



## MAIN TECHNICAL ISSUES REGARDING PROBLEMS WHEN DRILLING GEOTHERMAL WELLS

**Bayu Wedaj Habtemariam**

Ethiopian Geological Survey

Drilling Service Center

P.O. Box 2023, Addis Ababa

ETHIOPIA

*wedaj.bayu2@gmail.com*

### ABSTRACT

Geothermal well drilling is one of the most expensive activities of geothermal projects; well costs represent 35–50% of the total capital costs of a typical geothermal project. This report describes drilling of geothermal wells and the main technical issues regarding drilling problems.

Drilling information comprises both drilling rig data and well logging, used to study and explore geothermal wells. Data is collected on or around the drilling rig and downhole data is retrieved by some type of logging tool that is either lowered into the borehole or forms a part of the bottom hole assembly. Some down-hole logs are specially made as diagnostics for drilling problems. This report mainly describes general technical issues about geothermal drilling, not specific practical case histories of boreholes drilled in Iceland and Ethiopia.

This report includes a description of the most common problems encountered in geothermal drilling: loss of circulation, getting stuck, twist off, slow drilling, bit wear and cementing. Drilling records from the digital rig instrumentation system and from downhole logging are of great aid in handling these issues. Methods of cementing zones with large losses of circulation are briefly dealt with at the end of the report.

### 1. INTRODUCTION

Geothermal drilling relies primarily on technology employed in the oil and gas industry, modified for high temperature applications and larger well diameters. Geothermal drilling is more expensive than on-shore oil and gas drilling for three principal reasons:

- a) *Technical challenges*: Special tools and techniques are required for the harsh downhole conditions.
- b) *Large diameters*: Economically, there is a need to produce hot water or steam at large flow rates. Thus, a wide hole and casing are required. In many cases, to achieve a specific depth, the design will require more casing strings in a geothermal well than in an oil and gas well.
- c) *Uniqueness*: Geothermal wells, even in the same field, are more dissimilar than oil and gas wells in the same field.

As drilling has become more complex with directional drilling, additional well measurement techniques have been adapted such as measurement-while-drilling (MWD), a type of well logging that incorporates the measurement tools into the drill string and transmits real time information of the inclination and azimuth to the surface, helping with the steering.

Drilling information comprises both data collected on or around the drilling rig and downhole data retrieved by some type of logging tool that is either lowered into the borehole or forms a part of bottom hole assembly.

*Drilling problems:* Trouble is a generic name for many sorts of unplanned events during drilling, ranging from minor ones, such as small amounts of loss of fluid circulation, to catastrophic, such as the bottom hole assembly getting stuck in the hole and the drill string being twisted-off (broken). In some cases, experience in the same or similar reservoirs will give a hint that certain types of trouble are likely, but at other times events are completely unexpected. It is difficult, therefore, to estimate a cost for such risks, but all well expenditure planning must contain some contingency, typically 10% of the total budget.

Eliminating well problems requires time, materials, labour and equipment, all of which increase the cost of drilling. For this reason the study of the causes of drilling complications and their effective prevention and elimination is one of the priorities of drilling organizations.

*Cementing:* Casing has traditionally been cemented into place by pumping a calculated amount of cement slurry into the casing, placing a movable rubber plug on top of the cement, and then displacing the plug downward by pumping water on top of it. This forces the cement to flow out at the bottom of the casing and up the annulus between the casing and wellbore. In most oil and gas wells, the casing is cemented in place only at the bottom, with a completion fluid between the casing and the well bore wall, but geothermal wells must have a complete cement sheath from bottom to surface. This cement has three important functions: to give the casing mechanical support under its sometimes intense thermal cycling between production and shut-in, to exclude unwanted aquifers due to low temperatures and to protect the outside of the casing from corrosion by in-situ fluids.

## 2. RIG INSTRUMENTATION AND LOGGING

Complete information about the rig's performance is essential for safe, efficient operation, and the project planner should include an instrumentation list in the rig specifications. Detailed requirements may vary from project to project, but a typical set of desirable measurements includes the following: rates and temperature of drilling fluid inflow and outflow, H<sub>2</sub>S gas detection, stand pipe pressure, rotary speed, weight on the bit, torque and Kelly height. All these measurements should be digitally recorded on a data logger at reasonably short intervals so that they can be easily stored and retrieved, but selecting the interval between measurements is not straightforward. For steady-state drilling, in which operations are routine, data points should be refreshed every second on a display and stored every 5-10 seconds. In unstable, possibly damaging drilling conditions, such high resolution data can be extremely valuable. A sketch of a basic rig instrumentation system is shown in Figure 1.

Drilling time log, which may be recorded continuously by digital or mechanical instruments or by the driller, records the time required to drill each depth of the formation. As different formations drill at different rates, the drilling time log provides variable information concerning the lithological character of the formations being penetrated. Dull bits, changes in drilling speeds and weight on the bit affect the drilling time log.

One of the most difficult problems encountered in drilling operations is the correct evaluation of the formations being penetrated by the drill bit. The use of all possible formation evaluation tools would

not be practical or economical. A careful study of the advantages of each technique and the applicability of these techniques in specific cases, along with the amount and type of information required, will determine which method can be most effectively used in a specific operation.

Drilling into the crust of the earth makes it possible to lower instruments into the boreholes and carry out in situ measurements in order to gain information on the rock formation surrounding the well, temperature and pressure within the well and other parameters. This family of measurements recorded about the well is commonly called well logs or wire line logs to distinguish them from various drilling logs. This is a very heterogeneous family of measurements with the only thing in common being that they are carried out within a well. The purpose of the logs or measurements is manifold but the objectives are often divided into three types. The first type is logs that relate to the well itself i.e. its design, geometry and completion. Then there are logs to study the rock

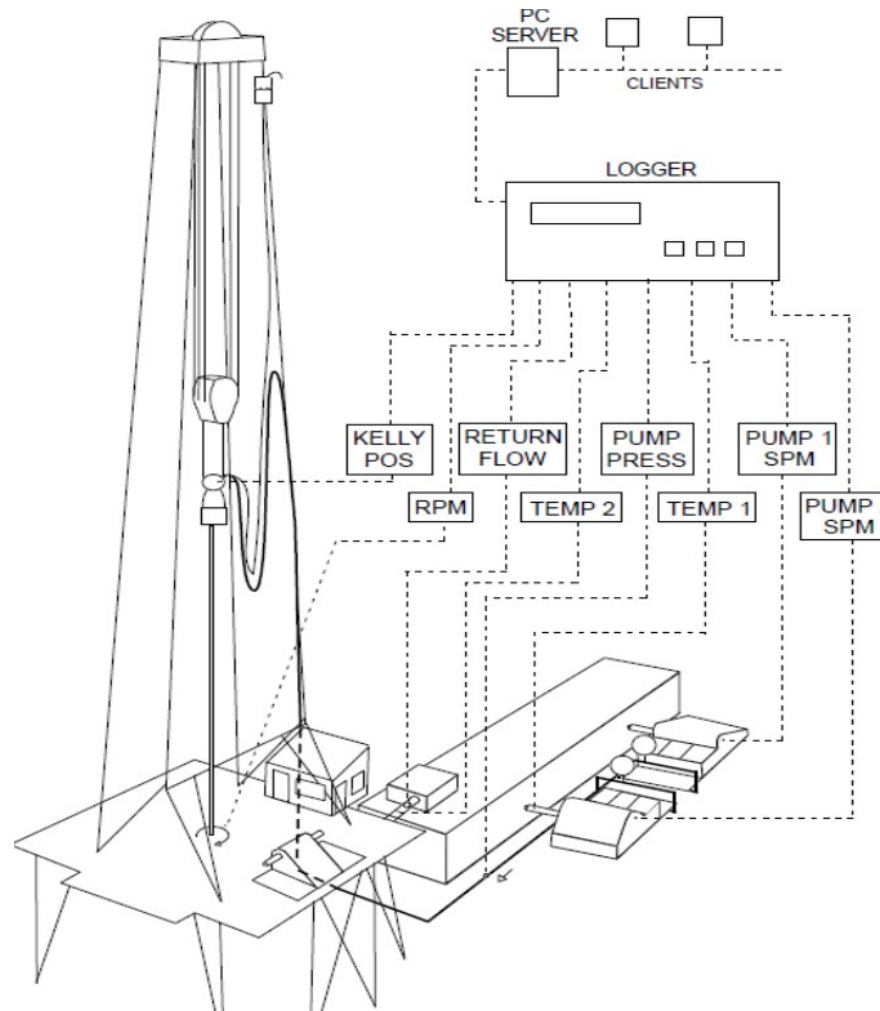


FIGURE 1: Simple rig instrumentation (Thórhallsson, 2012)

formations outside the well and the fractures intersected by the well and finally there are logs that determine the temperature of the well, fluid pressures and the location of the feed zones intersected by the well. Today, wire line well logging is a highly sophisticated technique where complex packages of electronics and sensors are placed inside a logging probe which is then lowered on a wire line (cable or steel wire) into the well to carry out measurements continuously or at discrete depth intervals while the probe is moved down or up the wells. The measurements are sometimes stored in an electronic memory in the logging probe but most commonly they are transmitted through the cable to the surface and stored along with the depth of the probe in a computer for later analysis and interpretation. Well logging is carried out in all kinds of wells but it is most advanced in oil well drilling where sophisticated and expensive well logging tools and interpretation methodology are applied to evaluate the geological structure around the oil wells and to determine the water, oil and gas content in the oil bearing formations. Application of wire line logging in geothermal exploration has, in most countries through the years, been mainly limited to temperature and pressure logging (Finger, 2010). A temperature and pressure memory tool with a thermal shield is used a lot during drilling, sometimes with a spinner, but even more so during the well heating up period and later flow tests (e.g. Kuster K-10 tool).

## 2.1 Surface measurements

The drilling rig will have a set of instruments that are required for its normal functions to guide the driller. For example, a representative rig logging system records the following measurements: depth, block height, rate of penetration, bit depth tracking while tripping, hook load, weight on bit, rotary table or top drive RPM, final bit RPM after mud motor, torque, standpipe pressure, casing pressure, pump stroke rates, return flow rate, individual pit volumes, mud gain / loss, and mud temperature in and out.



FIGURE 2: Weight indicator (Thórhallsson, 2012)

A weight indicator is a device for measuring the weight of the drill string hanging from the traveling block. This device, as originally designed was intended principally to show the load on the derrick at all times, thus preventing derrick overload. The instrument has gained wide use, for in addition to showing visually, at all times, the load on the derrick structure, it also displays the weight on the bit during drilling and friction loads when removing the drill pipe from the hole. A very important use of the weight indicator occurs when maximum pulls are being applied to recover stuck equipment and during fishing operations (Figure 2).

Understanding how to use the measurements is clearly important, and should be part of the driller's training. Mud flow rates in and out of the wellbore are diagnostic for lost circulation and well control issues. Many of the measurements can be combined electronically in such a way that an alarm will sound if undesirable conditions appear (Finger and Blankenship, 2010).

It is also possible to use trend data, torque and weight on bit related to rate of penetration, pump efficiency compared to mud flow rate, and temperature change as a function of depth to establish statistical trends that are a measure of drilling performance or downhole conditions. It is also possible, in principle, to combine surface measurements in a way that provides diagnostics for various drilling conditions and then employs an expert-system approach to recommend subsequent actions.

## 2.2 Downhole measurements

Geothermal wells are drilled with a drill bit. This action is expected to form a circular well of a diameter corresponding to the diameter of the drill bit. This is, however, not necessarily the case. During drilling, the drill cuttings created at the bottom are flushed to the surface through circulation of drilling mud and water. This sandy fluid, together with the rubbing of the drill string against the wall of the well, will erode the formations as it flows up the hole, creating a larger hole than the drill bit size. The formations drilled through are of different hardness. The erosion will be greater in soft formations than in the harder formations. Some formations drilled into might even be unstable, formations such as sand, gravel or sediments, in which case caves will appear in the well. The caliper log measures the diameter of wells to obtain information on their true size and shape. An example of a caliper log is given in Figure 3.

During drilling, down hole data can represent reservoir conditions or drilling performance or both and this information can lead to:

- a) A change in the drilling method for greater efficiency and lower cost;
- b) A decision to set casing;
- c) Initiation of lost circulation mitigation; and
- d) Possibly even preventive measures that can avert a disastrous loss of well control.

Apart from the clear necessity to know whether the hole is approaching a geothermal resource, pressure and temperature logs can clarify a number of other drilling situations (Steingrímsson, 2011).

For the cases cited above, real-time data are not critical, so memory tools would be quite adequate. These examples indicate the versatility of pressure and temperature logs, so having this capability as a standard part of the drilling program is very useful.

- a) Logs can provide a warning if any temperature-limited downhole equipment (including drilling fluid) is approaching its limit;
- b) If a lost circulation zone appears during drilling, logs can often define its location;
- c) Logs can guide the amount of retarders to add to cement before cementing the casing;
- d) For an injection test in a potential production zone, logs can identify fracture locations; and
- e) Logs can usually identify favourable (impermeable) zones for setting packers, if that is part of the test program.

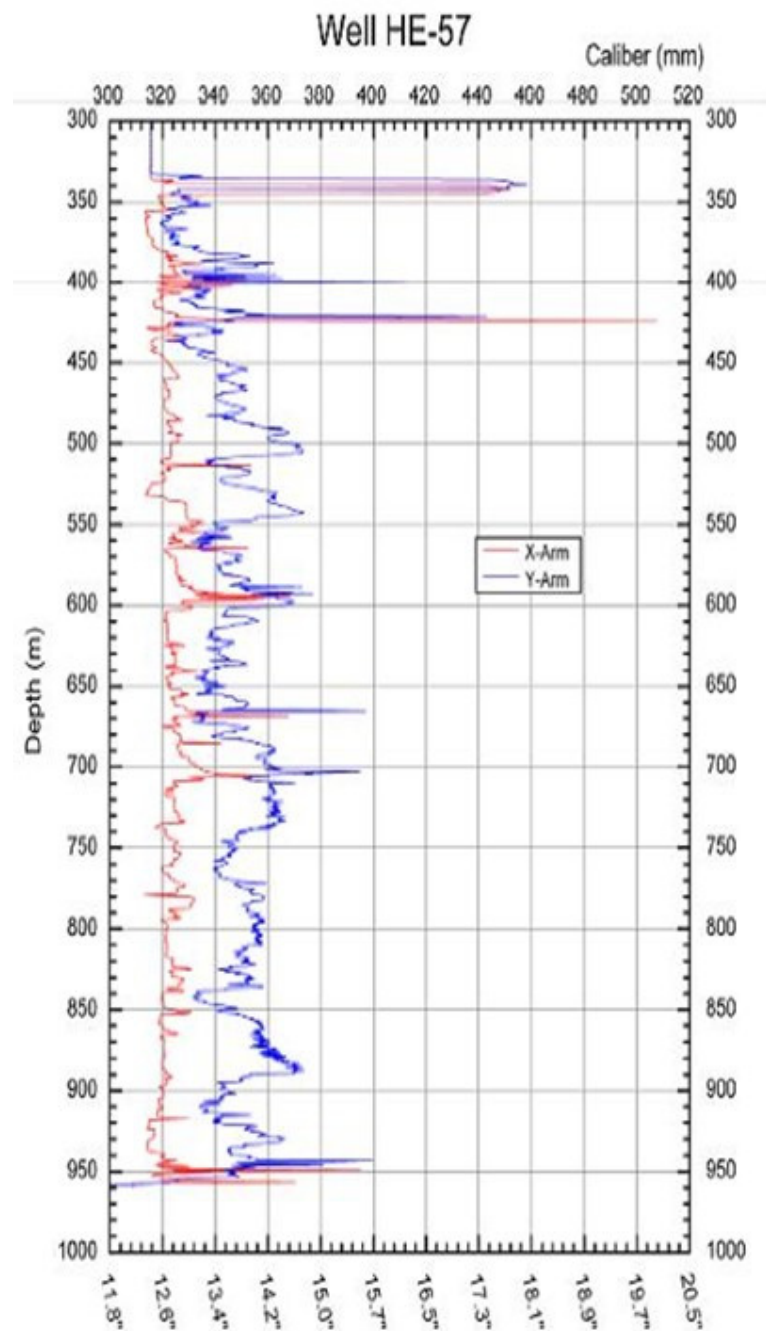


FIGURE 3: Caliper log (Steingrímsson, 2011)

### 2.2.1 The caliper log

Many different types of caliper logging probes are in use. Most of them are mechanical tools equipped with several spring-loaded arms which are opened and closed with a small electric motor placed inside the logging probe (Figure 4).

In the open position the arms are pushed against the wall of the well by springs. The position of the arms is registered electronically to measure the diameter of the well. Commonly, the tools can register diameters up to about 1 m (40"), but extensions to the arms are available for wider holes. In a circular well a tool with a one arm wobble is sufficient, but as the open section of wells is often oval in shape,



FIGURE 4: X – Y (4 arm) caliper probe (Steingrímsson, 2011)

most caliper probes have several arms. Probes with 3, 4 or 6 arms are most common and in special cases, i.e. inspection of casing wear or corrosion, probes with up to 60 arms are available. The arms in the 3 arm tool are all interconnected and only show an average diameter for the well, whereas the arms in the 4 and the 6 arm probes are independent pairs. The 4 or 6 arm probes are independent pairs and will reveal if the well is elliptical. Caliper logging starts as the tool is run into the hole with the arms closed. At the bottom or the deepest logging point, the tool is stopped and the arms are opened until the springs push them properly against the wall of the well. The tool is then run up the well at a constant logging speed, typically 15-30 m/min while the diameter is registered at a few centimetres interval. The electronic components in the caliper logging probe, as well as the logging cable used, have a limited temperature tolerance. The most common tools have only a maximum temperature rating of 150-175°C. This is generally sufficient during the drilling phase, even for very high temperature wells, as the wells are cooled during the drilling by the circulation of the drilling fluid or by cold water injection. A casing inspection tool has been developed by a New Zealand company that can tolerate up to 320°C (Stevens, 2000).



FIGURE 5: Go devil (Steingrímsson, 2011)

High-temperature tools are available for hot wells, mechanical clock driven tools with downhole registration, similar to the well-known Kuster temperature and pressure gauges, and also tools of conventional design but with high-temperature electronics. These tools are, however, rather expensive and the same applies for the high-temperature logging cables. Go devils (Figure 5) are frequently used in high-temperature wells when cooling the well is not an option. They are in fact sinker bars with baskets of different fixed diameters and, therefore, show only the maximum depth of clearance in the well.

The go devils give a much cruder picture of the well diameter than the conventional caliper tool. Go devils are mainly used to study scaling in wells and casing damages in hot wells where the caliper tools would fail.

Caliper logs also give information on the rock formations that wells intersect. Soft formations tend to wash out but stronger formations do not. Cavities are seen where the well crosses sediments, sandy layers or fracture zones. The cavities can become a problem for the drilling as the circulation fluid is slowed down when it flows through a cavity (Steingrímsson, 2011).

At critical cave diameters the circulation fluid velocity will become too small to carry (lift) the drill cuttings up through the cave and the drill cuttings accumulate in the cavity. This will lead to insufficient cleaning of the well and the drillers will observe filling in the well, irregular torque in rotating the drill string and even sticking of the drill string. If the drillers do not act on this they will sooner or later find the drill string stuck in the well. Running a caliper log in the well will show the location of the cavities

and their size. Large cavities can then be filled with cement; when it has set the cement plug is drilled out leaving a cement shell filling the cavities.

The success of the cementing of the cavities can then be checked by running a caliper log. This is an example of the application of caliper logs to solve drilling problems. The main applications of caliper logs are the following:

- a) Estimating the amount of cement slurry required to fill the annulus between the casing and the wall of the well.
- b) Comparison of the caliper logs with the lithological section of the well according to drill cuttings studies with respect to formation strength.
- c) Location of cavities, determination of their diameter and length.
- d) Evaluation of the success of cementing large cavities causing problems during drilling.
- e) Finding location for a packer, ideally in hard formations where washout is minimal.
- f) Evaluate depositions in wells (calcite or silica scaling).
- g) Evaluate casing corrosion.
- h) Evaluate casing damages.
- i) Correction of other geological logs. The response of those logs is influenced by the amount of water surrounding the probe, which is determined by the size (diameter) of the well.

### 2.2.2 Measurement while drilling (MWD)

As drilling has become more complex, with directional wells increasing in numbers, well logging has also had to adapt and improve. MWD is a type of well logging that incorporates the measurement tools into the drill string and provides real-time information to help with steering the drill. Once a well inclination angle exceeds 60 degrees, the logging tools can no longer be lowered through the well to retrieve information, making conventional logging tools ineffective. Originally designed in the 1980s to overcome well logging challenges of wells being drilled at extreme angles, MWD records measurements on a real time basis while drilling is in progress. Vieira (2009) states that the measured data may be transmitted to the surface by one of the three methods stated below.

- a) Via a wireline;
- b) Through pressure variations in the drilling mud/fluid (mud pulse); and
- c) Through electromagnetic or radio waves.

In drilling, the three most important parameters for the directional driller are the inclination, the direction (azimuth), and the direction of the tool face. Inclination is measured by accelerometers which can measure the components of the earth's gravitational field. The direction of the hole is measured by magnetometers which can measure the earth's magnetic field.

The MWD tools used for geothermal drilling employ pulse transmission of the signal from the tool to the surface.

*Mud-pulse telemetry:* The MWD transmits signals to the surface through the drilling fluid column inside the drill string, allowing the driller to obtain real time readings on the monitoring screen while drilling is in progress, including when the drill string is rotating. Five components are identified in the mud-pulse telemetry equipment (Vieira, 2009):

- a) Downhole unit that senses direction and inclination;
- b) Mud pulse generator, also called a pulser;
- c) Surface transducer that decodes mud pressure variations and transforms into electric signals;
- d) Computer that receives the electric signals and interprets them; and
- e) Rig floor unit that displays the data.

The mud pulse generator contains a microprocessor that converts the survey data (inclination, direction and tool face orientation) into a series of positive and negative pressure pulses. A positive pulse

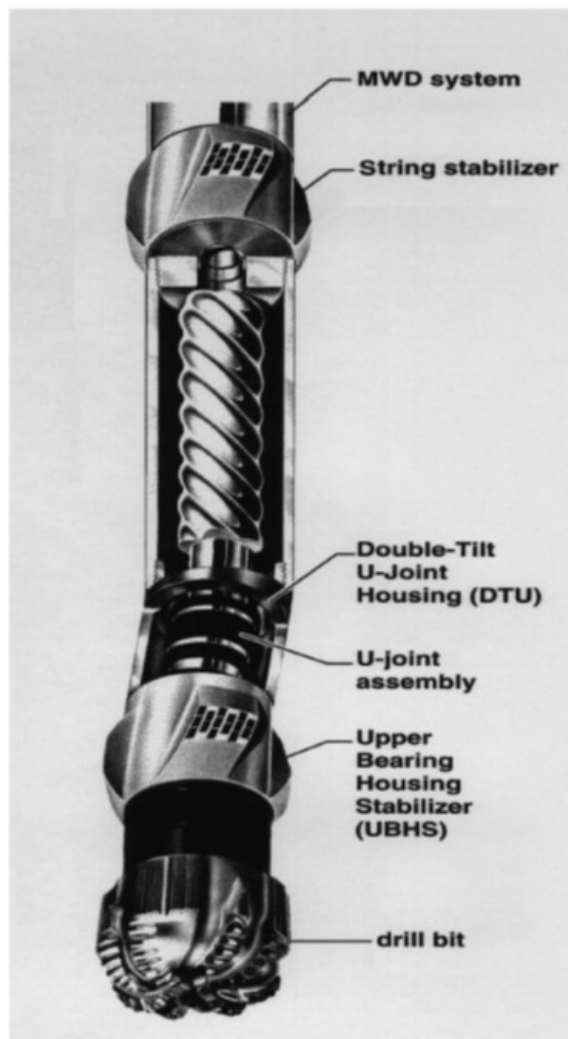


FIGURE 6: Parts of downhole motor  
(Baker Hughes INTEQ, 1995)

indicates pressure increase and a negative pulse indicates pressure decrease. The pulses are usually transmitted to the surface coded in a binary signal. The mud-pulse telemetry unit inside the hole contains accelerometers and magnetometers for measuring inclination and direction (Figure 6).

To avoid magnetic interference, the MWD tool is placed within the nonmagnetic drill collar. The downhole unit is powered electrically by a turbine which is rotated by the drilling fluid. The unit can also be powered by batteries. Some mud pulse units contain both batteries and turbine. Measurements are made continuously as drilling goes on, whether there is circulation or not. The data is transmitted to the surface only when there is circulation or when circulation resumes. The limitation of mud pulse telemetry is that it cannot transmit data when drilling with air or aerated drilling fluids or when there is no continuous column of drilling fluid (Miyora, 2010).

With such precise wells being drilled, MWD aids drilling engineers with real-time information so that they can make important decisions while drilling. Geo-steering is a relatively new concept of positioning wells according to the geological features in the reservoir obtained through MWD.

Wireline logs are used for directional drilling, either single or multi-shot, to confirm the MWD results or are used alone to drill the well.

Figure 7 shows inclination, azimuth, true vertical depth (TVD) and intended horizontal displacement in well HE-53 at Hverahlíd geothermal field, Iceland. Black lines show the true trajectory and the numbers indicate measured depth. Red dotted lines show the intended trajectory and blue lines the tolerance from the intended trajectory.

### 3. DRILLING PROBLEMS

Trouble is a generic name for many sorts of unplanned events during drilling. The following drilling problems are most important: loss of circulation, getting stuck, twist off, slow drilling, bit wear and difficult cementing jobs.

#### 3.1 Loss of circulation

The common denominator of all convective hydrothermal systems – the majority of all developed geothermal fields – is the highly permeable, fractured and faulted nature of the formations in which the geothermal reservoirs reside. This high permeability is fundamental and a requisite component for any geothermal system to exist (Figure 8).



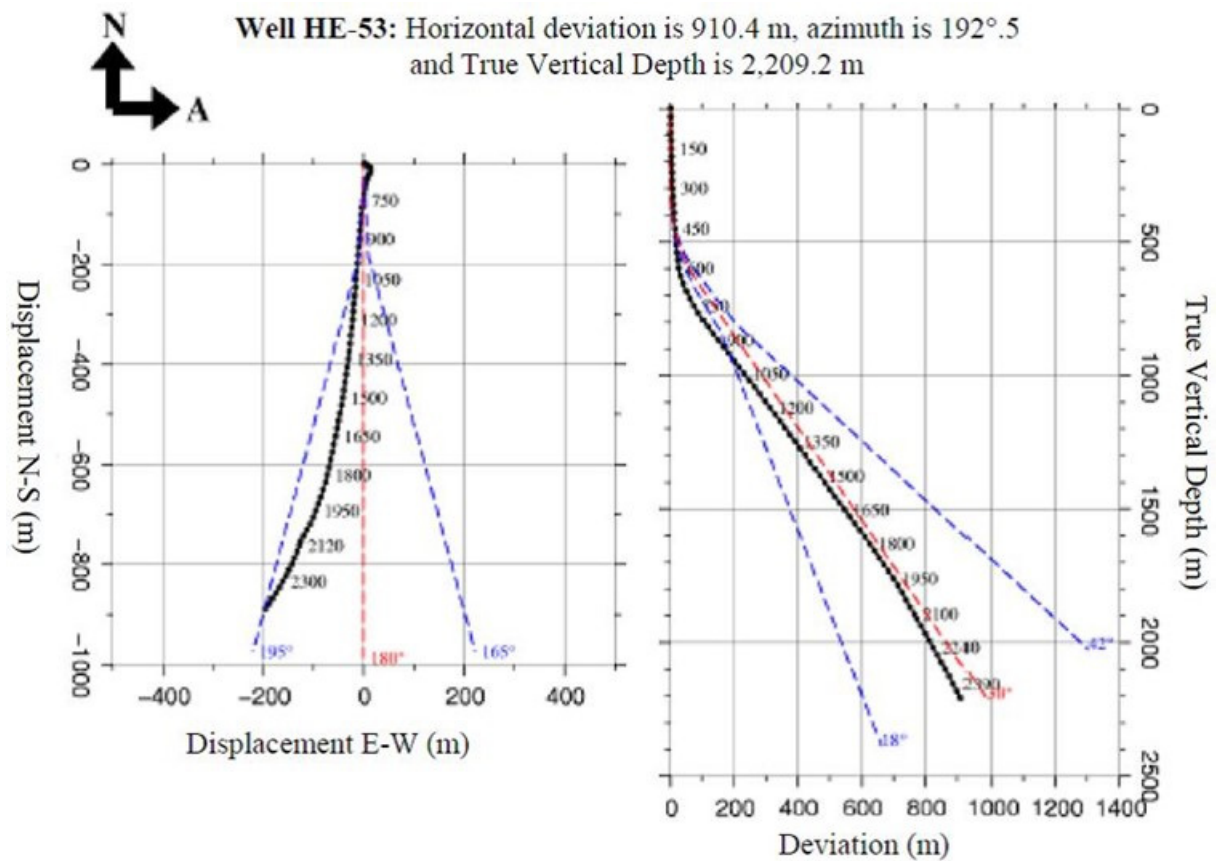


FIGURE 7: Trajectory of well HE-53 at Hverahlid geothermal field, SW-Iceland (Nielsen and Tryggvason, 2011)

Typically, the permeable nature of the formations is not limited to the geothermal reservoir structure alone, but often occurs in the shallower and overlying formations as well. This, coupled with the under-pressured nature of most geothermal systems, results in the partial or total loss of circulation of drilling fluid at some stage during the drilling of the well. In fact, ultimately if circulation is not lost in an under-pressured system, it is an indication that there is no permeability and, therefore, the well is a dry well (Finger and Blankenship, 2010).

The most expensive problem routinely encountered in geothermal drilling is loss of circulation which is the loss of drilling fluid to fractures and pores in the rock formations being drilled; lost circulation represents an average of 10% of the total well cost in mature geothermal cases and often accounts for more than 20% of the costs in exploratory and production wells.

Lost circulation occurs only when the drilling mud column pressure exceeds that of the formation fluid and when the formation permeability is sufficient. Lost circulation may also result from hydraulic fracturing of the formation. It may take place in incompetent formations in which fractures are induced by the hydrostatic pressure of the fluid column.

This loss is harmful for several reasons and the tendency toward lost circulation is aggregated by the pressure imbalance between the relatively cool-denser-column of drilling fluid and the hot-lighter fluids in the formation.

- a) If the drilling fluid fails to clean the hole and returning cuttings to the surface, the cuttings can fall back onto the bottom hole assembly and stick the drill pipe.
- b) Drilling mud, when used, is expensive and losing it to the formation instead of re-circulating it is costly.

- c) In geothermal wells the productive zones are usually lost-circulation zones, so it is not possible to cement and preserve its productive potential.
- d) 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 and lead to a blow-out.
- e) In the depth intervals of the well that are not to be produced, the lost circulation zone may have to “sealed” to provide a wellbore that can be cased and cemented to the surface, or the cementing process must accommodate backfill cementing. Adequately cementing the casing through lost circulation zones is a major problem and a major cost due to the time it takes and also for materials.
- f) The lost circulation materials (LCM) or cement being used to heal the loss zone is 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.
- g) Combating lost circulation can be approached in different ways: drill ahead with lost circulation; drill with a light weight drilling fluid (aerated) that will have a static head less than the pressure in the formation; mix into the drilling fluid material fibres or particles that will plug the loss apertures in the formation (LCM); or pause the drilling and try to seal the loss zones with some material that can be drilled out as the hole advances.

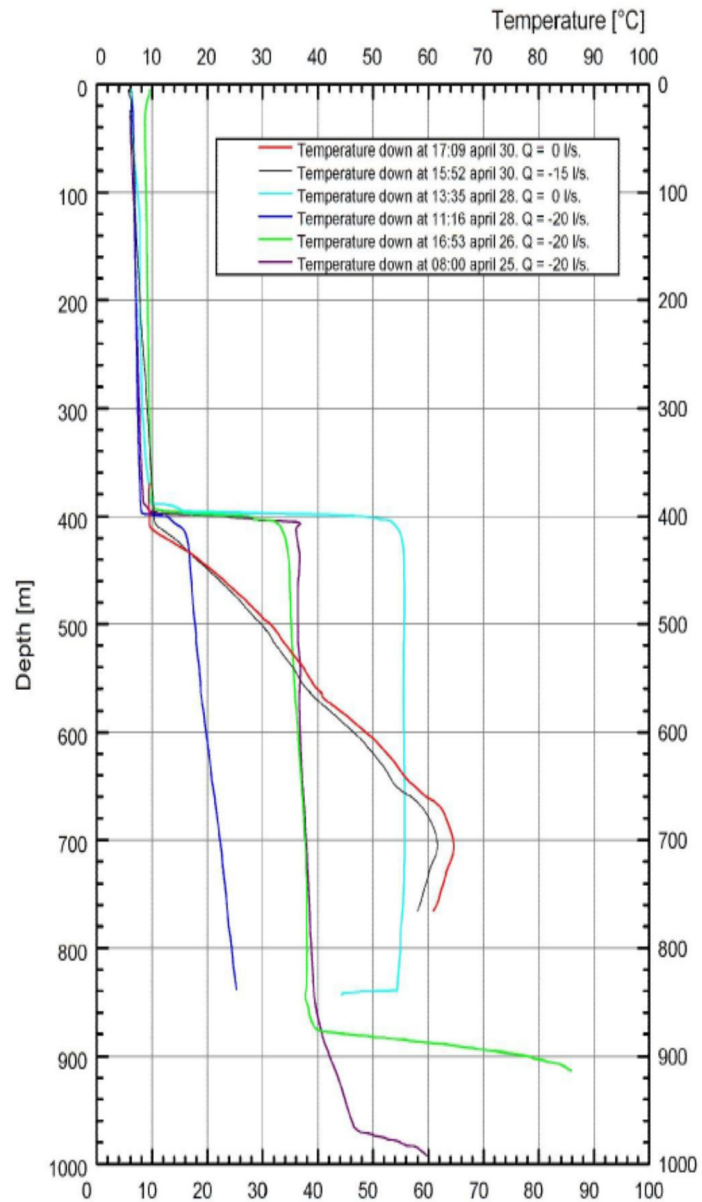


FIGURE 8: A temperature log (Steingrímsson, 2011)

At present, there are three categories of loss rate found in permeable formations: low – up to 10-15 m<sup>3</sup>/h; medium – up to 40-60 m<sup>3</sup>/h; and high – more than 60 m<sup>3</sup>/h (Sidorov, 1985).

High-rate losses, the so-called disastrous lost circulations, are distinguished as losses which cannot at present be eliminated by conventional methods.

Low-rate loss of circulation is eliminated by charging the drilling mud with filling materials (LCM), such as mica flakes, fine rubber curbs (1-5 mm in practical size), aqueous dispersion rubber, etc. Of the above fillers, the aqueous dispersing wet rubber in an aqueous medium is the least known. This material is used as filler in the amount of 5-10% of the drilling mud to prevent the pipe string from sticking. Lost returns of medium rate are remedied by forcing a quick-setting mixture with filling materials into the affected formation.

The thixotropic and gelling nature of water-based bentonite mud assists in sealing minor loss zones and, with the addition of loss circulation materials, many minor loss zones can be completely sealed. However, if major or total losses of circulation are encountered, and cannot be sealed with LCM added to the mud, then it becomes impractical and uneconomical to continue drilling with mud. If high permeability and, therefore, significant or total losses of circulation are 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 such cases, high-viscosity pills are circulated from time to time to insure proper hole cleaning (Finger and Blankenship, 2010).

### 3.1.1 Drilling with water

Water as a drilling fluid was, in the past, used to continue drilling past an unsealable loss zone and for the final production section of a geothermal well. When drilling into a permeable zone that is under pressured, the drilling fluid circulation is lost, and the drilling fluid flows into the formation rather than returning to the surface.

The traditional method for dealing with this situation was to continue drilling 'blind' with water – the pumped water being totally lost to the formation with the drilling cuttings being washed into the formation as well. The major problem with this method of drilling is that the cuttings rarely totally disappear into the formation. Stuck drill strings, due to a build-up of cuttings in the hole, and well-bore skin damage are common occurrences (Hole, 2008). The advantages of using water as drilling fluid are:

- a) As the water is not recirculated but is lost to the formation, the downhole temperature becomes significantly lower, extending drill bit life and reducing the likelihood of a kick developing.
- b) As lower bottom hole circulating pressures are developed, penetration rates are higher.
- c) Because mud and thick wall cake are not squeezed into permeable zones, reduced formation sealing and increased well productivity are achieved.
- d) Because a wall cake is not developed, differential sticking does not occur. Where a wall cake is present from earlier drilling, the lower downhole circulating pressure significantly reduces or eliminates the risk of differential sticking.

The disadvantages of using water as drilling fluid are:

- a) A continuous large volume (~30-60 l/s) supply of water to the drilling rig is required.
- b) As water has a low viscosity, is not thixotropic and cannot develop gel strength, slip velocities are higher requiring increased annular fluid velocities, and as soon as pumping to the drill string is stopped (e.g. to make a connection), any cuttings suspended in the annulus will start settling immediately, which increases the risk of a stuck drill string.
- c) Cuttings are not returned to the surface, but washed into the permeable zones.
- d) There is no geological data in total loss, as there is no return of cuttings to the surface.
- e) The loss of cuttings into the permeable zones may reduce permeability (not as much as mud).
- f) When pumping is stopped, cuttings accumulated in permeable zones may flow back into the well increasing the risk of a stuck drill string.
- g) Loss of large volumes of cold water to the formation can cause long thermal recovery periods after drilling is completed and before the well can be discharged.

Great care must be exercised when drilling with water to avoid becoming stuck with cuttings settling down the annulus.

### 3.1.2 Drilling with lost circulation

If an adequate water supply is available it is practical to drill without returns. For drilling in total loss with water in 361.95 mm (12¼") holes, 50-60 l/s of water are required and 30-40 l/s for 215.90 mm (8½"). If fresh water is not available, produced effluent from flowing wells, which would normally be re-injected, can be used for drilling wells within a developed project. Drilling without returns is frequently used when core drilling, where the cuttings are very fine and much of the rock comes out of the hole in

the form of a core. 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. High viscosity sweeps of polymer or mud pills are usually used to reduce this risk. Once a 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).

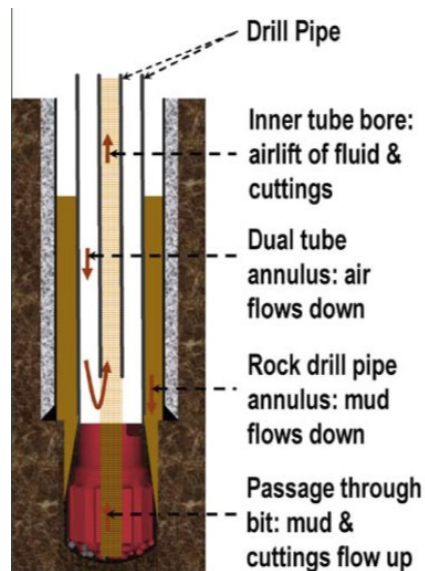


FIGURE 9: Drawing of DTRC (Finger and Blankenship, 2010)

Another technology that is useful with lost circulation is dual tube, reverse circulation (DTRC) drilling. It requires a dual tube drill string. This method uses a drill string annulus between the inner and outer tubes for the compressed air, circulating out through the bit, and carrying the cuttings back up through the centre tube (Figure 9). This means that it is only necessary to maintain fluid around the bit and bottom-hole assembly, so drilling with complete lost circulation is possible. This technique has been used on several geothermal wells and, in one case, reduced the cost per foot of drilling comparable wells by more than one-third (Finger, 2010). A number of contractors offer this service, and it is readily capable of operation at geothermal temperatures. However, as stated in the reference, conventional well control is not applicable to flooded reverse circulation drilling. If this technique is used, appropriate well control procedures must be designed into the drilling method, providing a substitute for conventional well control procedures, so a safe operation can be maintained. For the time being, reverse circulation is mainly applicable for drilling large diameter sections to shallow depths.

### 3.1.3 Lightweight fluids

There are three categories of lightweight fluids: foam and aerated fluids from the lowest density to the highest density. Air only can be used where liquid production is minimal or non-existent such as in vapour-dominated geothermal reservoirs. Foam will tolerate some water dilution, but not much, while aerated fluids can tolerate a significant amount of dilution. Aqueous (water-based) foam is attractive because of its simplicity, but it is important to use the proper surfactant (soap).

Aerated drilling may be defined as the addition of compressed air to the drilling fluid circulating system to reduce the density of the fluid column in the wellbore annulus such that the pressure within the wellbore annulus is balanced or slightly underbalanced with respect to the formation pressure in the permeable loss zones of a geothermal well (Hole, 2007).

The equipment required to undertake aerated drilling operations varies with the type of fluid system selected. A schematic layout of this equipment is shown in Figures 10 and 11. Aerated fluids, liquids with compressed air injected into it, produce a static head less than or only slightly greater than the pore pressure and are common remedy for lost circulation in geothermal drilling. They also reduce the probability of differential sticking. Aerating drilling is used extensively in many locations. Its use not only avoids problems with lost circulation, but may also improve the well productivity after drilling. The primary objective of utilising aerated drilling fluids is the ability to maintain drilling fluid circulation and, therefore, the cleaning of cuttings from the hole as drilling proceeds into permeable and 'under pressured' zones. This continuous cleaning of cuttings from the hole significantly reduces the risk of the drill string getting stuck in the hole and enables drilling to the target depth.

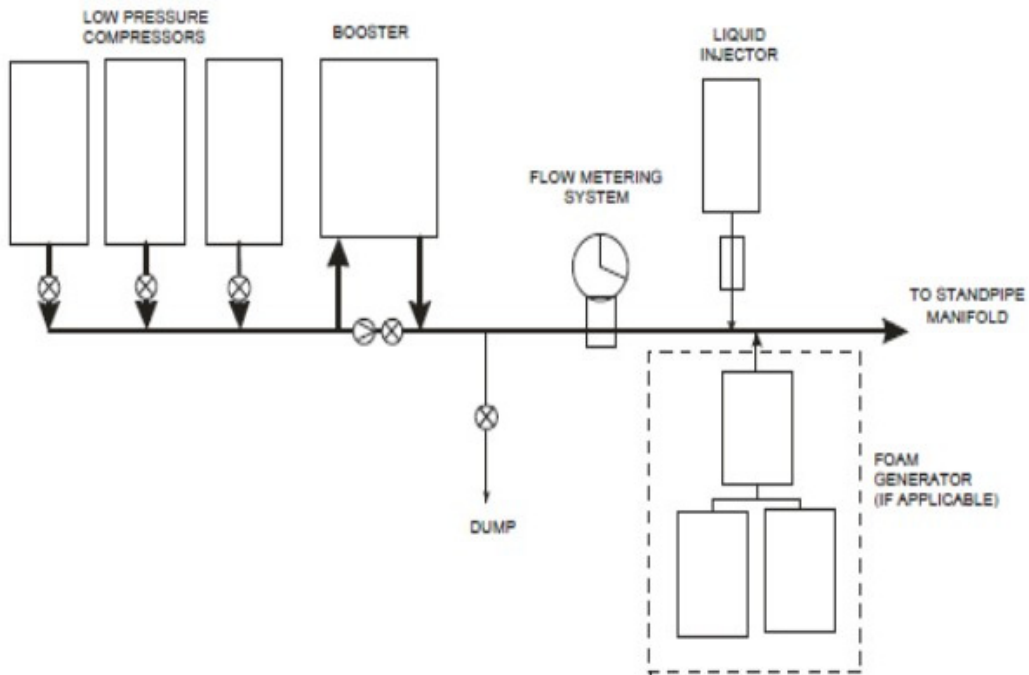


FIGURE 10: Aerated drilling air compression equipment schematic layout (Birkisson and Hole, 2007)

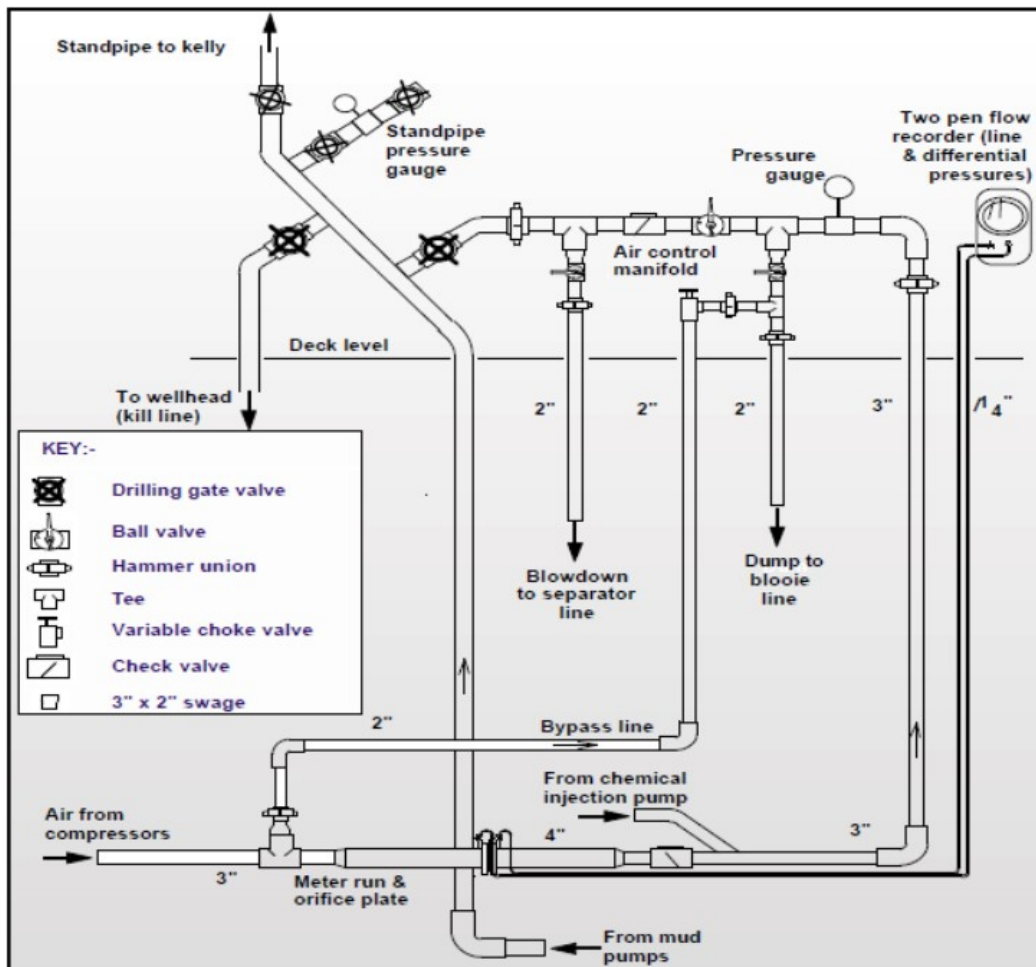


FIGURE 11: Aerated drilling standpipe manifold schematic (Birkisson and Hole, 2007)

As the introduced air is a compressible medium, the density of the column varies with depth. At the bottom of the hole where the hydrostatic pressure is greatest, the air component is highly compressed and, therefore, the density of the fluid is greatest. At the top of the hole, where the hydrostatic pressure is least, the air component is highly expanded and, therefore, the density of the fluid is lowest. The ratio of air to water pumped into the hole, and the back pressure applied to the 'exhaust' or flowline from the well, allows the down-hole pressures in the hole to be 'balanced' with the formation pressure in the permeable zones, thus allowing for the return of the drilling fluids to the surface and, therefore, maintaining drilling fluid circulation.

Initially the technique was utilised only in the smaller diameter production hole section of a well, however in some fields permeability is prevalent in the formations located above the production zone, and significant amounts of lost time can be incurred in attempting to plug and re-drill such zones. Utilising aerated fluids to drill these zones has proven to be a highly successful solution.

Perhaps the most important feature of aerated drilling is its effect on the productivity of the well. The removal of drill cuttings from the well bore, rather than washing the cuttings into the permeable zones, reduces the potential of blocking up and, in some cases, sealing the permeability close to the wellbore; this effect is called well-bore skin damage. A relatively small amount of interference to the flow from the formation into the well-bore, or skin damage, can have a significant effect on the productivity of the well (Birkisson and Hole, 2007).

Wells drilled with aerated fluids, and thus with full circulation and removal of drill cuttings, 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.

### **3.1.4 Lost circulation materials (LCM)**

LCM particles that will plug the bit nozzles are unacceptable, but for smaller fractures or for smaller matrix permeability, the wellbore can theoretically be sealed by pumping solid or fibrous material mixed with the drilling fluid. This method is much less effective with larger fractures. Such particles have been used in the oil and gas industry to plug lost circulation zones, but most of them have been of organic or cellulosic material that cannot withstand geothermal temperatures, but mica flakes and seed hulls can (Finger and Blankenship, 2010).

Lost circulation material, in general, has often been unsuccessful in geothermal drilling. Several candidate materials that withstand high temperature have been identified, but they should only be used in the non-productive intervals, since they could permanently plug the productive intervals.

### **3.1.5 Cementing loss zones**

Fractures too large to be plugged by LCM can only 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 in resumption of drilling. Conventional lost circulation treatments practiced in geothermal drilling consist of positioning the lower end of an open end drill pipe near or below the suspected loss zone and pumping a given quantity of cement slurry down the hole.

The objective is to emplace enough cement into the loss zone to seal it. However, this does not always occur. There are many issues in getting cement placed into the fractures that are causing the loss zone. If the loss zone is not on 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 and contaminates the drilling mud with cement fines. Furthermore, because of the relatively small aperture of many loss-zone fractures, the loss zone may preferentially accept wellbore fluids into the fractures,

instead of cement. This causes dilution of the cement in the loss zone and loss of integrity of the subsequent cement plug. If there are any cross flows in the wellbore, they will contaminate and dilute the cement, making it impossible to get a good cement plug. As a result, multiple cement treatments are often required to plug a single loss zone, with each plug incurring significant time and material costs. The problems of lost-circulation have not yet been solved completely. Plugging mixtures and other materials may essentially cut down the time and money spent in eliminating lost circulation troubles (Finger and Blankenship, 2010).

### 3.1.6 Measurement of loss

Measuring and monitoring the loss of circulation in geothermal drilling is important because it indicates fractures which are being sought in the production zone. When drilling the non-productive zones, measuring can assist in understanding the location and size of the fracture. It is important to measure and monitor the loss of circulation and the points where they occur for the purpose of designing or choosing the right casing cementing procedure. There are mainly three methods of measuring or estimating the loss of circulation while drilling (Chemwotei, 2010).

- a) The use of a magnetic, sonic or flapper flow meter on the flow-line: In this method the volumetric flow rate of the fluid being pumped into the well is read from the strokes per minute (SPM) of the mud pumps and the flow out of the well is measured using a flow-meter. The fluid loss is the difference between the total pumping rate and the outflow measured in the flowline.
- b) The tank method: In this method the filling of the tank by make-up water is stopped for a certain interval of time (say 15-30 min.) and then the change in the total mud/water tank volume is measured either by a measuring stick or from the rig instruments. The rate of change in volume (change in volume divided by time) is the fluid loss.
- c) The driller's method: In this method the driller adjusts the pumping rate to keep the well full to the brim after the level has dropped while adding a new drill pipe. The pumping rate (l/s) is then the rate of fluid loss.

## 3.2 Getting stuck

Sticking is an accident of arresting the pipe string in the borehole so that it cannot be overcome by applying the maximum permissible axial forces (pull). Sticking is usually the result of natural factors, such as the presence of a permeable formation which is liable to cave and slough, or beds with abnormally high pressure and temperatures. Sticking troubles are also influenced by the degree of hole deflection, the dog leg severity where there is a keyhole and so forth (Sidorov, 1985).

Though few stuck pipe problems occur while drilling, it is wise to keep in mind that they can happen. The most commonly monitored drilling parameters which will indicate problems are changes in: torque, drag in pulling out or tripping in the drill string, pump pressure, and drill rate. Changes in these parameters, when matched with known data (i.e. cuttings lithology, ECD), can pinpoint mechanisms which can result in a stuck pipe and other borehole problems (Baker, 1995). Several problems, with their drilling parameter correlations are listed in Table 1. The summary of the causes of pipe string sticking is as follows:

1. Pressure differential when the pipe string comes in contact with the permeable formation;
2. Jamming of the string's bottom-hole portion (bit) when lowering it down a tight hole;
3. Sticking of the drill collars, in well cuts when lifting the drill pipe string;
4. Caving and sloughing in loose formation;
5. Sticking due to balling (inadequate hole cleaning);
6. Fractured/faulted formations;
7. Pipe string jamming from foreign matter which fell into the hole;
8. Key seating; and
9. Cement blocks.

TABLE 1: Stuck pipe indicators during operations (Baker Hughes INTEQ, 1995)

Indicator problem	Torque	Pump pressure	Drill rate
Poor hole cleaning	Increase	Increase	Gradual decrease
High overbalance and permeable sands	Gradual increase	No change	Gradual decrease
Mobile formations	Gradual increase	Increase	Gradual decrease
Fractured and faulted formation	Sudden increase	May be unaffected	Sudden increase
Geo-pressured formation	Increase	Increase	Initial increase with a gradual decrease
Reactive formations	Gradual increase	Increase	Gradual decrease
Unconsolidated formation	Increase	Increase	Decrease
Junk	Sudden increase	No change	Sudden decrease
Cement blocks	Sudden increase	No change	Sudden decrease

### 3.2.1 Pressure differential sticking

Under the influence of gravity, the drill pipe string is pressed against the crooked hole walls and sticks to the clay mud cake. Under the effect of this pressure the clay mud cake becomes denser, its permeability decreases and a pressure difference arises in the pipe cake contact area which presses the string against the wall still more. As a rule, such sticking troubles occur when the pipe string lowered down the hole is left motionless for a certain period of time. In this event, the pump discharges pressure and the drilling mud circulation remains unchanged. Symptoms of possible sticking are a strain effect on the pipe string when lifting is begun after the pipe string is motionless for 3-5 min.

To free a differentially stuck drill string, the driller must overcome the restraining force of the drilling fluid, which is pushing the drill string against a permeable formation. The drill string (drill pipe or collars) will soon become imbedded in the filter cake opposite the permeable zone if corrective action is not taken as soon as the sticking situation is noticed (Baker Hughes INTEQ, 1995). As much has been said in this section about differential sticking, it should be remembered that this type of sticking will develop if six factors are present: a permeable formation, thick filter cake (due to high filter loss), the drill string in contact with that filter cake, an over balance situation exists, insufficient drillstring movement, and a lack of calculation between the drill string and the filter cake. Preventive measures include:

- a) Move the drill string as much as possible;
- b) Rotate the drill string on connections;
- c) Always begin pipe motion in a downward direction;
- d) Ensure a pit is available for pumping pills;
- e) Use grooved or spiral drill collar;
- f) Minimize the length of the drill collars and BHA; and
- g) Consider placing the jar in the heavy-weight pipe section.

There are basically three methods which can be followed if the drill string becomes differentially stuck:

1. The first operation is to immediately work / jar the drill string downwards (if possible) and apply right hand torque;
2. Secondly, reducing the hydrostatic pressure may be an option (well control considerations must be taken in to account); and
3. The third operation involves spotting a friction reducing fluid within the stuck zone.



### 3.2.2 Jamming of the string's bottom-hole portion (bit) when lowering it down a tight hole

When drilling long sections of an abrasive formation, the gauge protection on the bit and stabilizer can become so worn it becomes ineffective. The jamming generally occurs when a new bit is lowered down a hole drilled by a bit worn out in diameter. Preventive measures include:

- a) Properly gauge the bit stabilizer after each run;
- b) Ream back to bottom if an under gauge hole is suspected;
- c) Never force a new bit to the bottom; and
- d) Select bits with good gauge protection.

If the new bit is run into an under gauge hole, maximum upwards working / jarring forces should be applied immediately (Baker Hughes INTEQ, 1995).

### 3.2.3 Sticking of the drill collars in wallcuts when lifting the drill pipe string

The borehole is seldom drilled in a smooth manner. Ledges and washouts are common, especially when alternating hard / soft formations are drilled. Problems with borehole geometry normally occur during tripping operations. Remember, when tripping-in the drill string is compressed making it more flexible. When tripping-out, the drill string is tensed making it more rigid. Preventive measures include:

- a) Minimize doglegs;
- b) Reduce the number of BHA changes;
- c) Ream if the BHA configuration is changed; and
- d) Do not run stabilizers above a jar.

If borehole geometry problems are suspected when tripping in, a gradual upwards working force should be applied. If this occurs when tripping out, upwards forces should be applied gradually to prevent the drill string from further jamming. If a ledge is suspected, then upward force should be used to try and remove the ledge (Baker Hughes INTEQ, 1995).

### 3.2.4 Caving and sloughing in loss formation

Sloughing and caving-in troubles occur due to losses of formation stability under the effects of various factors. Holes do not stand up commonly during drilling-in operations in formations crushed by tectonic faults, reversed faults, etc. Penetrating such formations through fissure cracks and channels, the filtrate of drilling mud weakens the bonds between the rock particles and aggregates which then cave into the borehole (Sidorov, 1985).

Sloughing occurs in boreholes where the rig has drilled into sheet clays and other thin-bed fissured formations. Sloughing troubles occur in the same manner as caving-in troubles (Figure 12).

Symptoms of sloughing and caving intervals in the borehole are an increased amount of rock fragments lifted by the drilling mud, an increase in the drilling mud viscosity, an increase in the mud pump discharge, an increased hook load in pulling the drill pipe string and bridges in the borehole formed by sloughs and caving

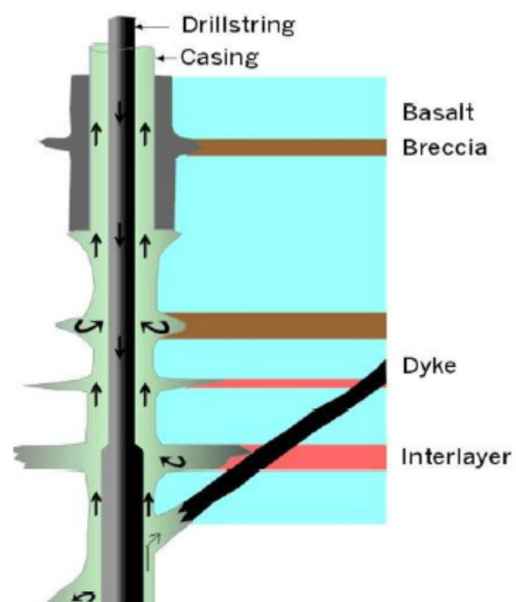


FIGURE 12: Forming of cavities, as water is circulated through the drill string during drilling (Steingrímsson, 2011)

which must be drilled out before a new bit can reach the bottom hole face.

Sloughing enlarges the borehole created by the bit. The presence of enlarged diameter intervals can be detected by caliper logging. The enlargement coefficient  $K$  is a good criterion of the degree of rocks caving-in (Sidorov, 1985).

$$K = \frac{V_a}{V_{th}} \quad (1)$$

where  $V_a$  = The actual volume of the borehole within the caving interval ( $m^3$ ); and  
 $V_{th}$  = The theoretical volume of the borehole within the same interval ( $m^3$ ).

At no caving,  $K$  is 1; in a case of caving,  $K > 1$ ; and in a case of a tight section  $K < 1$ .

All clay rocks, argillaceous shale's included, have the tendency to slough. Hole enlargements can be prevented and eliminated by taking the following steps.

- a) Increase the density and decrease the filter loss of the drilling mud.
- b) Make use of drilling fluids which add to the strength of the formation. An example of such a fluid is a calcium chloride drilling mud.
- c) Speed up the drilling process to cut down the time of drilling affecting the sensitive formations.
- d) Make use of a well program providing for insulation of the sensitive formation.

If sticking does occur, establish circulation first. Then concentrate on working the drill string downwards to disturb the bridge. Once the drill string is free, ensure the material is circulated out before drilling. Increase the mud density if possible (Sidorov, 1985).

### 3.2.5 Sticking due to balling (inadequate hole cleaning)

This type mainly occurs in drilling out clay formations with inefficient flushing. The drilling mud does not carry all the cuttings to the surface and some of them stick together to cause balling. The trouble is indicated by an increase in the discharge pressure of the mud pumps, dragging on the bit as it is lifted from the bottom and poor cutting recovery. Preventive measures include (Baker, 1995):

- a) Control the drill rate to ensure the hole is cleaned;
- b) Circulate bottoms-up until shakers are clean;
- c) Maintain the correct drilling fluid properties;
- d) Recognize increased over pull;
- e) Always reciprocate and rotate pipe while circulating;
- f) Use viscous sweeps; and
- g) Control the annular velocities.

If the annulus becomes overloaded, attempts to establish circulation must be made. In addition, a downward force should be applied gradually until circulation begins. Once circulation is established, the drill string should be rotated to further disturb the cuttings.

In low-angle holes, a weighted high viscous pill should be used to float out the cuttings. In high-angle holes, a low viscous pill should be used to disturb the cuttings bed, followed by weighted pills to carry the cuttings out of the hole (Baker Hughes INTEQ, 1995).

### 3.2.6 Fractured / faulted formations

These are naturally occurring formations. When the fractured or faulted formation is drilled, there will be a tendency for pieces of the formation to fall into the borehole. The size of the pieces will vary from pebbles to boulders. They will more commonly occur in limestone and shale. Preventive measures include:

- a) Clean out excess fill before drilling;
- b) Minimize surge pressure;
- c) Place the jar in the heavy-weight pipe section;
- d) Be prepared to wash / ream when tripping in;
- e) Design a BHA to minimize the risk of hitting a ledge; and
- f) Use low circulation rates / pressures to clean the hole.

If it is found that faulted/fractured formations are the cause of the sticking, the drill string should be worked up and down to try to break up the pieces of formation. If limestone is causing the problem, an inhibited acid (HCl) pill can be used to dissolve the limestone. The pill should be spotted with a large water spacer (Baker Hughes INTEQ, 1995).

### **3.2.7 Sticking due to pipe string jamming by foreign matter in the borehole**

Junk is a foreign object in the borehole, which is not meant to be there. Those troubles result from careless work by the drilling crew, the use of defective tools, etc. Power tongs dies, sledge hammers, ranch-bars, etc. fall down the hole during work causing jamming (Baker Hughes INTEQ, 1995). Since the clearance between casing and collars / stabilizers is not great, even a small piece of junk can stick the drill string. Preventive measures include:

- a) Ensure down hole tools are in good condition;
- b) Inspect downhole tools regularly;
- c) Be careful when working around rotary table; and
- d) Leave the hole covered when the drill string is out of the hole.

If junk sticking is suspected, upward and downward working and jarring should commence to try and dislodge the obstruction. This force should be gradually increased until the drill string is free.

### **3.2.8 Key seating**

Key seats are the result of the drill string wearing an additional hole into the side of the borehole. This extra hole will generally have the diameter of the drill pipe's tool joints and the drill collars will not pass through this extra hole when tripping out. Preventive measures include:

- a) Minimize pipe rotation;
- b) Minimize dogleg severity;
- c) Carefully design the BHA;
- d) Minimize the length of the rat hole below the casing; and
- e) If the problem is recognized, cure before drilling ahead.

If the drill string becomes key seated, the drill string should be worked upwards gradually, this will depend on how long the key seat is, and if the BHA is not jammed into the key seat. Attempts should be made to rotate the drill string up and out of the key seat with minimum tension (Baker Hughes INTEQ, 1995). In wells where this problem is expected, sometimes a tool called a key-seat reamer is included in the BHA. This is a reamer shell on a sub that is engaged to open up the hole enough for the drill collars to pass if it encounters an obstruction such as a key seat when being pulled out of the hole.

### **3.2.9 Cement blocks**

After a leak-off test has been performed and drilling has resumed, the large sized collars or stabilizers can cause blocks of cement to break loose and fall into the borehole (Baker Hughes INTEQ, 1995). These large blocks can easily jam against the drill string. Preventive measures include:

- a) Minimize the length of the rat hole below the casing shoe;
- b) Always ream rat holes or cement plugs before drilling ahead; and
- c) Be careful when tripping back through the casing shoe.

If jamming occurs, attempt to dislodge or break up the obstructions by using alternating upward and downward working and jarring. These freeing forces should be gradually increased until the drill string is freed, and if available, an acid solution can be pumped to dissolve the cement.

### 3.3 Twist-off

As used in drilling, the term accident refers to breakage and loss of drilling and casing string parts, bits and downhole motors, casing pipe failures, including defective cementing and the falling of foreign metal matter into the hole (Sidorov, 1985).

Accidents hinder drilling and may lead to well abandonment. Accidents raise the costs of the drilling work and lower the drilling rates. To reduce the number of accidents, measures should be taken to prevent accidents from occurring and to eliminate accidents occurring as quickly as is practical. To this end, the cause and symptoms of accidents must be known. There should also be a set of emergency tools and instruments at hand for accident elimination work. Wells are drilled with the aid of jointed drill pipes which usually break at the thickened part in the pipe to the tool joint connection.

In order to prevent such failures, the threads of the tool joint and pipe are calibrated and the required thread joint tightness is determined. Ultrasonic flow detectors are used to test the drill pipes for flaws as they are taken to the drilling rig and during round trips. Pipes with cracks within the boundaries of the upset part are rejected. The drill pipes and collars are inspected at regular intervals. Broken parts of a drilling string are removed from the well by fishing tools of various designs.

The catchers of the overshot fishing tool grip a pipe by its body or the tool joint, depending upon the type of the slips it is fitted with (Figure 13). A catcher is lowered down the hole on the drilling string. Several meters on the top of the broken pipe, the circulation is resumed and the catcher is forced over the pipe end. The end of the broken pipe forces the slips apart and passes into the tool. When the catcher is being lifted, its slips grip the pipe, while the collar seals the space between the catcher case and pipe, allowing the drilling mud circulation through the part of the pipe left in the hole. If the pull fails to release the pipes, this is increased and more attempts are made to reciprocate the string. If this results in failure, the catcher is removed and another method is used.

The taps perform the functions of recovering drill pipes left in a well. They are classified into all purpose and special taps also known as gauges. The all-purpose are used if the broken end of the object in the well terminates in a tool joint pin or box, and also into a thickened part of a drill pipe. The taps are often



FIGURE 13: Fishing catchers and taps (Weatherford, 2012)

used together with centralizers. The special taps gauge is used to withdraw pipes by their pipe or tool joint thread (Figure 13).

In eliminating accidents, the taps can apply a substantial torque and high axial loads to the broken object. The tap is run down on a pipe string. With the tap above the top of the broken part, the circulation is resumed; the tap is inserted inside the broken pipe and secured by rotating pipe string with the aid of the rotary table. An initial load of 20-30 kN is applied to the tap, which is then raised to 30-40 kN. Next, the pipe string lost in the hole is released by intensive flushing and reciprocating. If the broken part of pipe string is stuck, a liquid bath may be employed. Taps are available in right and left hand models.

Spear fishing tools are used for recovering lost pipes that are not stuck. They come in internal and external models. The spear enters the pipe bore by slow rotation of the rotary table. The split bush contacts the pipe wall and becomes unscrewed upward. In lifting the split bush engages the lost pipe. The spear is realised by unloading it and turning it counter clockwise through two turns (fishing spear, jar hugger shock absorber and collar, see Figure 14).

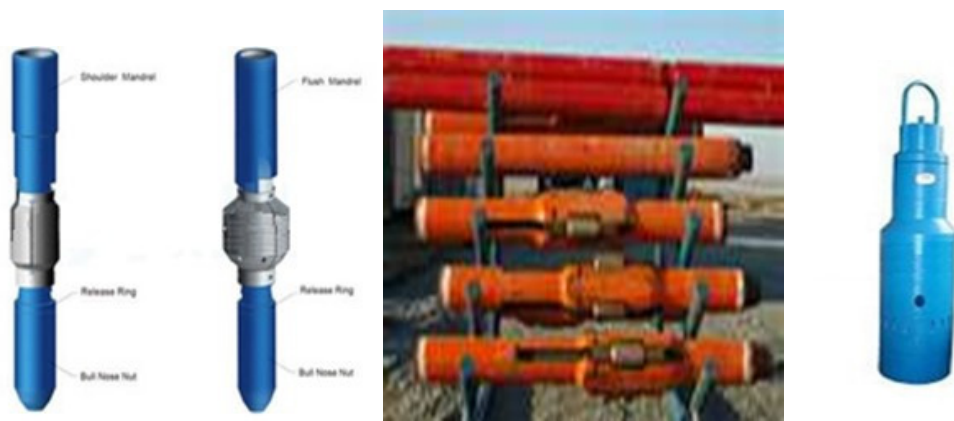


FIGURE 14: Fishing spear, jar hugger shock absorber and collar (Weatherford, 2012)

Rotary drill bit failures (lost rolling cutters) are prevented by monitoring the torque. An increase in the torque indicates a bearing locking in the rolling cutter drilling bit and calls for lifting.

Roller cutters or a drilling bit leg lost on a well bottom can be recovered by a bottomhole magnet or destroyed by a bottom hole mill. Bits altogether lost can be destroyed by discharging a shaped shot, the resultant pieces of metal being destroyed by bottom hole mill or recovered by a bottom hole magnet (Sidorov, 1985).

All fishing and trouble elimination jobs are very dangerous. Therefore, they should be performed in full accordance with safety engineering and accident prevention regulations.

Before an attempt is made to recover a stuck drilling tool (casing string), check the condition of the derrick, block and tackle system and the weight indicator. The rig floor should be tidy and free of unnecessary parts and tools. The attending personnel must be totally alert. All accident control instructions and orders given by the engineers must be fulfilled quickly and implicitly.

### 3.4 Slow drilling

Many of the costs attributed to drilling are time-dependent (primarily related to the rental rate on the rig and service company expenses) so it is clear that anything that speeds up the hole advance without compromising safety, hole stability, or the directional path is beneficial. The three parameters that can be easily changed for any bit are rotary speed, weight on bit (WOB) and hydraulic combination of jet

size and flow rate; it often takes some experimentation to determine the best combination of these values. Bit performance data from offset wells in the same formations, and with the same hole size and bottom-hole assemblies can often be very useful. The efficiency of actual drilling is assessed by the on-bottom drilling rate, rate of meterage per run, and costs of metre penetration. The most general figure of efficiency in drilling practices is the cost of metre of penetration. The combination of these drilling parameters, which ensures the minimum costs of per meter of penetration, is referred to as optimal drilling practices (Finger and Blankenship, 2010).

If in the course of drilling, certain limitations are imposed on the drilling parameters, the drilling practices are called special. Special practices are employed in drilling out unstable formations, high loss of circulation formations of abnormally high pressure as well as in side-tracking and in penetrating rock masses with fluctuating degree of hardness, etc. Generally, limitations are imposed on the axial weight of the drilling bit, drilling bit rotations per minute and the amount of drilling mud pumped in the well. Such parameters of drilling mud density, viscosity, gel strength, filter loss and the like should always satisfy the geological conditions, for which reason these parameters should not be restricted no matter what the drilling practice (Finger and Blankenship, 2010).

The effect of drilling parameters on the bit performance on rock destruction in well drilling is a complicated process. Quantitative figures of bit performance are e.g. meterage per bit run or the on-bottom drilling rate and the total number of revolutions that the bit lasts. The effect of a drilling parameter on the bit performance figures, say on the bottom drilling rate, is determined with all the other parameters being fixed (Sidorov, 1985).

#### **3.4.1 Axial weight on the drill bit (WOB)**

The effect of the axial weight on the bit (WOB) performance is especially high. The depth, at which the bit cutting elements penetrate rock, accounts for the nature and rate of rock destruction and depends on the amount of the axial weight on the drilling bit. Under an insufficient axial weight, surface destruction takes place, which is the least effective. With an increase in bit load, volumetric rock destruction occurs which is the most effective. After the on-bottom drilling rate has been raised to its maximum by varying the axial weight on the bit, a further increase in the axial weight leads to a decrease in the drilling rate. This is because at the given drilling mud delivery from the mud pumps, the circulating drilling mud is unable to carry away all cuttings. Some cuttings remain on the bottom hole face and are additionally ground up by the bit (Sidorov, 1985).

Increasing the weight on the bit also raises the meterage per bit run. Not that the effect of this on the overall efficiency of the drilling is essential as it cuts down the round-trip time and the time taken by auxiliary jobs (flushing the well before lifting the bit and chemical treatments of the drilling mud).

The drill collar, the lower portion of the drill string, should be considered as the tool which holds the bit and forces it against the rock formations. As such, the weight, stiffness, mass distribution, and vibration characteristics of the drill collar influence the action of the bit and the degree of stability with which it is held on the bottom. The importance of the drill collar increases with the amount of drilling weight applied to bit.

In drilling harder rocks, a uniform weight may not be held on the bit throughout its run. When a new bit is first rotated, the driller may apply a comparatively light weight in order that the full-length teeth may wear their own drilling pattern into the bottom of the hole.

#### **3.4.2 Drilling bit rotation per minute (RPM)**

The effect of the rotary speed on the rate of penetration of toothed wheel bits is somewhat more difficult to evaluate than the effect of bit weight. The rotation of the drill string and bit, when the bit is drilling on the bottom, is associated with vibrations which originate at the bit. Such vibrations probably influence the action of the bit on the rock and may be instrumental in rock failure and so aid the drilling

process. In order to avoid such unfavourable results, drilling practice has tended toward slower rotary speeds with greater bit weights to obtain faster rates of penetration (Sidorov, 1985).

With bit rotations per minute increasing, the on-bottom drilling rate rises, reaches a maximum and then decreases. It should be emphasized that each class of formation has its own critical speed of rotation which, if exceeded, will lower the on-bottom drilling rate. Increasing the rotary speed of rolling-cutter drilling bits decreases their life by inflicting intense wear on the bearings, thus cutting down the meterage per bit run. For geothermal drilling it has become common practice to drill with a mud motor to the total depth of the well, not only the build-up portion of directional wells. This is because the final bit rotary speed is more than doubled with a corresponding improvement in the rate of penetration.

### 3.4.3 Drilling mud circulation rate

Both the on-bottom drilling rate and the meterage per bit run reach their maximum only when the cuttings are completely removed from the bottom-hole face immediately after they have been chipped off by the bit. If the cuttings recovery is incomplete, then excessive grinding action will occur between the hole bottom and the bit, which has to crush the remaining cuttings; this affects the drilling rate and meterage per bit run (Sidorov, 1985).

The influence of the drilling mud circulation rate ( $Q$ ) on the on-bottom drilling rate is determined experimentally by the rotary drilling method. It has been revealed that as  $Q$  increases, the on-bottom drilling rate rises, but only to a certain point associated with a definite value  $Q_{\max}$  after which an increase in  $Q$  no longer raises bit efficiency. This is because an increase in the drilling mud circulation rate leads to an increase in the pressure in the annular space. The rock under the bit becomes more compact and its drill-ability decreases.

Note also that the efficiency of cuttings removal from the bottom hole is determined not only by the specific flow rate of the drilling mud, but also by the velocity the drilling mud is discharged through the bit nozzles, the arrangement of the nozzle parts with regard to the bit cutters and bottom-hole face and by other factors.

### 3.4.4 Effect of the drilling fluid basic properties on drilling efficiency

- a) *The effect of density:* Density is defined as mass per unit volume and is measured in  $\text{kg/m}^3$ . It has been established that the on-bottom drilling rate is dependent upon the difference between the pressure exerted by the column of drilling mud and the pressure of the confined fluid in the formation, known as the differential pressure.

The pressure exerted by the column of drilling mud is directly proportional to its density:

$$P = H \times d \times g \quad (2)$$

where P = Hydrostatic pressure (Pa);  
 H = Vertical depth (m);  
 d = Fluid density ( $\text{kg/m}^3$  or  $\text{g/cm}^3$ ); and  
 g = Gravitational acceleration ( $9.81 \text{ m/s}^2$ ).

The meterage per bit run is also dependent upon the drilling mud density. The bit performance obviously can be improved by using drilling fluids having the least density allowable under actual drilling conditions.

The higher the drilling mud density, the higher the pressure exerted on the bottom of the hole. The higher the differential pressure, the more compact the bottom face rock will be, affecting rock drilling ability. The value of the differential should not exceed 3.5 MPa, or better if close to zero. A negative value of differential pressure is maintained if the well does not contain high-

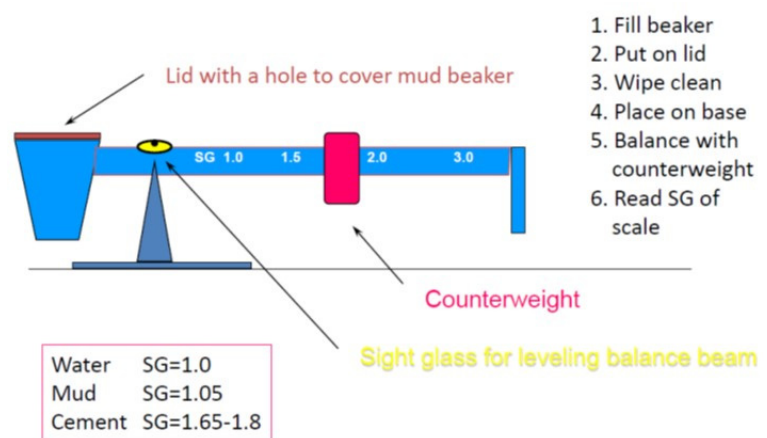
permeability formations. The higher the drilling mud density, the smaller the meterage per bit will be; the density is determined using a mud balance (Figure 15).

- b) *The effect of viscosity:* The measures of resistance of a fluid to flow or to deform by either shear or tensile 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 velocity of drilling fluid. At the well site the viscosity of the drilling fluid is measured by the use of a Marsh funnel (Figure16), measured in seconds per liter (sec/l or sec/qt). It is important that the viscosity of the drilling fluid is maintained to provide the required hole stability and loss control. Less viscous fluid has a good impact on cleaning the bit and optimizing the drilling rate, but more viscous fluid is good in cleaning out coarse gravel from the hole.

- c) *The effect of gel strength:* Gel strength is a measure of the ability of the 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. This coming together and bonding is termed flocculation and it is the structure responsible for suspending cuttings when the flow ceases.

- d) *The effect of filter loss:* 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 natural permeable zones of formations. The ability of a fluid to deposit mud solids on the walls of the borehole to limit fluid loss to the formation is referred to as filtration. Drilling fluid would filtrate into the formation due to hydrostatic pressure which could be greater in the borehole than in the formation. On one hand, a high filter loss leads to thick filter cakes in the wells, thus reducing the flow area on the annular space and increasing the hydrodynamic resistance. On the other hand, the drilling mud filtrate penetrates the pores of the surrounding formation and helps the bit break it up. A good, well-conditioned bentonite drilling mud will deposit a thin filter cake. Polymer muds have low concentration of 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 (Chemwotei, 2011).

- e) *The sand content:* Excessive sand and other solid particles in a non-weighted drilling mud are undesirable because of their detrimental effect on the bit performance and their abrasive properties which cause excessive wear on mud pump parts, drill and casing pipes, down hole motor, etc. Because of this the drilling fluids are cleaned of cuttings on the surface with the aid of the screen, desanders and desilters.



1. Fill beaker
2. Put on lid
3. Wipe clean
4. Place on base
5. Balance with counterweight
6. Read SG of scale

FIGURE 15: Mud balance to measure density (Thórhallsson, 2012)

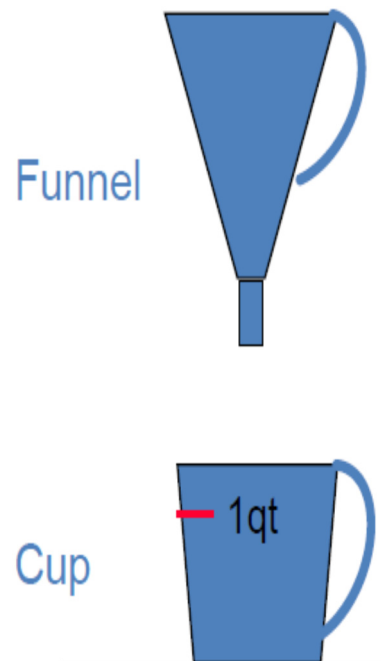


FIGURE 16: Marsh funnel to measure for mud viscosity (Thórhallsson, 2012)



### 3.5 Bit performance

Much of the commentary above about rate of penetration applies to bit performance. Improved bit performance means, of course, that the expense of replacing a bit or other piece of equipment can be avoided or deleted, but there is also a time saving if the number of trips can be reduced. This becomes more important as the hole gets deeper and the trips take more time (Finger and Bankenship, 2010). The abrasive nature of many geothermal reservoir formations accelerates the wear on downhole tools. This may lead to additional trips to replace under-gauge bits.

The three factors that most affect bit life are lithology, drilling parameters and bottom hole assembly design. If the drill bit is exposed to excessive temperature, the elastomer seals may be destroyed which results in a shorter bit-bearing life as the lubricant will be lost. The drilling engineer has no control over lithology, but significant improvements can sometimes be made by changes in the latter two factors. Common rock types in geothermal reservoirs include granite, granodiorite, quartzite, greywacke, basalt, rhyolite and volcanic tuff. Compared to the sedimentary formations of most oil and gas reservoirs, geothermal formations are, by definition, hot (production intervals from 160°C to above 300°C) and are often hard (240+ MPa compressive strength), abrasive (quartz content above 50%), highly fractured (fracture apertures of centimetres), and under-pressured. They often contain corrosive fluids, and some formation fluids have very high solids content (TDS in some Imperial Valley brines is above 250,000 ppm). These conditions mean that drilling is usually difficult, the rate of penetration and bit life are typically low, corrosion is often a problem, lost circulation is frequent and severe, and most of these problems are aggravated by high temperature.

The bit is usually either a roller-cone, which crushes and gauges the rock as the cones turn and their teeth successively come into contact with unbroken areas, or a drag bit, which shears the rock in the same way that a machine tool cuts metal. Because of shearing action, drag bits are inherently more efficient than roller-cone bits but result in greater torque.

The great majority of rollers-cone bits today have three cones, with either milled steel teeth that are part of the cone itself or hard-metal (tungsten carbide) teeth inserted into the body of the steel cone. Milled-tooth bits are less expensive but are suitable only for softer formations. Insert bits are used in medium to harder formation, with the size, shape bearings, and number of inserts varied to fit the specific drilling conditions. The bits are available with either roller or journal bearings, depending on operating conditions, or the bearings seals, and lubricants should all be specified to withstand high temperature if the bits are to be used in geothermal drilling. Roller cone bits dominate drilling for geothermal resources because of their durability in the hard, fractured rocks that are characteristic of these reservoirs. Drag bits with polycrystalline-diamond compact (PDC) cutters began to be widely used in the early 1980s for their ability to drill faster and last longer in soft to medium formations, and they now dominate oil and gas drilling. A particular advantage of drag bits for geothermal drilling is that they do not have any moving parts, so temperature limitation on bearings, seals and lubricants are not a factor (Figure 17).

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. The drill bits and bottom hole assemblies used are, therefore, exposed to higher temperature fluids especially when tripping in, reducing bearing and seal life, and thus the bit life. Drilling rigs with a top-drive have an advantage for bit cooling as circulation can be maintained while running in the hole.

PDC bits have not had an acceptable life in hard or fractured formations, and a great deal of work has been done to extend their use to harder rocks; significant progress has been made, and these bits are slowly becoming accepted by the geothermal industry. Rate of penetration with PDC has been similar to roller-cones in most wells but the lifetime of PDC bits is much longer in medium formation with a rate of penetration of 1.5 to 20 m/hr.; roller cone bits are used to drill 250-350 m per bit whereas PDC bits have been rerun to drill 1000 m per bit with some bits exceeding 3000 m (Finger, 2010).



FIGURE 17: Milled tooth, insert roller cone and PDC drag bits (Finger and Blankenship, 2010)

Many exploratory slim holes have been drilled with minerals-type core rigs, and those bits are completely different from the rotary drilling bits described above. In a mineral type system, the core is removed from the bottom hole assembly (BHA) with a wire line, instead of tripping the entire drill string, as is done with oil-field type coring. It is consequently much faster to retrieve a wire line core, although the rate of penetration for coring is usually fairly low. Much of the rock volume removed from the hole is in the form of a core, and the rock cuttings themselves are much smaller, because virtually all hard-rock coring is done with diamond-impregnated bits that grind away the rock. Principal variations in this kind of bit are the diamond grains size, the diamond grain density, and the hardness of the matrix metal in which the diamond grains are embedded. These bits typically turn with much higher speeds than conventional rotary bits (either roller-cone or drag) and have a much lower drilling fluid flow rate because of the smaller annular space between the drill rods and the borehole wall.

Diamond-impregnated bits are also used in full size conventional drilling when a turbine is used to provide high rotary speed. Turbines are available that have no rotating elastomeric seals, so they can withstand high temperature, but their high rotary speed is not compatible with rotary bits, so diamond-impregnated bits are used. These bits are generally only used when nothing else will work – the rate of penetration is low, and they are extremely expensive. Diamond-impregnated core and full size bits are shown in Figure 18.

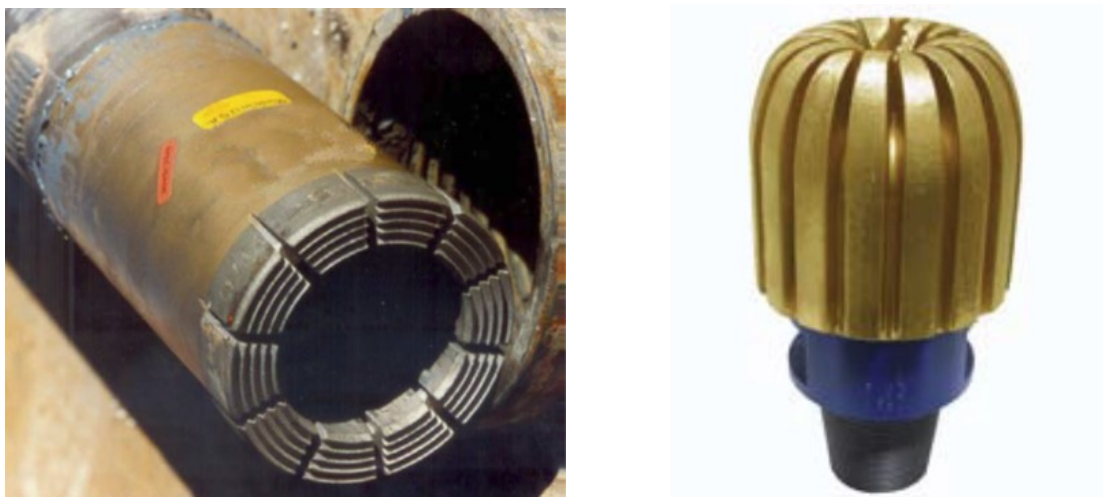


FIGURE 18: Diamond-impregnated core and full size diamond-impregnated bits (Finger and Blankenship, 2010)

Percussion drilling (air hammer drilling) uses a reciprocating downhole piston assembly to apply impact loading either to a conventional roller-cone bit or to a one piece bit set with tungsten-carbide inserts (Figure 19). The rate of penetration is above 20 m/hr (Finger, 2010).



FIGURE 19: Solid-head bits for percussion drilling (Finger and Blankenship, 2010)

#### 4. CEMENTING

Cementing is the process of mixing and pumping cement slurry to fill the annular space behind the casing. When setting, the cement will establish a bond between the casing and the formation. In most oil and gas wells, the casing is cemented in place only at the bottom, with a completion fluid between the casing and wellbore wall, but geothermal wells must have a complete cement sheath from bottom to surface. This cement has two important functions: to give the casing mechanical support under its summations-intense thermal cycling between production and shut-in, and to protect the outside of the casing from corrosion by in-situ fluids (API, 2009). To achieve this, the cement must be all around the circumference of the casing for the entire length of the pipe. There are well known methods of getting a good cement job such as: proper well bore preparation (mud conditioning and flushes), centralization and casing movement. While it may not be possible to employ all these methods at the same time, careful planning can maximize the successful use of these techniques.

The success and long life of well cementation requires temperature-stabilized cementing compositions. A hydraulic seal must be established between the cement and the casing and between the cement and the formation. This requirement makes the primary cementing operation important for the performance of the well.

Geothermal wells are drilled in areas with hot water or steam and because of the hostile conditions, special planning is necessary to insure the integrity of the well (for typical cementing process see Figure 20).

##### 4.1 Objectives of cementing

The objective of casing cementing is to insure that the whole length of the annulus is completely filled with sound cement that can withstand long term exposure to geothermal fluids and temperatures. The most important functions of a cement sheath between the casing and the formation are:

- a) To prevent the migration of fluids from one formation to another or from the formation to the surface through the annulus;
- b) To hold the casing string in the well;
- c) To protect the casing from corrosive fluids in the formation and buckling;
- d) To support the well-bore walls to prevent a collapse of the formation;
- e) To prevent blowouts by forming a seal in the annulus; and
- f) To protect the casing from shock loads when drilling.

Cementing is also used to condition the well:

- a) To seal loss of circulation zones;
- b) To stabilize weak zones (washouts, collapses);
- d) To plug a well for abandonment or for repair; and
- e) To kick-off side tracking in an open hole or past junk.

For cementing operations to be successful, all the annular spaces must be filled with cement, and the cement properly bonded to the previous casing and formation. In order for this to occur, all the drilling fluid must be displaced by the cement slurry. This is not always an easy matter, because there are several factors which affect the removal of the drilling fluid (Evans, 2010):

- a) Washout in the open hole, making it difficult to remove drilling fluid and filter cake;
- b) Crooked holes, making casing centralization difficult and drilling fluid not being removed from the low side; and
- c) Poorly treated drilling fluids having high fluid losses.

Good drilling practices will not assure a good cement job, but they may help to prevent a failure. The ideal drilling fluid just before the cementing operations should have:

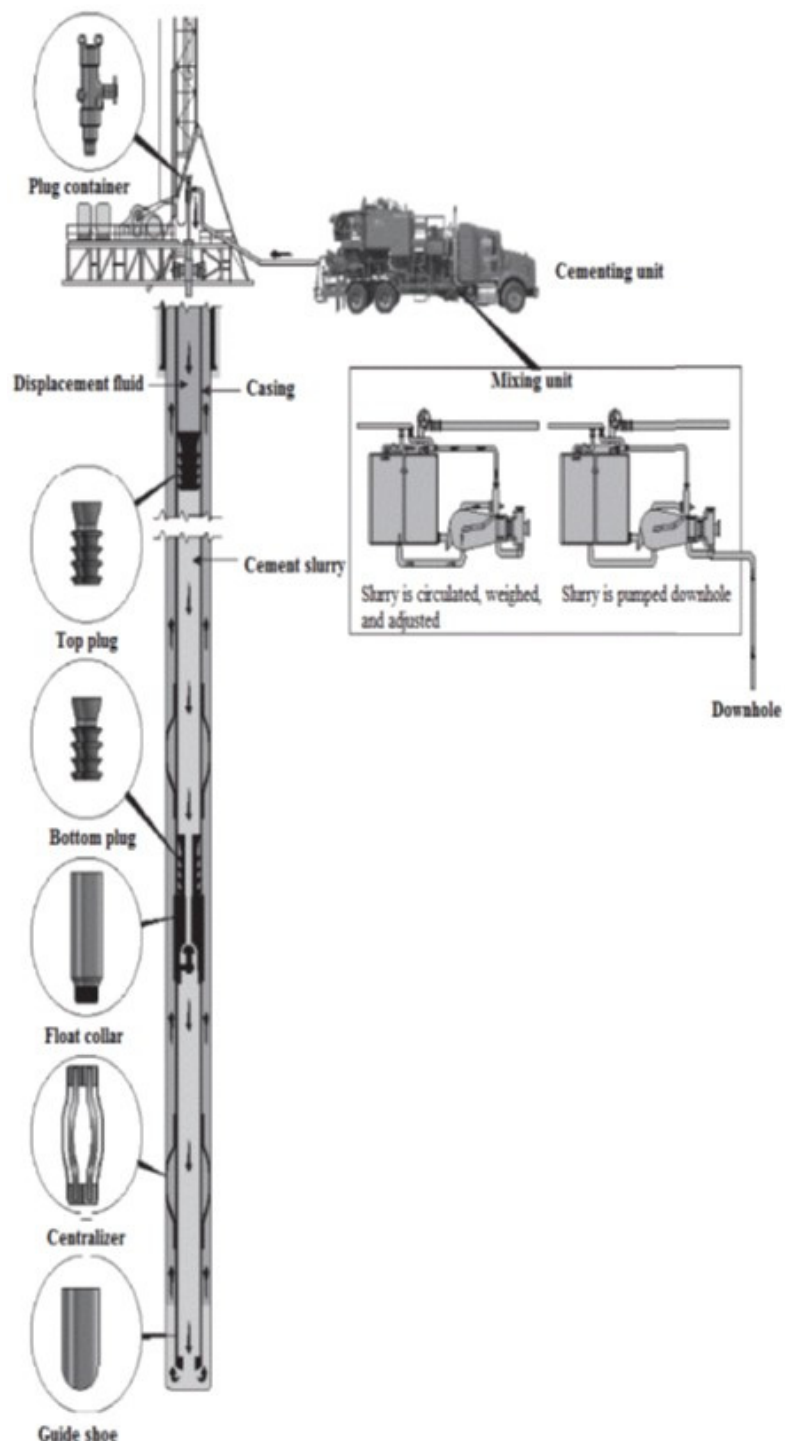


FIGURE 20: Typical cementing process (API, 2009)

- a) Low gel strength;
- b) Low density;
- c) Low fluid loss; and
- d) Chemical make-up similar to the cement.

Since these conditions are very seldom met, fluid washes and spacers are usually pumped ahead of the cement to remove as much drilling fluid as possible.

#### 4.2 Cementing nomenclature

Casing centralizers assist in the removal of filter cake and the displacement of drilling fluid by providing a more uniform flow path for the cement slurry.

Well scratchers are most useful when running casing through a high fluid-loss drilling fluid. There are two types of well scratchers, rotating scratchers used when the casing can be rotated (normally in vertical wells), and reciprocating scratchers used when the pipe is reciprocating (moved up and down). When these scratchers are placed in 5-7 m intervals, overlapping cleaning occurs. Scratchers are not used everywhere.

Wiper plugs (both top and bottom plugs) are used during cementing operations. They are used to separate the cement slurry and the drilling fluid (Figure 21) and are placed inside the cement head to deploy (Figure 22).

A bottom plug has a shallow top, is made of rubber, and has a hollow core. It is used ahead of cement slurry to prevent cement / drilling fluid contamination and to clean the casing wall of filter cake. After the bottom plug comes into contact with the float valve, sufficient pressure (10-25 bar) causes the top diaphragm to rupture, allowing the cement slurry to flow through it.

Chemical washes are fluids containing surfactants and mud thinners, designed to thin and disperse the drilling fluid so that it can be removed from the casing and bore hole. Washes are available for water-based drilling fluids. They are designed to be used in turbulent flow conditions. Spacers are fluids of controlled viscosity, density and gel strength used to form a better reaction between the cement and drilling fluid. They also help in the removal of drilling fluid during cementing (Nelson, 1990).

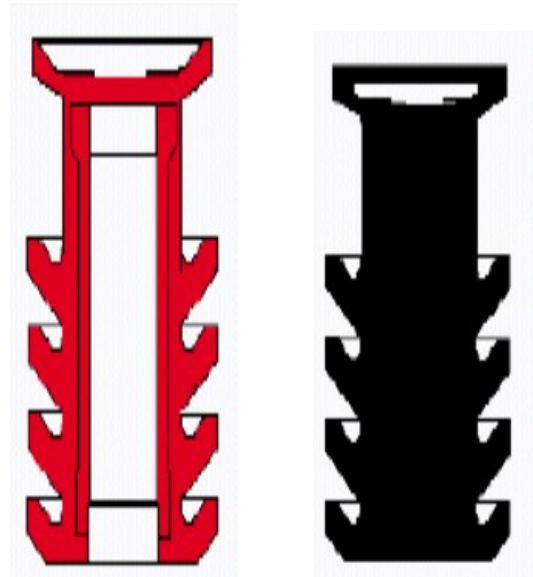


FIGURE 21: Bottom hollow and top plug (Nelson, 1990)

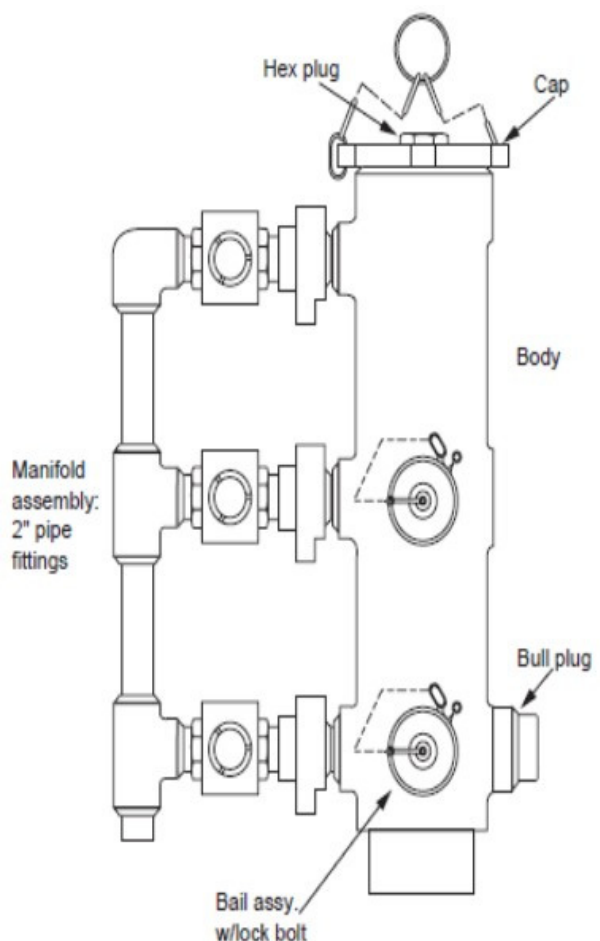


FIGURE 22: Cementing head (Nelson, 1990)

### 4.3 Cement additives

An *accelerator* is a chemical additive used to speed up the normal rate of reaction between cement and water which shortens the thickening time of the cement, increases the early strength of cement, and saves time on the drilling rig. Cement slurries used opposite shallow, low-temperature formations require accelerators to shorten the time for waiting-on-cement. Most operators wait on cement to reach a minimum compressive strength of 500 psi before resuming drilling operations. When using accelerators, this strength can be developed in four hours. It is a good practice to use accelerators at temperatures below 40°C, because at that temperature cement may require one or two days to develop a 500 psi compressive strength (Bett, 2010). Common accelerators are sodium meta silicate, sea water, anhydrous calcium chloride, potassium chloride and gypsum.

*Retarders*: A retarders is an additive used to increase the setting time of cement. Besides extending the pumping time of cement, most retarders affect viscosity to some degree. Neat cement slurries set quickly at a bottom hole temperature greater than 45°C. The governing factors for the use of retarders are temperature and depth. Cement lab tests are conducted on the candidate cement slurry to be used to confirm the properties. Common retarders are ligno-sulfonates, modified cellulose, organic acids, organic materials and borax.

*Extenders*: Extended cement slurries are used to reduce the hydrostatic pressure on weak formations and to decrease the cost of slurries. Extenders work by allowing the addition of more water to the slurry to lighten the mixture and to keep the solids from the mixture and to keep the solids from separating. These additives change the thickening time, compressive strength and water loss. Common extenders are fly ash, bentonite and diatomaceous earth.

Expanded perlite has also been added to cement mix and glass microspheres to reduce the slurry density. Furthermore, aerated or foamed cement slurry has been tested in geothermal wells where bubbles of nitrogen gas or compressed air reduce the slurry density.

*Pozzolance*: Pozzolance are natural or artificial siliceous materials added to Portland cement to reduce slurry density and viscosity. The material may be either a volcanic ash or clay high in silica. The silica in pozzolance combines with the free lime in dry cement, which means a soluble constituent is removed from the cement and the new cement is made more resistive. Common pozzolance materials are diatomaceous earth and fly ash.

### 4.4 Well cementing methods

There are several placement methods of cementing casing strings: Single-stage cementing, inner-string (stinger) cementing, two-stage cementing and reverse-circulation cementing (Nelson, 1990).

#### 4.4.1 Single-stage cementing

The single-stage cementing procedure is outlined below and the operation is illustrated in Figure 23.

- a) The casing string, with all the required cementing accessories such as a float collar guide / float shoe and centralizer (Figure 24), is run in the hole until the shoe is just a few metres off the bottom.
- b) The cementing head, shown in Figure 22, is then connected to the top of the casing string; it is essential that the cement plugs are correctly placed in the cementing head.
- c) The casing is then circulated clean before the cementing operation begins.
- d) The bottom (wiper) plug, shown in Figure 21, is released and pumped down to wipe the inside of the casing clean. It is followed by a spacer, then cement slurry. A spacer is meant to provide a barrier to avoid cement slurry mixing with the mud. When the plug reaches the float collar, its

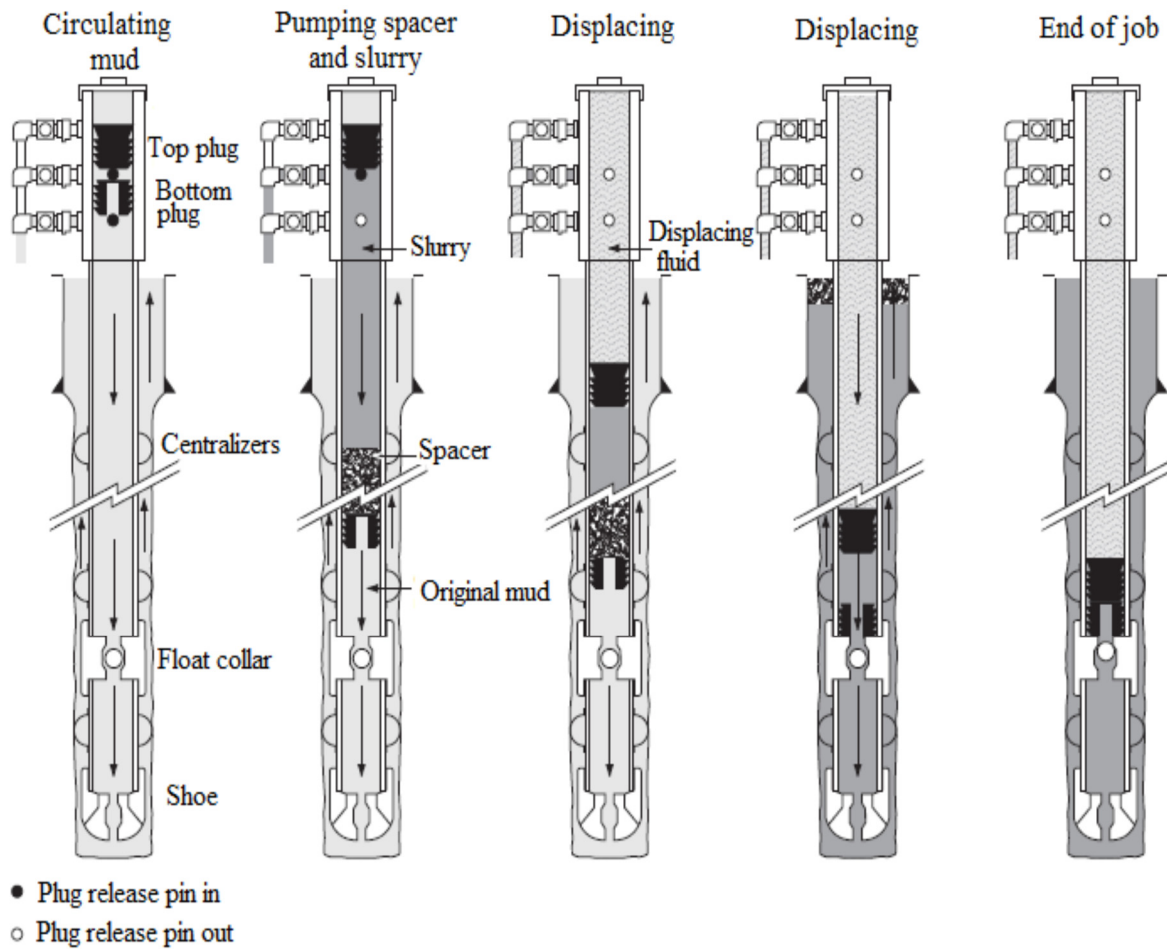


FIGURE 23: Single-stage cementing operation (Nelson, 1990)

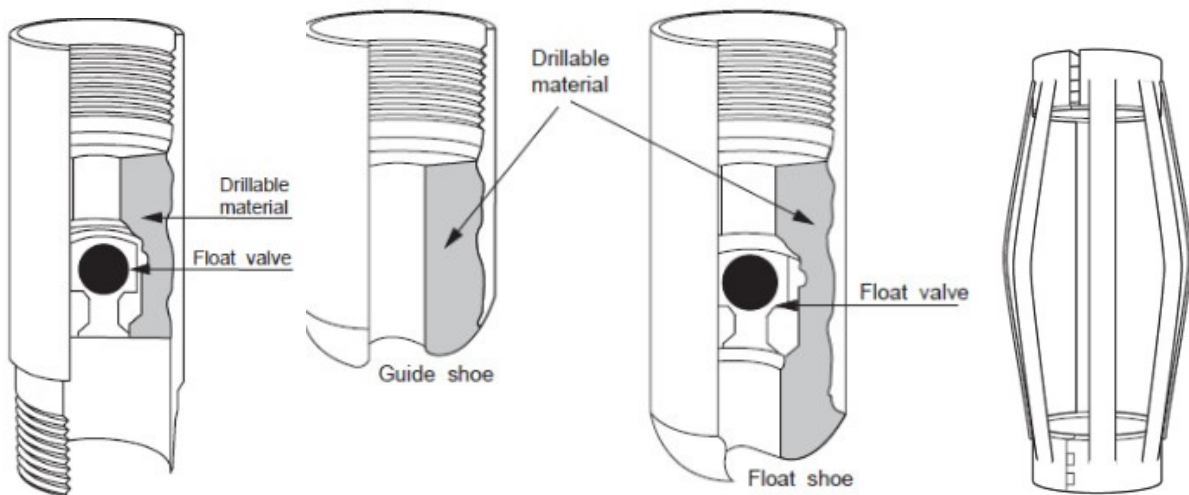


FIGURE 24: Float collar, guide shoe/ float shoe and casing centralizer (Heriot-Watt University)

rubber diaphragm is ruptured, allowing the spacer and slurry to flow through the plug, around the shoe and up the annulus.

- e) The top (shut-off) plug, shown in Figure 21, is released just behind the cement slurry and displaced fluid is then pumped. When the plug reaches the float collar, it lands on the bottom plug, and stops the displacement process.

#### 4.4.2 Inner-string (stinger) cementing

Inner-string cementing is common in geothermal well cementing operations. It allows a large-diameter casing string to be cemented through the drill pipe or tubing that is inserted and sealed in floating equipment (Figures 25 and 26).

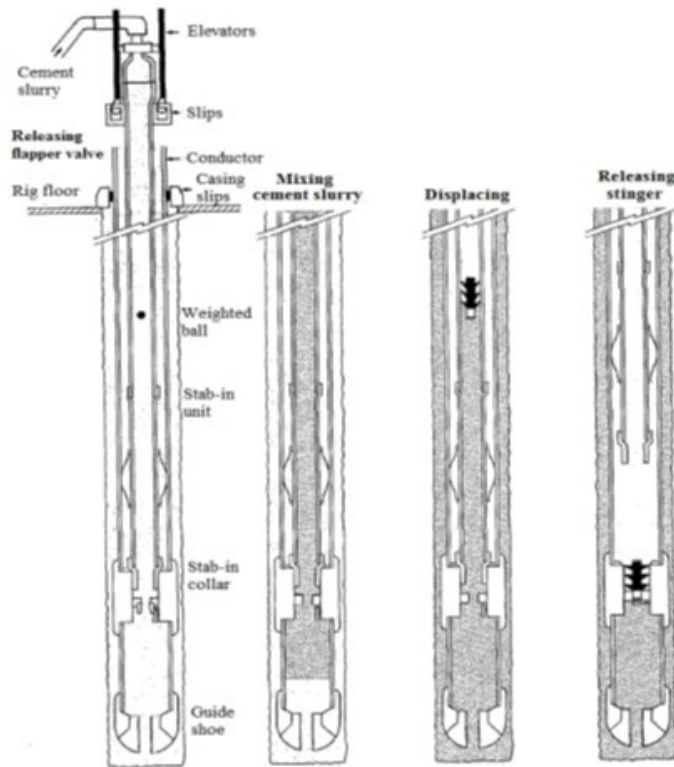


FIGURE 25: Inner-string cementing operation (Nelson, 1990)

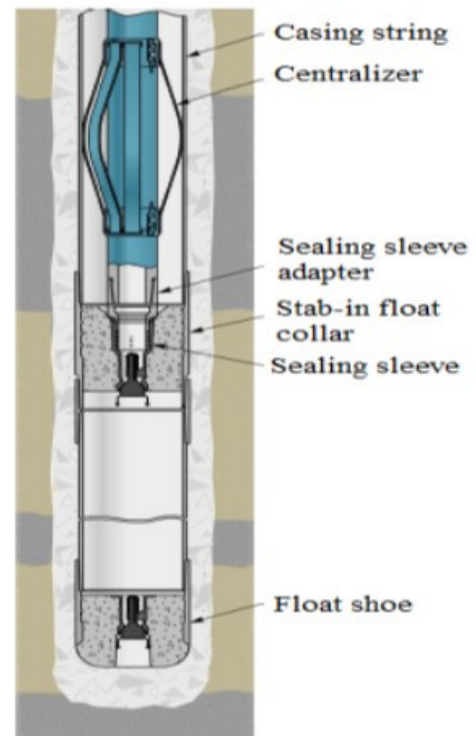


FIGURE 26: Stab-in float collar and adapter assembly (Case Intern. Inc., 2012)

Inner-string cementing has the following advantages (Nelson, 1990):

- a) Reduces the risks of cement slurry setting within the casing, since the cement reaches the annulus much faster than in conventional methods of cementing;
- b) Does not require large-diameter cementing plugs;
- c) Reduces cement contamination;
- d) Reduces the amount of cement that has to be drilled out of large diameter casing;
- e) Decreases cementing displacement time; and
- f) Allows cement slurry to be pumped until returns are obtained on the surface.

#### 4.4.3 Two-stage cementing

This method is rarely used in geothermal well cementing because of the risk of having water pockets in the cement sheath. In geothermal wells, it is mostly used with tieback casing to minimize the risk of casing collapse. In long casing strings and in particular where the formations are weak and may not be able to support the hydrostatic pressure generated by a very long column of cement slurry, the cement job may be carried out in two stages (Nelson, 1990).

The cement sheath in the annulus is split into two, with one sheath extending from the casing shoe to some point above the bottom of the hole and the second sheath covering shallower troublesome formations (Figures 27 and 28).



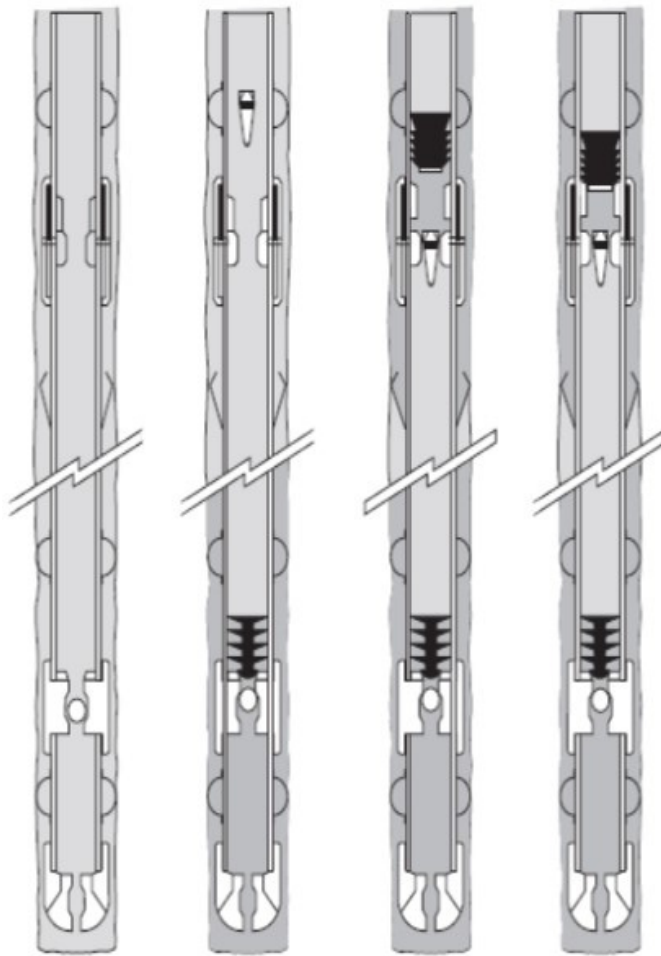


FIGURE 27: Two stage cementing operation (Nelson, 1990)

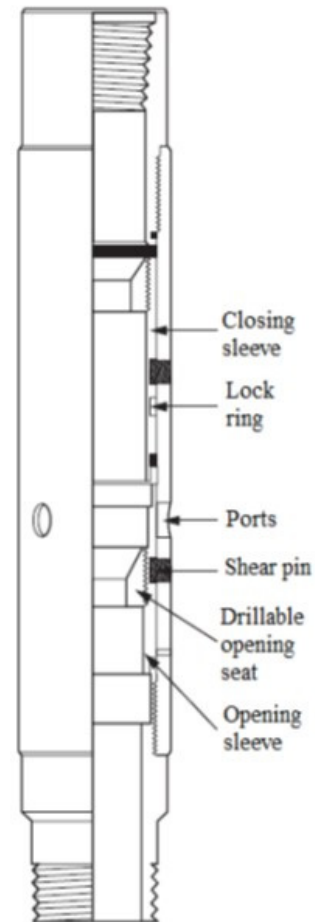


FIGURE 28: Stage cementing collar (Heriot-Watt University, 2010)

The reasons for using a two stage operation are to reduce:

- Collapse limit of casing;
- Long pumping times;
- High pump pressure; and
- Excessive hydrostatic pressure on weak formations due to the relatively high density of the cement slurry.

#### 4.4.4 Reverse-circulation cementing

This is mainly used in wellbores where loss of circulation is encountered, which has not been successfully healed. The technique involves pumping the slurry down the annulus and displacing the drilling fluid back up through the casing; the cement slurry direction is opposite that of the conventional method. The float equipment and well head assembly must be modified. This method is used when the cement slurry cannot be pumped in turbulent flow without breaking down the weak zones above the casing shoe (Figure 29).

Reverse circulation allows for a wider range of slurry compositions, so heavier or less retarded slurries can be placed at the top of the annulus. Caliper surveys should be made before the casing is run, to determine the required volume of cement and minimise over-placement (Crook, 2006). Reverse-circulation cementing can provide the following advantages:

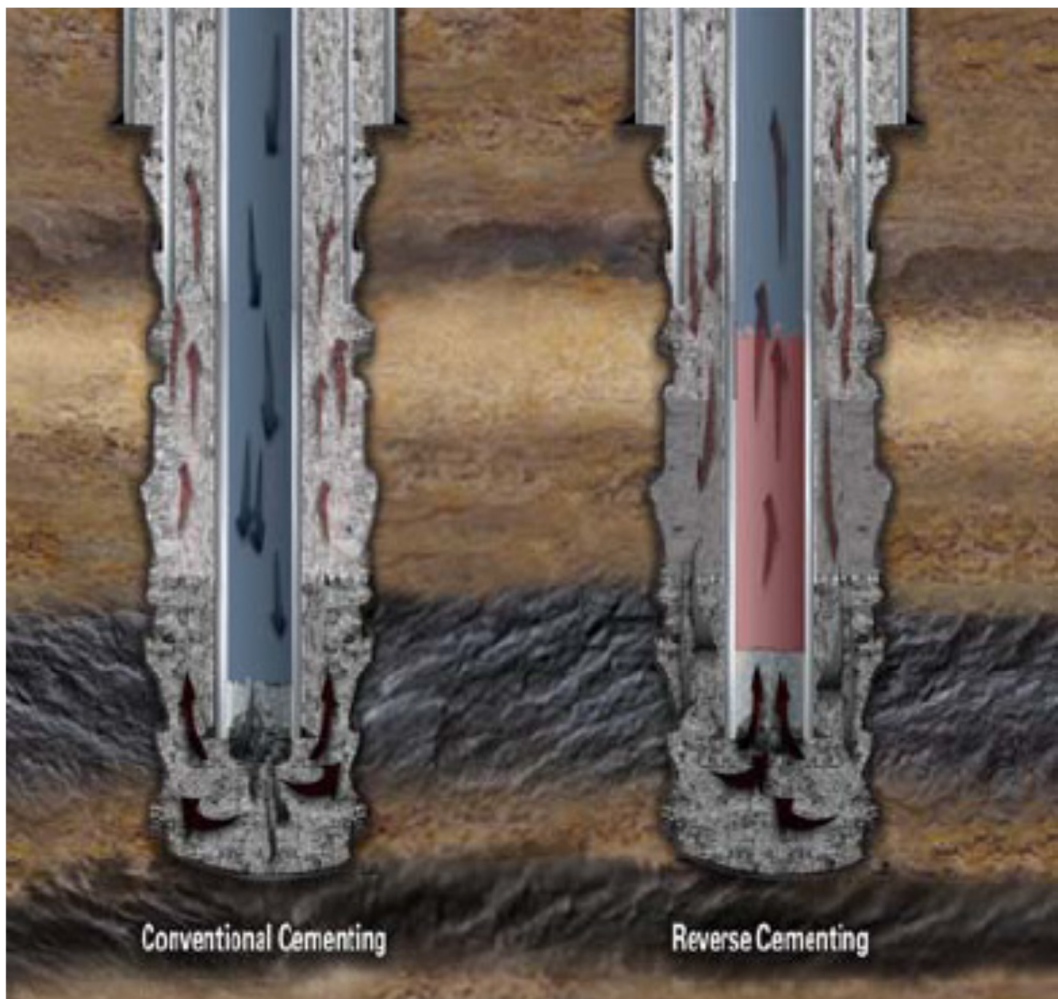


FIGURE 29: Conventional versus reverse cementing (Hernandez and Bore, 2010)

- a) Reduces fluid pressure, often reported as an equivalent circulating density (ECD), which is normally calculated at the shoe by combining the effects of hydraulic pressure and fractional fluid induced pressure in the casing. Because the heavier and more viscous cement slurry is not circulated back to the surface through the casing, the ECD can be significantly reduced in reverse cementing in comparison to conventional cementing.
- b) Enables shorter slurry thickening time since little or no retarders are used.
- c) Takes a shorter time to execute since no displacement is done.
- d) Reduces hydraulic horsepower of the cement slurry pumping equipment since the gravitational force is working in favour of the slurry flow.

#### 4.5 Difficult cementing jobs

Because geothermal casings must be cemented completely back to the surface, there is often a problem getting a competent cement job where the formation has shown either low strength or lost circulation. This results from the cement's higher density, and thus higher static head, relative to the drilling fluid.

As discussed previously, it is also critical that no water is trapped between the cement and the casing, due to the possibility that the water pressure could cause the casing to collapse as the well bore goes through its temperature cycles (Finger and Blankenship, 2010).

Methods using very light-weight cement (less than  $1.5 \text{ g/cm}^3$ ) have sometimes been successful in low-pressure / low-strength zones. Lost circulation during cementing often results in cement jobs where the cement either does not reach the surface or falls back after reaching the surface.

If the cement is not very far from the surface, it can be repaired by a top job, where the cement is placed into the annulus outside casing by small-diameter tubing, called a tremor pipe (also spaghetti or macaroni string). However, this is usually only effective down to the first centralizer as the tremor pipe may not pass that centralizer. For this reason, the top two joints or sometimes up to 200 m of casing are left without a centralizer. If the tremor pipe does not reach the top of the cement, there is too much risk of trapping water and collapsing the casing, so this method should not be used.

When there are large losses, the location is identified and the cement volume adjusted just to reach the loss zone. Perhaps only half of the calculated slurry volume is pumped through the shoe, the rest is placed by “reverse cementing”. The loss zone is kept open by a small flow of water down the annulus until the well is ready to receive the large “top job”. As there is a blowout preventer (BOP) on the well, a back flush and back fill process can be used. The BOP is closed immediately after the first cement job and fresh cement slurry pumped down the back side through the kill line to fill the annulus. If the cement comes to the surface, it is essential to keep all water from the casing, so the casing annulus does not get contaminated by any additional water, and periodically the annulus is filled with fresh cement slurry until it no longer falls.

Failed cement jobs are very difficult to repair. A cement bond log (CBL) is very useful in analysing such situations. As a last resort, the casing can be perforated and squeezed, but another casing string will have to be run over the perforations, as the integrity of the casing is unacceptably compromised by the perforation.

The need for a full-length cement sheath creates other problems that dictate how the well is drilled and completed. Standard geothermal practice used to be that lost circulation zones should be fixed as they are encountered, so that they will not interfere with the cementing work. This is expensive because some lost circulation zones may require several cement plugs to seal them and allow drilling to resume. Each plug requires cementing the loss zone and waiting on the cement until it is sufficiently set to re-enter the well and to drill ahead. This means that even a one-plug lost circulation seal will take 12-24 hours. Consequently, when severe lost circulation is encountered, the well is frequently drilled without returns to the next casing point. The method of cementing from the casing shoe and up to the loss zone while back flushing with water and then fill by “reverse cementing” was described above. It is currently the preferred placement method in several countries to cement casing strings when there are fluid losses.

The other possible approach is to use foam cement (the cement is foamed with nitrogen or air bubbles in the cement), including reverse circulation foam cementing. There are some concerns about the fact that the foamed cement is hard to control and that the resulting cement does not have the same very low permeability of regular cement to seal the casing from formation fluid chemicals (Finger, 2010).

## 5. CONCLUSIONS

Complete information about the rig’s performance is essential for safe, efficient operation and the project planner should include an instrumentation list in the rig criteria. A typical set of desirable measurements includes the following: rates and temperature of drilling fluid inflow and outflow, standard pipe pressure, rotary speed, weight on bit, torque, Kelly height, etc. Equipment to monitor and log these parameters should be available and in operational condition.

A highly productive fracture system is required to make geothermal projects economically viable, but is also the reason for the endemic lost circulation problems encountered when drilling geothermal wells.

Lost circulation treatment can represent 15% of the well's cost, and the under-pressured formation aggravates differential sticking, so these can be major impacts on drilling costs. Lost circulation is often massive, with complete loss of returns at pumping rates of 30-60 l/s. Drilling of geothermal wells has been cut short because of the inability to drill blind below a loss zone.

Eliminating well accidents requires time, materials, labour and equipment, all of which increase the cost of drilling. For this reason, the study of cases with drilling problems and their effective prevention and elimination is one of the priorities of a drilling organization. Frequent inspection of the drill string, the mast and other equipment is necessary to avoid downtime that may arise from fishing jobs.

Rock destruction in well drilling is a complicated process. Quantitative figures of bit performance, meterage per bit run, or the on bottom drilling rate, are not indicative of how the rock destruction efficiency is influenced by the three main drilling parameters. This is because all drilling parameters act concurrently. The effect of a drilling parameter on the bit performance figures, say on the on-bottom drilling rate, is determined with all other parameters being fixed.

Common rock types in geothermal reservoirs include granite, granodiorite, quartzite, greywacke, basalt, rhyolite and volcanic tuff. Compared to the sedimentary formations of most oil and gas reservoirs, geothermal formations are, by definition, hot (production intervals from 160°C to above 300°C) and are often hard (240+ MPa compressive strength), abrasive (quartz content above 50%), highly fractured (fracture apertures of centimetres), and under-pressured. They often contain corrosive fluids, and some formation fluids have very high solids content. These conditions mean that drilling is usually difficult, rate of penetration and bit life are typically low, and corrosion is often a problem.

If zones with fractures must be sealed in the upper intervals of the well, cement is usually the treatment of choice but is hard to place accurately. If the loss zones cannot be effectively repaired before casing is run, a more complicated cementing procedure must be used to accomplish an effective casing cement job. And sometimes an unplanned string of casing must be inserted to seal off a problem. Lost circulation that occurs above the production formation must be cemented off with a production casing to isolate the water that does not meet the minimum temperature criteria, while lost circulation treatment (e.g. aerated drilling) within the production formation strives to maintain the loss zones open.

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