deposited upon the filter paper (Baker Hughes, 2006). This is recorded in the daily drilling fluid report. This is typically more important in oil and gas drilling than in geothermal drilling.

5.5 pH (acidity or alkalinity)

pH is a value representing the hydrogen ion concentration in a liquid. pH indicates acidity or alkalinity of a drilling fluid. pH is presented by a numerical value (0-14) which means an inverse measurement of hydrogen concentration in the fluid. The pH of pure water is 7.0; also referred to as neutral, neither acidic nor basic. The pH of the drilling fluid can affect its performance and is important for corrosion control. Low pH (acidic) fluid is undesirable because it can corrode the drilling string. pH has an effect on borehole stability and filtration control. Normal drilling fluid pH will range between 9.5 to 10.5; higher values are not common (Finger and Blankenship, 2010; Wikipedia, 2011).

A pH paper is used to estimate the pH of the drilling fluid in the field. A calibrated pH meter is used to measure accurately the pH of a substance (Baker Hughes INTEQ, 1995). The pH of the drilling fluid (inflow and outflow) should be checked at regular intervals during the drilling operations so as to ensure that the fluid pH is maintained at acceptable limits and also to understand the reservoir fluid conditions.

5.6 Sand content

Sand content is defined as any solid material larger than 74 microns in size in the drilling fluid. Sand content is measured by the use of a sand content kit. High sand content may result in the deposition of a thick filter cake on the wall of the hole and furthermore may settle back at the bottom of the well when circulation is stopped. High sand content also results in increased fluid density, hence a reduced rate of penetration and may also be detrimental to the pumps and the drill string (Bennett et al., 2001).

Sand content is measured using a 200 mesh sand screen set, where a measuring tube is filled with mud and water and mixed evenly by shaking, and then poured over the 200 mesh sieve and washed clean with water. The remaining sand is then measured using the measuring tube and it’s the figure given as a percentage of the initial mud content. This shows how effective the solids control equipment are (Baker Hughes INTEQ, 1995). Sand content is reported as a volume percentage of the drilling fluid and less that 2% by volume is normally considered acceptable.

5.7 Hard water

Hard water is water containing dissolved calcium or magnesium salts. These salts impair the suspension and sealing properties of bentonite clay. Hard water results in an unsatisfactory bentonite clay mud performance. Drilling mud has low yielding when mixed with hard water. Soda ash or caustic soda is used to treat hard water. The resulting high pH suppresses the calcium ion concentration. Thus, hard water, or water which has some cement in it, is treated with the soda before the bentonite is added. Chemical analysis of drilling water or water used to make mud is made to ascertain the quantity of calcium and magnesium in water. The calcium content is measured in parts per million (ppm). This analysis can be done once in a drilling project if the same water is used throughout (Zhang and Ma, 2010).

5.8 Fluid volume and flow rate

Fluids cannot maintain a rigid shape like solids, meaning that fluids cannot sustain shear stress. Shear stress (a tangential force) causes the fluid to deform. Fluid flow is, therefore, defined as continuous deformation of a fluid due to shear stress. An orderly flow pattern is referred to as laminar flow, while a random flow pattern is called turbulent flow. Laminar flow takes place at low fluid velocities while turbulent flow takes place at higher velocities. Laminar flow is desired in the annulus during drilling because it does not produce excessive pressure drops and does not lead to erosion. Turbulent flow is always found in the drill-string (Baker Hughes INTEQ, 1995).

Geothermal wells are drilled into fractured formations and it is important to measure and record the fluid flow rate. Both the inflow and the outflow from the well is measured and recorded, the difference being the fluid loss or gain. This measurement is done using flow meters or by counting the pump strokes, recorded as strokes per minute. Changes in total drilling fluid volume over a short time interval is an accurate indicator of losses. Sometimes the loss is measured, after a drill pipe has been added and the fluid level has fallen in the well, by noting how much flow rate from the mud pumps (l/s) it takes to maintain the well full to the brim with fluid. The total volume of the fluid available in the mud tanks should be 3 times the volume of the well for safety purposes. A decrease in the outflow from the well would indicate loss of fluid, while an increase in the outflow means a gain of fluids which indicates a kick or that the formation pressure is higher than the wellbore pressure. Measurement of the flow rates into and out of the well is important since it gives a picture of what is happening inside the well; a loss is an indication of success in the open hole section. The flow rate records, therefore, aid in making important decisions during drilling such as at what depth the productive intervals are and how deep to drill (Thórhallsson, 2011).

5.9 Temperature

Temperature is a physical property of matter that quantitatively expresses the common notions of hot and cold. In the drilling industry, temperature is measured and expressed in the Centigrade scale. One major characteristic of geothermal wells is high temperature. The high temperatures experienced in drilling geothermal wells have detrimental effects on the availability, operation, and cost of down-hole instruments and equipment used. The high temperatures encountered in geothermal drilling also affect the drilling fluid properties. The fluid properties affect well control capabilities and the ability of the drilling fluid to carry cuttings. The drilling fluid, therefore, must have the ability to carry the heat out of the hole and release it at the surface. A cooling tower is used to cool the fluid before reuse (Finger and Blankenship, 2010; Thórhallsson, 2011).

Measurement of the temperature of the fluid at the inlet and outlet of the well helps in assessing the cooling effect that is achieved down-hole while drilling. The temperature of the circulating fluid must be closely monitored because its analysis can help to understand what is happening down-hole and possibly avert a looming problem. A sudden change in the temperature difference in and out of the well could indicate a loss zone or a gain being encountered (Thórhallsson, 2011).

5.10 Pressure

Pressure is defined as the force acting on a unit area. Pressure is commonly measured in pounds per square inch (psi) or bars. When drilling, drillers are concerned with the pressures throughout the circulating system. Various types of pressures exist due to different mechanisms, and are classified as hydrostatic, hydraulic, or imposed. The pressure at any given point in the circulating system is the sum of the hydrostatic, hydraulic, and imposed pressures which exist at that point. Hydrostatic pressure is the pressure created by a column of fluid due to its density and vertical height. Hydraulic pressure is the pressure created (or needed) to move drilling fluid through a pipe. In the drilling industry it is usually referred to as the pressure generated by the mud pump in order to move the drilling fluid from the mud pump around the system and back to the flow-line. Pressure drop or pressure loss is the amount of pressure needed to move the fluid over a given distance (Baker Hughes INTEQ, 1995).

The total pressure drop that occurs due to fluid friction is termed Stand Pipe Pressure or SPP and is measured at the stand pipe. SPP is an important drilling parameter, because it is used for selecting proper jet bit nozzle size, determining the optimum flow rate to ensure hole cleaning and selecting a proper mud pump liner. Continuous monitoring of SPP also helps in identifying downhole problems. For example, too low SPP can be caused by a washed out pipe or bit nozzle, loose joint or broken drill string, worn pump packing or liner, and lost returns due to formation fractures. On the other hand, too high SPP could indicate a plugged drill bit or an increase in mud density or viscosity. Reliable indications of SPP provide an early warning of circulation problems, warning the driller to make corrections to avoid major problems (Chowdhury et al., 2009)

6. DRILLING FLUIDS EQUIPMENT

The geothermal drilling fluid equipment is made up of a number of items which make up the circulating system (Figure 1). The mud pump takes in mud/water from the mud tank and sends it out through a discharge line to a standpipe. The drilling fluid then flows through the standpipe and into a flexible and reinforced rubber hose called the rotary hose or Kelly hose. The Kelly hose is connected to the swivel. The drilling fluid enters the swivel and goes down the Kelly, the drill pipe and drill collars and exits at the bit. The drilling fluid then does a U-turn and heads back up the hole in the annulus. Finally the drilling fluid leaves the hole through a steel pipe called the mud return line or the flow-line. When the drilling fluid is mud or water the drilling fluid returns through the flow line and falls over a vibrating wire screen called a shale shaker. Mud is then pumped through devices called desanders and desilters and finally the mud coolers after the shaker. Agitators installed on the mud tanks help maintain a uniform mixture of liquids and solids in the mud (Matanovic, 2007).

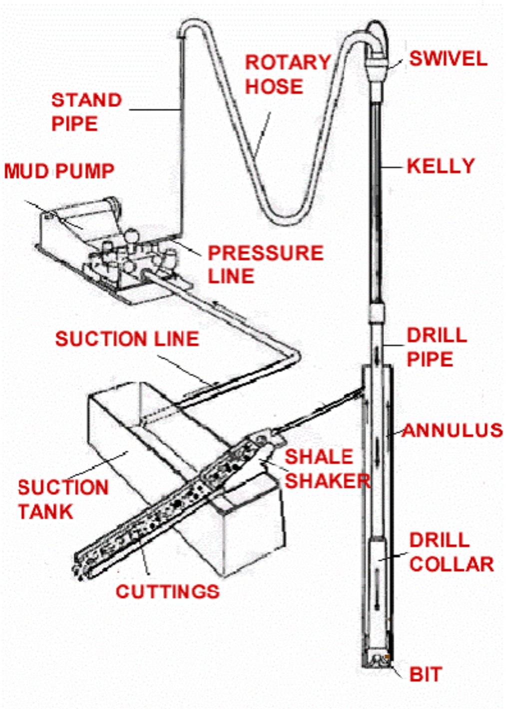

FIGURE 1: Fluid circulating system (Matanovic, 2007)

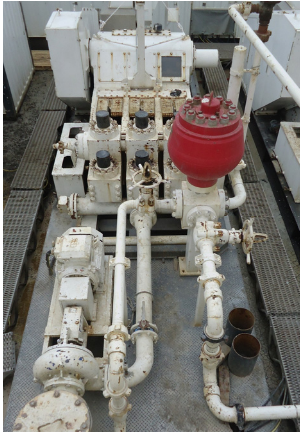

FIGURE 2: Mud pumps

6.1 Mud pumps

Mud pumps (Figure 2) are the primary components of any fluid-circulating system. These are large reciprocating piston pumps used to circulate the drilling fluid (mud or water) on a drilling rig. The pumps use positive displacement so by knowing the piston size and stroke length, the volume per stroke is known. Then, by counting the strokes per minute of the pump (SPM) the flow rate can be calculated. The pump drive is usually a variable speed electric motor so the output is easy to adjust. The pumps for rotary drilling rigs have high ratings and are capable of moving large volumes of fluid at very high pressures (Thórhallsson, 2011). During aerated drilling, both mud pumps and air compressors are used.

6.2 Mud tanks

These are open tanks made of steel plates. Mud or water is usually circulated through at low flow rates or sometimes made to stagnate to allow sand and sediments to settle out. Mud additives are mixed with the mud in the mud tanks, and the fluid is temporarily stored there before being pumped back into the well. The tanks contain agitators and jets that mix the mud. Mud tanks are also used for mud storage during water or aerated drilling; in this case, one or two tanks store the mud for different purposes during drilling (Thórhallsson, 2011; PETEX, 2001).

There are other auxiliary items installed on or alongside the mud tanks for different purposes. They are explained below:

6.2.1 Shale shakers

Shale shakers are made of a series of trays with screens that vibrate to remove cuttings from circulating drilling fluid. The size of the screen openings is selected depending on the anticipated size of cuttings (PETEX, 2001). The shaker screen screens out the cuttings and dumps them into a steel tank or a reserve pit (mud pit) or onto the ground. The cuttings are then collected and transported for safe dumping (Thórhallsson, 2011).

6.2.2 Desander and desilter

Desanders and desilters (Figure 3) are centrifugal devices used for removing sand, silt and other solids from drilling fluid (mud or water) before being recirculated back to the well to prevent abrasion of the mud pumps. Desanders are used to remove large particles of sizes equal or larger than sand but less than shale, while desilters are used to remove finer particles or silt that cannot be removed by desanders. They may be operated mechanically or by a fast moving stream of fluid inside a specially shaped vessel called cyclones (PETEX, 2001). The amount of solids in the circulated drilling fluid should be at the lowest possible level to avoid making the drilling fluid heavier than that desired and to avoid eroding the pump linings, the drill-string and other down-hole tools.

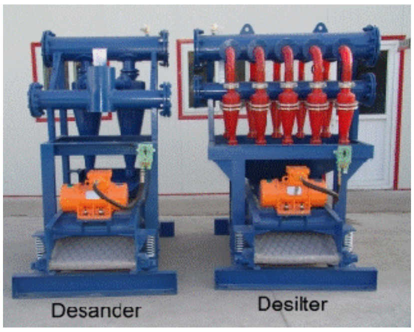

FIGURE 3: Desander and desilter

6.3 Water tanks

Water tanks are similar to mud tanks. They are used for storing water that is used for mud mixing, cementing, and rig cleaning. Depending on the drill site conditions, additional water tanks or storage pits may be a part of the water supply system (Thórhallsson, 2011).

6.4 Mud hoppers

Mud hoppers are mud mixing devices used for making drilling mud. Figure 4 shows a mud hopper's operating principles. Mud is mixed in the mud tanks with the help of a mud hopper into which most of the dry ingredients for the mud are poured and mixed evenly with the base fluid or the drilling fluid. It is very important to note that some dry ingredients, especially caustic soda, should never be added to the mud through

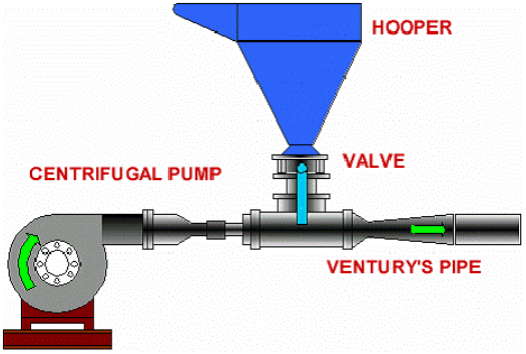

FIGURE 4: Mud hopper (Matanovic, 2007)

the hopper. The hopper works in such a way that it often throws out a little of the ingredients being added to it. Caustic soda can cause severe burns if it comes into contact with the skin or eyes (Matanovic, 2007). Eye protection and breathing masks are used when handling the drilling mud and additives. Material Data Sheets (MSD) of each product (provided by the manufacturers) have health and safety instructions and recommendations on the handling of the particular products.

6.5 Cooling tower

A cooling tower is a system that rejects heat by extracting it from the fluid and sending it to the atmosphere. When drilling in geothermal reservoirs, the drilling fluid is heated to high temperatures. Mostly, these fluids have to be reused and therefore need to be cooled before being pumped back into the well. The fluid sometimes is circulated in mud pits to cool when the volume is large and the quantity of heat to be dissipated is low. For greater quantity of heat to be dissipated, artificial means are used involving the cooling tower. Some rigs have a mud to water tubular heat exchanger where the clean water goes to the cooling tower. If the cooling load for the mud is low, fan cooled fin heat exchangers (mud to air) have also been used..

6.6 Air compressors

Air compressors are devices that convert power into kinetic energy by pressurizing and compressing ambient air (Wikipedia, 2011). There are two types of air compressor units used in air or aerated drilling and they are discussed below.

6.6.1 Primary compressors

These can be divided into two distinct types: positive displacement and dynamic. The positive displacement type (screw compressors) are generally selected for air or aerated drilling operations and are 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. Primary compressors typically have discharge pressures up to approximately 25 bar (Hole, 2006).

6.6.2 Booster compressors

Boosters are positive displacement (piston 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. Most booster compressors are of the piston type (Hole, 2006; Thórhallsson, 2011).

6.6.3 Air coolers

Both primary and booster compressors discharge compressed air that has temperatures higher than the ambient and needs to be cooled. The air from the primary compressors must be cooled to reduce the power requirements of the booster compressors, and the booster discharge must be cooled before entering the standpipe to prevent packing and equipment damage. Air coolers or intercoolers are therefore installed in-between at different stages in multi stage unit installations (Hole, 2006).

6.7 Detergent injection pumps

During mist, foam or aerated fluid plus foam drilling, small triplex pumps are used to inject water (and foaming chemicals or detergent) into the air supply line at a controlled rate. These pumps generally have capacities up to 300 lpm (Hole, 2006).

6.8 Air separator

An air separator, sometimes called a cyclone separator, is equipment used to separate compressed air from the returning aerated drilling fluid at the end of the flow line. If there is a steam or air kick, the flow will also be diverted through the flow-line to the separator and thus not endanger the crew (Thórhallsson, 2011).

7. CIRCULATION LOSSES

Lost circulation is the term used when the drilling fluid encounters permeability in the formation being drilled and is not returned to the surface. Lost circulation, or partial loss of circulation in the open production hole section of the well is a good thing as far as the success of drilling is concerned, as it indicates that the mass-flow from the well should be good during production (Thórhallsson, 2011). The "target" of geothermal drilling is where the well intersects zones with circulation losses. Loss of circulation creates well drilling problems, hence it should be dealt with in the cased zones of the well.

The most expensive problem routinely encountered in geothermal drilling is lost circulation, which is the loss of drilling fluid to pores or fractures in the rock formations being drilled. Lost circulation represents about 10% -20% of total well costs (Carson and Lin, 1982). Lost circulation is aggravated by the pressure imbalance between the relatively cool denser column of drilling fluid and the hot lighter geothermal fluids in the formation. This loss is harmful for several reasons (Finger and Blankenship, 2010):

- If the drilling fluid fails to clean the hole and return cuttings to the surface, the cuttings can fall back on the bottom-hole assembly (BHA) and may result in a stuck bottom-hole assembly.
- Drilling fluid, especially mud, is expensive and losing it to the formation instead of re-circulating it is costly.
- In geothermal wells, the production zone is usually a lost-circulation zone, so it is sometimes difficult to cure a harmful lost circulation zone while preserving its productive potential.
- Lost circulation can suddenly lower the fluid level in a well. Decreasing the static head of drilling fluid in a hot formation can allow the formation fluids, gas, hot water or steam, to enter the wellbore, causing a kick or a blow-out. This can occur either in productive or non-productive zones.
- In zones that are not hot enough (under 220°C for high temperature utilization), the lost circulation should be "sealed" to provide a wellbore that can be cased and cemented to the surface, or the cementing process should be designed to accommodate the loss of circulation to ensure a good cementing job. Adequately cementing a casing through lost circulation zones is a major problem and can be costly.
- Placement of lost circulation material (LCM) is difficult because the top and bottom of the loss zone are often not well known. The LCM or cement being used to heal the loss zone are especially likely to migrate away from the targeted placement zone if drilling has continued well past it into another loss zone, or if there is a considerable rat hole below the original loss zone.

7.1 Dealing with lost circulation

Lost circulation can be dealt with in different ways depending on where it is situated and the drilling fluid being used. The first way is to drill ahead with lost circulation; the second way is to drill with a lightweight drilling fluid that will have a static head less than the pore pressure in the formation; the third way is to mix the drilling fluid with fibrous material or particles (lost circulation material - LCM) that will plug the loss apertures in the formation; and the fourth way is to pause drilling and try to seal the loss zones with some material that can be drilled out as the hole advances, for example by cementing (Thórhallsson, 2011; Finger and Blankenship, 2010).

7.1.1 Drill with lost circulation

If an adequate water supply is available, it is practical to continue drilling the well blind without returns. In a case where fresh water is in short supply, produced brine (available in a developed project), which would normally be re-injected, can be used. Drilling without returns is frequently used when core drilling, where the cuttings are very fine and where much of the rock comes out of the hole in the form of core. There are many examples of wells where intervals of many hundreds of meters have been drilled with complete lost circulation (Finger and Blankenship, 2010).

When loss of circulation is encountered, the highest risk is when only partial returns are obtained, as the low annular velocities above the loss zones may not be adequate to clean the hole and furthermore the borehole pressure is low and the formation can easily collapse. There are available techniques used to prevent formation collapse and to keep the string from getting stuck. High viscosity pills or sweeps are usually used to reduce this risk. Once total loss is encountered, pumping water at high rates down the annulus as well as down the drill pipe will flush the cuttings away from the wellbore, preventing any sticking problems, and provide positive wellbore pressure to hold up weak formations (Finger and Blankenship, 2010).

7.1.2 Lightweight fluids

There are three categories of lightweight fluids: air, foam and aerated fluids from the lowest density to the highest density. Air can only be used where liquid production is minimal or non-existent. Foam will tolerate some water dilution, but not much, while aerated fluids can tolerate a significant amount of dilution. Aerated fluids produce a static head less than or almost equal to the pore pressure and are a common remedy for lost circulation in geothermal drilling; it also reduces the probability of differential sticking. Aerated drilling is now used extensively in many locations, and it has been claimed that its use not only avoids problems with lost circulation, but improves the well's productivity (Hole, 2006).

7.1.3 Lost circulation materials (LCM)

Lost circulation is divided into two regimes, differentiated by whether the fracture aperture is smaller or larger than the bit's nozzle diameter. When severe lost circulation is anticipated, it is usual to run large jets or no jets in the bit, to better accommodate pumping LCM. Smaller fractures or pores can be sealed by pumping solid or fibrous plugging material (LCM) mixed with the drilling fluid; this method is much less effective with larger fractures. Although traditional organic LCM can be used as long as the circulating temperature prevents degradation, LCM, in general, has often been unsuccessful in geothermal drilling. Several materials that will withstand high temperature have been identified (Loeppke 1986), but they should only be used in the non-productive zones, since they would permanently plug the productive zones. Mica flakes are commonly used as LCM for geothermal drilling.

7.1.4 Well-bore sealing

Fractures that are large and cannot be plugged by LCM can be sealed by withdrawing the drill string from the hole and injecting some liquid or viscous material that will enter the fractures, solidify to seal them, and then have its residue removed by resumption of drilling. Conventional lost-circulation treatment practice in geothermal drilling is to position the lower end of an open-end drill pipe (OEDP) near the suspected loss zone and pump a given quantity of cement (typically 10 m^3) down-hole. The objective is to have enough cement in the loss zone to seal it; however, this does not always occur. Since cement has a higher density relative to the wellbore fluid, the cement often channels through the wellbore fluid and settles to the bottom of the wellbore. This can be overcome by trying to seal off the loss zones as soon as they occur, maybe after drilling one joint. If the loss zone is not near the bottom or at the bottom, the entire wellbore below the loss zone must sometimes be filled with cement before a significant volume of cement flows into the loss zone. Consequently, a large volume of hardened cement must often be drilled to re-open the hole, which wastes time. Multiple cementing jobs are often required to plug a single loss zone, with each plug incurring significant time and material costs, making it an expensive venture (Thórhallsson, 2011; Finger and Blankenship, 2010).

7.2 Measurement of losses

Measuring and monitoring the loss of circulation in geothermal drilling is important because it indicates interception of fractures, which is what is being sought in the production zone. When drilling the non-productive zones, measuring can assist in understanding the size of the fractures or porous zone which is vital in the healing process of the loss of circulation encountered. It is not only important to measure and monitor the loss of circulation and the points where they occur for the purpose of healing but also for the purpose of designing or choosing the right casing cementing process. There are mainly three methods of measuring or estimating the loss of circulation while drilling, namely (Thórhallsson, 2011):

1. The use of a magnetic or sonic flowmeter.; in this method the volumetric flow rate of the fluid being pumped into the well is read from the strokes per minute of the mud pumps and the flow out of the well is measured using a magnetic or sonic meter. The fluid loss is the difference between the total pumping rate and the outflow measured in the flow line.
2. The tank method; in this method the filling of the tank by make-up water is stopped for a certain interval of time (say 15 or 30 minutes) and then the change in the total mud/water volume is measured. The rate of change in volume (change in volume divided by time) is the fluid loss.
3. The driller's method; in this method the driller adjusts the pumping rate to keep the well full. The pumping rate (l/s) is then the rate of fluid loss.

Note: It is not possible to measure fluid losses during aerated drilling. The only way is to stop the aerated drilling and measure the losses using the above mentioned methods, which is rarely done.

7.3 Loss of circulation policy

Different countries or organizations have a loss of circulation policy; the policies are similar in that the aim is to heal the circulation loss when drilling for the casing, and drill with water only or with aerated water when in the production zone.

The thixotropic and gelling nature of water based bentonite mud assists in the sealing of minor loss zones. When a big loss zone is encountered while drilling for casing, many organizations have a policy of drilling blind with water. Sometimes the loss of circulation heals by itself. The use of loss of circulation material (LCM), for example mica flakes, wood shavings and sawdust mixed with water based mud, may completely heal minor loss of circulation. However, if major or total loss of circulation is encountered, and can't be sealed with LCM added to the mud, then it becomes impractical and uneconomic to continue drilling with mud. If high permeability and therefore significant or a total loss of circulation is encountered within the upper cased sections of the well, the use of water based bentonite mud and additives is normally ceased, and drilling is continued with water or with aerated water. In Iceland large loss zones (more than 10 l/s) are cemented after drilling a 30 m rat hole, if they do not heal while drilling blind with water. The depth of loss zones is confirmed by temperature logs and precise measurements are made of the losses. Cementing is done through the drill pipe and topping up until the loss is covered (Fridleifsson et al., 2003).

The main section of a geothermal well, the open hole section, is drilled using water or aerated water. When loss zones are encountered, the section is drilled blind with water or aerated water. In Iceland the production section is mainly drilled using water, and occasional high-vis pills, while in other countries, for example Kenya, the production section is drilled using aerated water (Thórhallsson, 2011).

8. GEOTHERMAL FLUID CALCULATIONS AND CASE STUDIES

8.1 Pressure drop calculations

Pressure drop analysis and calculations are made to determine what effect a particular fluid will have on power consumption. Most of the pump energy is used to squeeze the drilling fluid down the drill pipe. The pressure drop in the annulus is much less. The circulating system is made up of a number of components or intervals, each with a specific pressure drop. The sum of these interval pressure drops is equal to the total system pressure loss which equals the standpipe pressure (SPP). The total pressure loss for this system can be described mathematically as:

$$P_{Total} = P_{Surf\ Equip} + P_{D\ string} + P_{Bit} + P_{Annulus} \tag{1}$$

where P_{Total} = The total circulation pressure drop;
$P_{Surf\ Equip}$ = The pressure drop in the surface equipment;
$P_{D\ string}$ = The pressure drop in the drill string;
P_{Bit} = The pressure drop across the drill bit; and
$P_{Annulus}$ = The pressure drop in the annulus.

Each of these pressure loss groups will be broken down into their component parts depending on the geometry and configuration and the pressure drop ascertained and or calculated by the use of the Drilling Data Handbook (Gabolde and Nguyen, 1991).

8.1.1 Losses in surface connections (surface equipment)

Surface pressure losses include losses in the standpipe, Kelly-hose, swivel, and Kelly or top drive. The pressure drop is read from the handbook as the figure coinciding with the drilling fluid flow rate.

8.1.2 Losses in the drill-string

The pressure loss in the drill-string is equal to the sum of the pressure losses in drill pipes, heavy wall drill pipes, drill collars, mud motors, and any other down-hole tools. For the purpose of this analysis and comparison, a simple drill string of drill pipes and drill collar will be used. The pressure drop for the drill pipe and drill collar is read from the Drilling Data Handbook at the drilling fluid flow rate used, and for the particular size and geometry of the drill-pipe and drill-collar.

8.1.3 Losses in bit

For the purpose of these analyses, the pressure drop across the bit for the biggest nozzle configuration is used. This is also read from the Drilling Data Handbook as the figure corresponding to the drilling fluid flow rate.

8.1.4 Losses in annular space

The annulus is made up of different intervals and the pressure loss for each interval is calculated separately and summed up as the total annular pressure loss. The intervals are: between drill collar and formation, between drill pipe and formation, and between drill pipe and casing. The figures for the different geometries aforementioned are read from the Drilling Data Handbook.

8.2 Aerated drilling calculations

Aerated drilling is mainly used when the well is to be drilled balanced or underbalanced. The pressure difference between the annular pressure and the formation pressure must be underbalanced to get better results and for successful aerated drilling. A simulation of the calculation model, ST-air (put forward by Thórhallsson, 2005) will be used to calculate the pressure profile of aerated drilling at the annulus and drill-string. The profile is then compared with the formation pressure to obtain the differential pressure between the annular pressure and the formation pressure. This analysis helps to ascertain whether the well is being drilled underbalanced or not. The underbalanced condition can be varied by either increasing or reducing the back pressure at the wellhead or by changing the air flow rate from the compressors and the pumping rate of the water.

8.3 Drilling fluid and energy consumption

The fluid circulation system is one of the major power consumers at the rig. The choice of the drilling fluid influences the power requirement at the rig, because each drilling fluid has an optimum flow rate for carrying the cuttings. Tables 1 and 2 compare three main drilling fluids and how circulating at different sections of the wells affects the circulating system fuel consumption. The comparison is based on an assumption that the flow is practical (can be achieved by the pumps) and the ideal minimum velocity is met. The ideal minimum annular velocity, when drilling using mud is about 0.3 m/s and 0.7 m/s for water. The ideal flow rate for aerated drilling fluid is about 0.6 l/s for water and 900 scfm of air for the 8 ½″ hole and 1500 scfm for the 12 ¼″ hole.

TABLE 1: Large diameter hole (13⅜″ casing) drilling fluid versus energy and fuel analysis

	Depth (m)	**Hole diameter**	**Flow rate**	**Pressure (bar)**	**Power (kW)**	**Fuel (diesel) equivalent**	
						L / hr.	**L / day**
Mud	200	22½″	4,350 l/min	53.00	502.35	140.66	3,375.82
Mud	700	18⅝″	3,600 l/min	69.92	548.38	153.55	3,685.09
Mud	1,500	13⅜″	2,400 l/min	61.00	318.95	89.31	2,143.37
Water	1,500	13⅜″	3,600 l/min	91.90	720.78	201.82	4,843.67
Aerated water & foam	1,500		3,000 l/min (water) 1,500 scfm (air)	96.73	-	281.02	6,744.54
Mud	2,500	13⅜″	2,400	77.00	402.61	112.73	2,705.57
Water	2,500	13⅜″	3,600 l/min	129.90	938.82	262.87	6,308.89
Aerated water & foam	2,500	13⅜″	3,000 l/min (water) 1,500 scfm (air)	132.43	-	340.49	8,171.64

TABLE 2: Standard diameter hole (9 ⅝" casing) drilling fluid versus energy and fuel analysis

	Depth (m)	Hole diameter	Flow rate	Pressure (bar)	Power (kW)	Fuel (diesel) equivalent	
						L / hr.	L / day
Mud Mud	200 700	20″ 13⅜″	3,600 l/min 2,400 l/min	40.85 47.93	320.36 250.61	89.70 70.17	2,152.82 1,684.13
Water	700	13 ⅜″	3,600 l/min	77.50	607.84	170.20	4,084.71
Aerated water & foam	700	13 ⅜″	3000 l/min (water) 1,500 scfm (air)	86.17	-	197.86	4,748.64
Mud	1,500	9⅝″	1,800 l/min	67.97	266.55	74.63	1,791.21
Water	1,500	9⅝″	2,100 l/min	89.10	407.65	114.14	2,739.39
Aerated water and foam	1,500	9⅝″	1,800 l/min (water) 900 scfm (air)	97.73	-	211.00	5,063.97
Mud	2,500	9⅝″	1,800	83.52	327.53	91.71	2,201.00
Water	2,500	9⅝″	2,100 l/min	110.60	506.01	141.68	3,400.41
Aerated water & foam	2,500	9⅝″	1,800 l/min (water) 900 scfm (air)	113.52	-	235.59	5,654.26

For these comparisons, two scenarios will be considered: a standard (9⅝″ production casing) and a large diameter hole (13 ⅜″ production casing). In both cases, the surface casing, the anchor casing and the production casing will be assumed to be set at 60 m, 300 m and 800 m deep, respectively. The standard diameter hole was assumed to have been drilled with a 5" diameter drill-pipe and 100 m of drill collars. The drill-collar used was 6½" in diameter for the main hole (8½"), but an 8" diameter drill-collar was used for the rest of the sections. The large diameter hole was assumed to have been drilled entirely with a 5½" diameter drill-pipe and 100 m of 8" diameter drill-collar. The pressure at different points was calculated using the methods explained earlier in this section. The pump power required to drive the fluid through the string and the annulus and overcome the pressure is calculated from Equation 2 below, provided in the Drilling Data Handbook (Gabolde and Nguyen, 1991):

$$P = \frac{pQ}{600\eta_m\eta_t} \tag{2}$$

where P = Pumping power (kW);
p = Pump discharge pressure (bar);
Q = Fluid flow rate (l/min);
η_m = Pump mechanical efficiency, assumed to be 0.85;
η_t = Transmission efficiency, assumed to be 0.9 (for a motor).

The fuel required to produce the pumping power is then estimated from the generator manufacturer's data sheet. The hourly diesel fuel consumption is about 0.28 l/kW, as calculated from the specifications offered for a 1250 kVA diesel generator (Caterpillar, 2011).

For aerated drilling, the power for pumping was calculated according to Equation 2 and the fuel consumed was estimated according to the Caterpillar fuel consumption specifications. The fuel consumed by the compressors was estimated to be 68 l/hr (18 gal. per hour) for 1150 SCFM @ 350 PSI primary compressors and 83.3 l/hr (22 gal. per hour) for 2700 CFM to 2500 PSI booster compressor (Air Drilling Associates, 2005).

An analysis of Tables 1 and 2 shows that less energy and fuel is required to drill using mud than with water and aerated fluids. Drilling using aerated fluids means that more fuel is required to run the compressors, significantly more fuel than drilling with water alone. It can also be seen that the larger and the deeper the hole, the greater the energy requirements of the circulating system.

8.4 Case studies

8.4.1 Reykjanes well 19 (RN-19)

Well RN-19 is located in the eastern part of the Reykjanes high-temperature geothermal field, in Iceland. The well was drilled to produce steam for the production of electricity in conjunction with the building of a new 100 MWe geothermal power station for Hitaveita Sudurnesja hf., now HS Orka. The well was predrilled by Saga drilling rig to 84 m when measured from the working floor of the Geysir drill rig, which is 8,5 m above the flange of the well. The main drilling was carried out by Iceland Drilling Company Ltd. in accordance with the contract with Hitaveita Sudurnesja hf., while the research and logging was carried out by Iceland GeoSurvey (ÍSOR).

The drill rig Saga (Soilmec G-55) initially pre-drilled well RN-19 with a hammer and 26” drill-bit and a 22 ½” surface casing was installed to a depth of 84 m from the working floor of the Geysir (Drillmec H-200) drill rig. The well was drilled using mud and water at different sections of the well. Polymer pills were also used to clean the cuttings while drilling using water. Table 3 summarizes the different sections, the fluids used and the losses encountered. The descriptions and the summary in the table were extracted from the well completion report for RN-19 (Mortensen et al., 2006).

TABLE 3: Summary of drilling parameters when drilling well RN-19

Hole size	Bottom hole assembly	Casing size	Depth	Casing depth	Drilling fluid	Losses
26″		22½″		84 m	- Foam	
21″	21″ bit, 10DCs, 1 jar, 2 STB, 1 shock absorber and DPs.	18⅝″	349 m	347 m	-Water (70-85 m; drill out cement) -Mud (85-349 m)	-An average loss of 2 l/s.
17½″	17½″ bit, mud motor, 2 STB, 1 shock absorber, 1 inclinometer, 1 jar, 5 subs and 12 DCs and DPs	13 ⅜″	746 m	742 m	-Water (321-349 m; (drill out cement) -Mud (349-746 m) at the rate of 60-65 l/s.	-Average loss of 25-30 l/s. -Major loss zone of 50 l/s at 746 m, plugged using cement.
12¼″	12¼″ bit, 3 STB, 1 sub, 1 jar, 1 inclinometer, 10 DCs and DPs		1302 m	None	-Water and polymer pills	- 50 l/s at 790 m. - Reduced to an average of 25 l/s.
12¼″	12¼″ bit, 2 STB, 1 sub, 1 jar, 1 inclinometer, 1 X/O, 9 DCs and DPs	9⅝″ (liners)	2235 m	2208 m	-Water and polymer pills -Water pumped at about 65 l/s	- Average loss below 30 l/s.

Well RN-19 was pre-drilled using foam by rig Saga with an air hammer to a depth of 84 m. There is no data from the pre drilling section of the well as it was carried out by a truck mounted rig. The remaining part was drilled using a Drillmec H-200 Jardboranir rig. Mud was used to drill the 21″ hole of well RN-19 and the driller increased the flow rate from 50 l/s to 60 l/s and finally to 65 l/s. The well was drilled with a flow rate of 65 l/s from about 130 m deep to the end of this section. The 17 ½″ hole section was drilled using water at an approximate flow rate of 80 l/s throughout. The main hole (12¼″ hole) was drilled using water at different flow rates. The section was drilled using water at a flow rate of 60 l/s from the beginning of the section to 1155 m and then the flow rate was increased to 65 l/s. The flow rate of 65 l/s was used to drill the section from 1155 m to 1245 m and then dropped again to 60 l/s and drilled to 1265 m. The well was then drilled at a flow rate of 65 l/s from 1265 m to

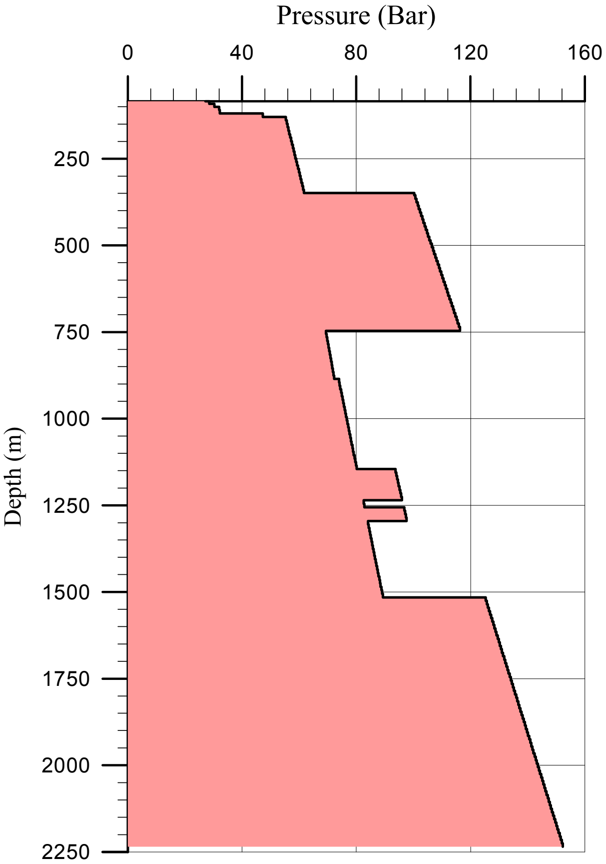

FIGURE 5: RN-19, calculated pressure drop profile

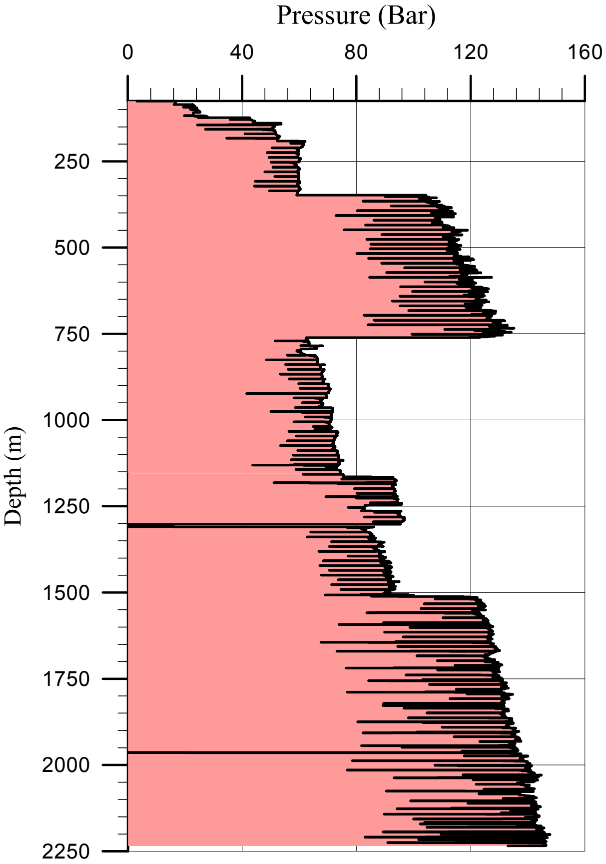

FIGURE 6: RN-19, measured stand pipe pressure

1305 m, dropped again to 60 l/s and drilled at this rate to a depth of 1525 m. The flow rate was then increased to 70 l/s and drilled to the end.

The increase in flow rates resulted in increases seen in both the calculated pressure drop profile (Figure 5) and the stand pipe pressure as measured and reported (Figure 6). The measured standpipe pressure compares well with the calculated pressure drop profile.

8.4.2 Olkaria well 38 (OW-38)

Olkaria well 38 is located in the Olkaria central field in Kenya. The well is a production well, drilled to provide steam for Olkaria I unit IV. The well was drilled to a depth of 3000 m using rig GWDC 120 (Great Wall Drilling Company). The well was drilled using mud, water and aerated water and foam as drilling fluids at different sections of the well. Table 4 summarizes the different sections, the fluids used and the losses encountered. The figures are derived from the OW-38 daily drilling reports.

Olkaria well OW-38 was drilled using mud at a flow rate of 50 l/s to a depth of 42 m where there was total circulation. The remaining part was then drilled blind with water at a flow rate of 70 l/s to the casing depth of 63 m. After cementing the 17½″ hole was drilled using water at a flow rate of 65 l/s to the casing depth of 306.45 m. The 12¼″ borehole section was then drilled to a depth of 334 m using water at a flow rate of 60 l/s and then the fluid was switched to aerated water and foam. During the whole interval the flow rate was approximately 60 l/s and the compressed air flow rate was 1800 scfm.

TABLE 4: Summary of drilling parameters when drilling well OW-38, Kenya

Hole size	Bottom hole assembly	Casing size	Depth	Casing depth	Drilling fluid	Losses
26″	26″ Bit, 1 sub, 1 STB, 3 X 8″ DCs, X/O and 5″ DPs	20″	63 m	62 m	Mud (10.7-42 m) at 50 l/s. Water (42-63 m, at 70 l/s	Total loss at 42 m. Drilled blind with water.
17½″	17½″ bit, 1 STB, 2 subs, 3 X/O, 9 X 8″ DCs and 5″ DPs	13 ⅜″	306.45m	305.5 m	Water at 65 l/m	The loss was not measured (circulation returns at about 80%).
12¼″	12¼″ bit, 1 STB, 1 subs, 3 X/O, 9 X 8″ DCs and 5″ DPs.	9⅝″	753 m	751.7 m	Water (292.3-334 m) at 60 l/m. Aerated water and foam (334 m – 753) at 60 l/s.	Lost circulation at 334 m and switched to aerated water and foam. Loss was not measured when drilling with aerated water and foam.
8½″	8½″ bit, 1 STB, 2 subs, 3 X/O, 15 X 6½″ DCs and 5″ DPs.	7″ (liners)	3000 m	3000 m	Drilled out cement using water (686-787 m), at 60 l/s. Aerated water and foam (787- 3000 m), at 55 l/m.	Total loss between 1403 and 2562 m.

The main hole was drilled mainly using aerated drilling except the drilling out of cement which was done using water at a rate of 60 l/s. During the aerated drilling, the water flow rate was 55 l/s and the compressed air flow rate was 1800 scfm.

Figure 7 shows the pressure drop profile while drilling OW-38 and Figure 8 shows the pressure profile inside the drill-string, the annulus and the reservoir pressure profile during aerated drilling. Figure 7 shows that the pressure drop while drilling using mud was low because mud is able to carry the cuttings at a lower flow rate. The pressure drop increased after starting to drill with water, then increased steadily to the final depth even with the introduction of aerated water and foam, confirming that the pressure drop while using water and aerated water and foam is almost similar. Figure 8 shows that the well was drilled underbalanced and therefore the benefit of aerated drilling was achieved.

9. ENVIRONMENT, HEALTH AND SAFETY

9.1 Environmental impacts

A few years ago, used mud was dumped in open pits, polluting the natural environment. This is no longer acceptable, and the drilling fluid should be disposed of in a manner where there is little or no pollution of the environment (Huang, 2001). Chemicals used in the drilling fluid can pollute the environment as well, generating a variety of environmental problems (Hunt, 2000). Some of the environmental, health and safety concerns arising from drilling fluids are discussed below.

9.1.1 Surface disturbances

Before a rig is moved onto a site, preparations are made by excavating the drill site and the recirculation ponds. The excavation should be done according to the country or international excavation environmental laws. Rehabilitation should also be done by planting local grass and trees (Huang, 2000; Mwangi 2007).

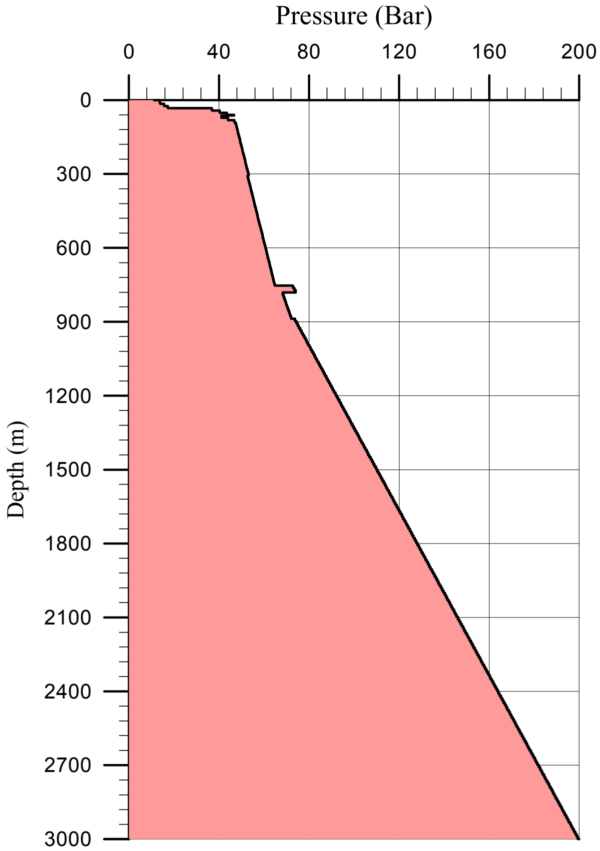

FIGURE 7: Pressure drop profile for OW-38

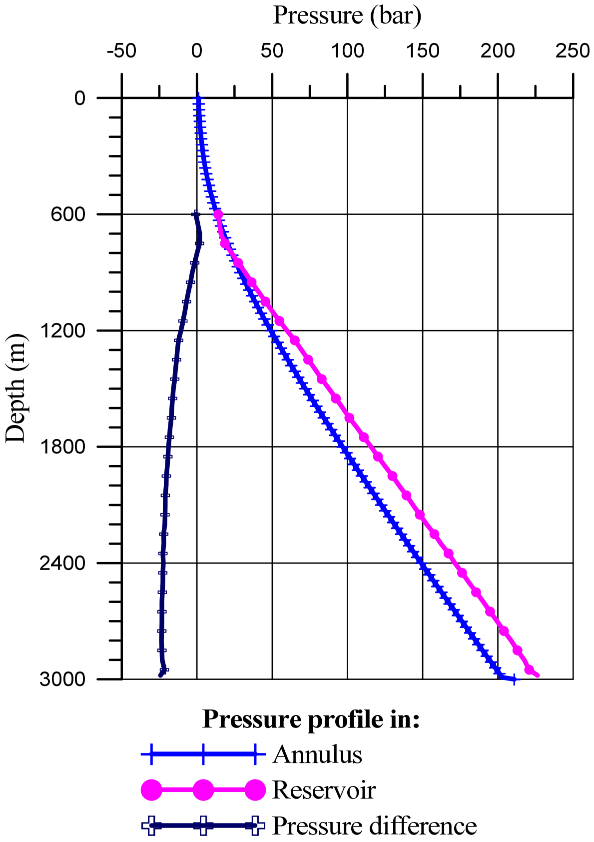

FIGURE 8: Aerated drilling pressure profile of OW-38

9.1.2 Waste management

Geothermal drilling produces significant amounts of solid waste; therefore, suitable disposal methods are needed. Geothermal drilling fluids produce wastes such as drilling mud, dirty water, foam, drill and cement cuttings. Drilling mud is either lost through circulation in the well or ends up in drilling mud tanks as solid waste for disposal. Drilling foam and dirty water end up in the recirculation pond.

While the foam may be unsightly, it is totally biodegradable and harmless. Waste mud should be stored and transported in accordance with environmental practices, as stipulated in the organization’s environmental policy (Kubo, 2001).

9.1.3 Noise management

The large compressor and booster units used in air and aerated drilling provide an additional and significant source of noise. These units are fitted with very large cooling fans which are the primary noise source. However, compressor and booster units can now be provided with full silencing to accepted noise emission standards. During air or aerated drilling, cyclone separators/silencers should be used to minimise noise as the fluids leaving the well are separated (Hole, 2006).

9.1.4 Gas emissions

There are two main gases that could be emitted while drilling a geothermal well. These are carbon dioxide and hydrogen sulphide. Carbon dioxide is not highly toxic compared to hydrogen sulphide, but at high concentrations it can be fatal due to the exclusion of oxygen or alteration of pH in the blood. Hydrogen sulphide is detectable to humans at low concentrations by the characteristic “rotten egg" smell. It is extremely dangerous, the first poisonous gas used in the first world war, and can be fatal even in low concentrations. Hydrogen sulphide dissolves in water and therefore may not be a problem during drilling using mud, water or aerated drilling (Huang, 2000). It is, however, important for the drilling crew to have gas detectors with alarm for the purpose of identifying these gases and that proper action be taken when the recommended emission limits are exceeded. The most dangerous places for gas accumulation and poisoning are down in the cellar and mud tanks.

9.1.5 Water usage

All drilling fluid and especially water should be recycled in order to conserve water and reduce the strain on the water sources (lakes, rivers etc.). Where surface waters are scarce and already over-utilized, and abstraction from groundwater is equally problematic, air drilling or drilling with foam should be considered as the first options (Ball, 2001).

9.2 Health and safety

Personal protective equipment (PPE) such as earmuffs, goggles, gloves, eye rinsing stations, self-contained breathing apparatus and other safety equipment should be provided to workers working on drilling fluids and air compressors. The necessary first aid kits should be provided alongside trained personnel at the rig site. Further, an ambulance or an emergency vehicle should be available at the rig site or nearby to assist in case of emergencies. High pressure areas should be demarcated and the entry to such areas restricted when dangerous high pressure is being utilized.

10. CONCLUSIONS

Primarily, there are four fluids utilized in the geothermal industry: water, water based mud, aerated fluids and foam. The choice of the drilling fluid depends for the most part on the cost associated with its use, its properties and the advantages associated with the fluid. It is cheaper and convenient to drill the large hole sections of wells using mud when there is no circulation loss. In general, the large top hole is drilled with mud or using foam or mud for down hole hammers, while the intermediate hole is drilled using mud and sometimes water with polymer pills/sweeps. The production section of the well is mainly drilled using water or aerated water and foam.

Loss of circulation in the cased off sections of the geothermal well should be healed either naturally or artificially. A loss of circulation in the production zone is the target of geothermal well drilling and is, therefore, what is sought for.

Energy consumption by the fluid circulation system increases with depth and the increase in hole diameter. It is cheaper and convenient to drill the production section using water. Aerated fluid drilling is expensive but it also has superior advantages when used to drill the production zones. In general, the choice of the drilling fluid used at different intervals of the well influences the cost and safety of the well.

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REFERENCES

Air Drilling Associates, 2005: *Aerated drilling services for the petroleum and geothermal industries.* Air Drilling Associates, Inc., website: *www.airdrilling.com/equipment/index.php*

Baker Hughes, 2006: *Drilling fluid reference manual.* Baker Hughes, Inc., 775 pp.

Baker Hughes INTEQ, 1995: *Drilling engineering workbook.* A Baker Hughes INTEQ distributed learning course, 410 pp.

Ball, P., 2001: *Drilled wells. Series of manuals on drinking water supply, Vol. 6.* Pat Drill, Thailand, 83 pp, website: *www.pat-drill.com/pdf/drilled_wells.pdf.*

Bennett, R.D., Ariaratnam S.T., and Como C., 2001: *Horizontal directional drilling good practices guideline.* HDD Consortium, 456 pp.

Carson, C.C., and Lin, Y.T., 1982: The impact of common problems in geothermal drilling and completion. *Geothermal Resources Council, Trans., 6,* 195-198.

Caterpillar, 2011: *STANDBY 1000 ekW 1250 kVA generator specifications.* Cat Electric power, webpage: *www.cat.com/cda/files/1563847/7/C32+1000+ekW+Standby+Low+BSFC_EMCP4.pdf.*

Chowdhury, D., Skalle, P., Rahman, M.M., 2009: Prediction of stand pipe pressure using conventional approach. *Chem. Engineering Res. Bull, 13,* 7-11, website:
http://www.banglajol.info/index.php/CERB/article/view/2703/2475.

Finger, J., and Blankenship, D., 2010: *Handbook of best practices for geothermal.* Sandia National Laboratories, report SAND2010-6048, 84 pp.

Fridleifsson, G.Ó., Ármannsson, H., Árnason, K., Bjarnason, I.T., and Gíslason, G., 2003: Part I: Geosciences and site selection. In: Fridleifsson, G.Ó. (editor), *Iceland deep drilling project, feasibility report.* Orkustofnun, Reykjavík, report OS-2003-007, 104 pp.

Gabolde G., and Nguyen, J.P., 1991: *Drilling data handbook.* Gulf Publ. Co., Houston, TX, 542 pp.

Hole, H., 2006: *Lectures on geothermal drilling and direct uses.* UNU-GTP, Iceland, report 3, 32 pp, website: *http://os.is/gogn/unu-gtp-report/UNU-GTP-2006-03.pdf.*

Hole, H., 2008: Drilling fluids for drilling of geothermal wells. *Presented at Petroleum Engineering Summer School, Dubrovnik, Croatia, Workshop 26,* 21 pp.

Huang H., 2000: Study on deep geothermal drilling into a supercritical zone in Iceland. Report 7 in: *Geothermal training in Iceland 2000.* UNU-GTP, Iceland, 105-137, website:
http://os.is/gogn/unu-gtp-report/UNU-GTP-2000-07.pdf.

Huang M., 2001: Possible environmental impacts of drilling exploratory wells for geothermal development in Brennisteinsfjöll area, SW-Iceland. Report 5 in: *Geothermal training in Iceland 2001*. UNU-GTP, Iceland, 83-114, website: *http://os.is/gogn/unu-gtp-report/UNU-GTP-2001-05.pdf.*

Hunt, T.M., 2000: *Lectures on environmental effects of geothermal utilization*. UNU-GTP, Iceland, report 1, 109 pp, website: *http://os.is/gogn/unu-gtp-report/UNU-GTP-2000-01.pdf.*

IADC, 1992: *Drilling manual* (11th ed.). International Association of Drilling Contractors, USA.

Jónsson, Í., 1975: The use of water in geothermal drilling. *Proceedings of the 2nd UN Symposium on the Development and Use of Geothermal Resources, 1, San Francisco, CA*, 1501-1502.

Kubo, B.M., 2001: Environmental management at Olkaria geothermal project. *Technical Seminar Proceedings, 2001*. Kenya Electricity Generating Co., Ltd., Kenya, 6 pp.

Lake, L.W., 2006: *Petroleum engineering handbook.* Society of Petroleum Engineers (SPE), vol. II, 770 pp.

Loeppke, G, 1986: Evaluating candidate lost circulation materials for geothermal drilling. *Geothermal Resources Council, Trans., 10,* 7 pp.

Matanovic, D., 2007: *Drilling techniques*. University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, website: *rgn.hr/~dmatan/nids_dmatanovic.*

Mortensen, K.A., Gudmundsson, Á., Richter, B., Sigurdsson, Ó., Fridleifsson, G.Ó.,Franzson, H., Jónsson, S.S., Danielsen, P.E., Ásmundsson, R.K., Thordarson, S., Egilsson,Th., Skarphédinsson, K., and Thórisson, S., 2006*: Well report for RN-19.* ÍSOR – Iceland GeoSurvey, Reykjavík, report ISOR-2006/025, 139 pp.

Mwangi, M., 2007: Environmental management in geothermal development: Case history from Kenya. *Presented at Short Course on Geothermal Development in Central America – Resource Assessment and Environmental Management, organized by UNU-GTP and LaGeo in San Salvador, El Salvador*, 11 pp.

PETEX, 2001: *Dictionary of petroleum terms, Oil and gas well drilling and servicing E-tool.* PETEX of University of Texas, Austin, website*: www.osha.gov,* 86 pp.

Thórhallsson, S., 2005: *ST-Air; programme for calculation on aerated drilling.* ÍSOR – Iceland GeoSurvey, Reykjavík.

Thórhallsson, S., 2011: *Geothermal drilling technology.* UNU-GTP, Iceland, unpublished lecture notes.

U.S. Army Corps of Engineers, 2001: *Geotechnical investigations*. Department of the Army, U.S. Army Corps of Engineers, Engineering and Design, website: *140.194.76.129/publications/eng-manuals/em1110-1-1804/entire.pdf,* 449 pp.

Zhang, X., and Ma, X., 2010: *Drilling fluids.* Geological Publ. House, China, 193 pp.