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GEOTHERMAL WELL DRILLING

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ABSTRACT

Drilling of geothermal wells is a complex process that entails breaking the ground and lifting the rock cuttings from the resulting hole. The ultimate geothermal drilling objective is to access the resource for exploitation. However, during resource development and exploitation, drilling is used to confirm existence of the resource, obtain data for resource assessment, provide adequate steam fuel for the power plant and resolve well production complications. Tri-cone tungsten carbide insert bits are very often used in geothermal drilling. Mobile and conventional land rigs are predominantly used in the geothermal drilling industry. The rigs are selected to technically fit the job at the lowest cost possible. The wells are made useful by casing them. Several casing string are used for each well. They are cemented to bond them to formation.

1. INTRODUCTION

Geothermal well drilling is basically making a hole. The actual breaking of the rock is achieved by the use of a drill bit which is rotated with weight. Drilling of geothermal wells is carried out in a series of stages with each stage being of smaller diameter than the previous stage and each being secured by steel casings. These casings are cemented in place before drilling the subsequent stage. The final section of the well use a perforated uncemented liner which allows the geothermal fluids to pass into the pipe (Semancik and Lizak, 2009).

The main objective for drilling of geothermal wells as discussed by Ngugi (2008) include:

Exploration
The very first evaluation of a prospect is achieved through detailed surface reconnaissance. It is aimed at defining the resource by its key system characteristic namely: existence of a heat source in the form of hot magmatic body near earth surface, existence of hydrological system, characteristic of the geological setting and areal extent of the prospect. However, while the surface measurement and mapping and evaluation of the surface manifestations provide great insight as regards the resource characteristics and potential, results of the reconnaissance remain inferences and are inconclusive. The initial employment of drilling in geothermal prospecting is aimed at providing proof of exploitable steam and data required for further refining of the conceptual model.

Appraisal
Striking steam with the first well while is exciting opens up doors for more questions. Having confirmed existence of the resource, the next question is its technical, economic and financial viability. Further drilling (appraisal) is therefore carried out to delineate the resource and establish production well and reservoir fluids characteristics.

Production and re-injection
At this stage of development, a decision to construct a plant is already made. The drilling is therefore to provide sufficient steam to run the plant. Additional wells are drilled for reinjection purpose. One reinjection well is required for every 4 to 5 production wells.

Make up wells
After commissioning of the power plant, with time the reservoir surfers pressure decline which affects well productivity. In addition, deposition may occur within the formation around the wells further reducing wells productivity. With time, therefore further drilling is carried out to replenish the reduced steam delivery.

Work over
Two types of problem may arise during exploitation. Steam depletion in the shallow reservoir may necessitate deepening of the initial wells or deposition of scales within the well bore may necessitate a mechanical removal of the scales. These two cases require some form of drilling to accomplish.

2. WELL CONTROL SYSTEM

Perhaps one of the most crucial differences between geothermal and oil and gas drilling operations is the nature of the formation fluids and how they can be controlled.

A geothermal well has the potential of being filled with a column of water at boiling point. Even the slightest reduction in pressure on that column can cause part of, or the entire column to boil and flash to steam. This process can occur almost instantaneously. The potential for 'steam kick' is always there and requires special drilling crew training and attention. Whilst the likelihood of a well kicking at any time is real, the method of controlling such a kick is simple and effective. Steam is condensable, so by simply shutting in the BOP's and pumping cold water into the well – both down the drilling and down the annulus, the well can be quickly controlled.

If control of that flow is lost, then the resulting disaster is a "blowout" which, at the least will be very expensive and, at worst, can result in loss of life, equipment, and the drill rig, as well as damage to the environment.

Two situations that can cause loss of control are:

- Circulating hot fluids from deeper depths to the surface, resulting in the fluids flashing to steam. This causes a loss in hydrostatic pressure, and a further flashing or boil down effect.
- Lost circulation causes the fluid level, and thus the pressure, in the wellbore to suddenly fall far enough for the same thing to happen.

The equipment that controls a kick and potential outflow at the wellhead is called the blowout preventer (BOP). The BOP stack comprises of five types of device to shut off the wellbore and prevent fluid flow. They include:

- Rotating heads;
- Annular preventers;

- Pipe rams;
- Blind rams; and
- Shear rams.

3. WELL DESIGN

The geothermal well design process includes consideration of the objectives and purpose of the well, the subsurface conditions likely to be encountered during the drilling process, and the identification of required equipment, materials, and drilling procedures needed to ensure a satisfactory well completion and an acceptable well life.

The well design information required include:

- Purpose of the well;
- Surface or shallow hole conditions;
- Reservoir conditions – the temperature and pressure and brine chemistry which dictate the casing selection and as a result the cost of the well;
- Logistical requirements;
- The problems likely to be faced while drilling; and
- Casing requirements.

The most critical aspects of these design steps is the selection of casings, casing specification, casing shoe depths, and how the well is completed (Hole, 2008a).

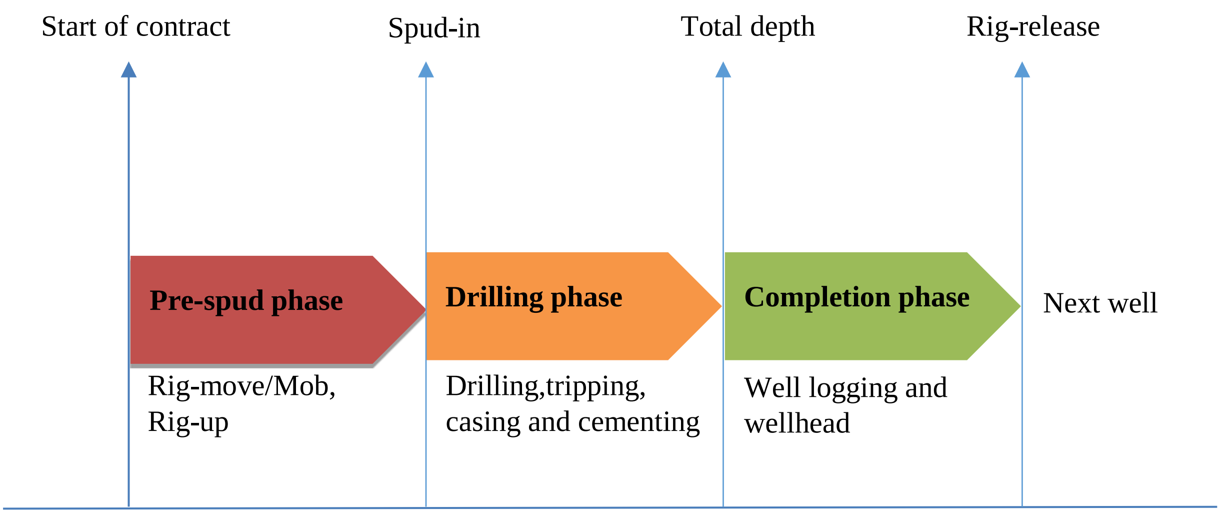

FIGURE 1: Summary of the phases of geothermal drilling

Casing design
The first design task in preparing the well plan is selecting the depths to which the casings will be set and cemented. These depths are determined such that the casings can safely contain all well conditions encountered as a result of surface operations and from the behaviour of the formations and fluids encountered as drilling proceeds. Casing shoe depths are determined by analysis of data from adjacent wells. This includes rock characteristics, formation and formation temperatures, fluid types, composition and pressures and in particular, the fracture gradient data that is gathered from nearby wells. Figure 2 (Hole, 2008b) illustrates how the shoe depth may be chosen using a somewhat simplistic and

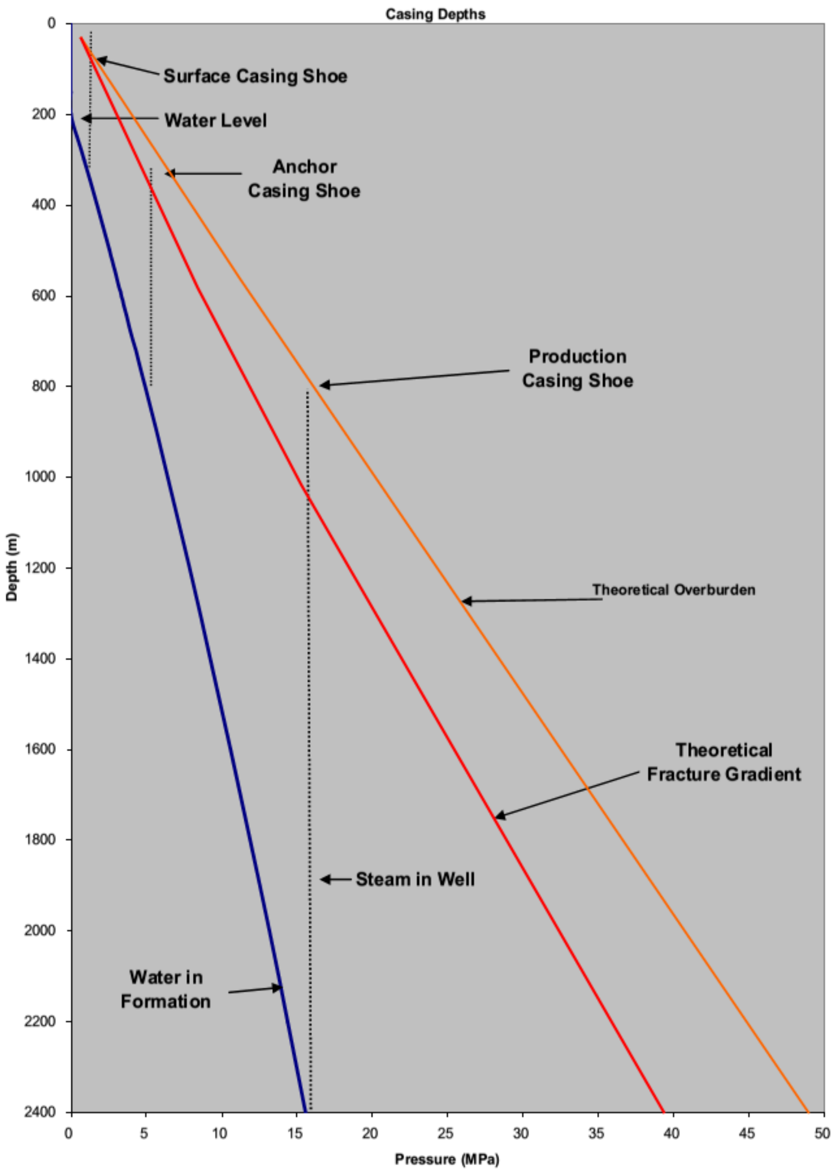

FIGURE 2: Theoretical minimum casing depth selection.

theoretical model with boiling point for depth fluid pressure condition from a nominal water level at 200m depth; and a uniform formation fracture gradient from the surface to the total depth of 2400m.

From this simplistic model, the production casing shoe would need to be set at about 800m, the anchor casing shoe at approximately 350m; and a surface casing at around 50m depth.

4. DRILL STRING

Choosing the drill pipe specifications can be complicated in some cases, but the primary considerations are as follows;

4.1 Strength

The principal requirements are for tensile and torsional strength, so that the pipe can pull the drillstring out of the hole (often with some overpull required because of tight spots, or even partially stuck pipe) and can apply the torque needed to rotate the bit. Internal pressure may become an issue in some cases, and bending strength is important in directional drilling. Higher strength grades can be susceptible to hydrogen sulfide embrittlement. Drilling torque is often limited by drillpipe connections so high torque connections may be desirable.

4.2 Size

Given that several different pipe configurations might be strong enough, a major driver for size selection is hydraulics. The internal diameter of the pipe must be large enough to avoid excessive pressure drop in the circulating drilling fluid. It is also necessary that the inside diameter of the pipe be large enough to pass any expected logging tools, and the outside diameter of the drill pipe tool joints be small enough that overshot fishing tools can be used in the event of trouble. Usually the fishing constraint results in the outside diameter of the drill pipe tool being small enough to pass through the smallest casing to be used, with enough clearance for the same fluid flow, again without excessive pressure drop, on the outside of the pipe.

4.3 Corrosion resistance

Many formation fluids are corrosive; this is especially true in much geothermal drilling. There are a number of special grades of drill pipe made from alloys designed for corrosive environments.

4.4 Wear resistance

Because many geothermal formations are extremely abrasive, drill pipes tend to wear much faster than in other types of drilling. "Hard-banding" which is simply applying layers of wear-resistant material such as tungsten carbide to the outside diameters of the tool joints is common in geothermal drilling, although hard-banding can also damage the casing if extended time is spent drilling.

4.5 Bottom-hole assembly (BHA)

A drill sting is relatively flexible compared to its length. The total weight of the drillstring is generally much greater than the desirable force on the bit, so the rig's hoisting capability holds back some of the string weight to control force on the bit. The upper part of the drillstring is therefore in tension, while the lower part that applies force to the bit is in compression.

Drilling with the relatively thin drill pipe in compression is likely to cause buckling, so it is important that the neutral point (where the drillstring stress changes from tensile to compressive) falls within the drill collars. The outside diameter of the collars is controlled by the necessary annulus between the collars and the wellbore. The inside diameter is determined by hydraulic considerations (large enough to prevent excessive pressure drop) and by the necessity of passing logging tools, and possibly explosive charges large enough to sever the collars should they become irretrievably stuck.

The overall length is that required to provide maximum expected weight on bit, and to capture the neutral point. Although very large diameter holes are drilled for geothermal, the outer diameter of the drill collars is usually limited.

Other components that are often part of the BHA include the following.

4.5.1 Stabilizers

Because the drill collars and other components must be smaller than the wellbore diameter to provide a path for fluid circulation, they can have major lateral deflections. This can produce serious vibration as well as high fatigue loads in the threaded connections, so stabilizers that have full wellbore diameter on ribs along the outside surface, but leave a flow path between the ribs, are widely used at multiple points in and above the bottom-hole assembly (Figure 3). However, a minimum number of stabilizers should be run to reduce the risk of getting stuck in cuttings or cavings.

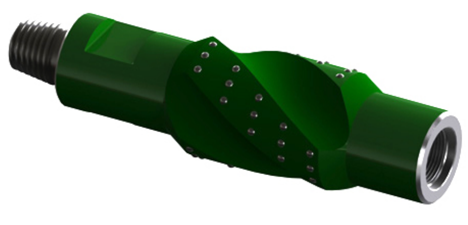

FIGURE 3: Stabilizer

4.5.2 Reamers

The outside diameter or "gauge" of drill bits tends to wear, causing the hole to be smaller than the nominal diameter. When a new bit is tripped in, it has to ream the smaller hole out to the desired diameter, which is time consuming and which causes the new bit to wear prematurely on its own outside diameter. Additional cutting elements, either as fixed cutters or as toothed, cylindrical rollers are often added to the BHA just above the bit, to help maintain the full hole diameter. This is more common in abrasive geothermal formations than in much of oil and gas. Near-bit roller reamers are not favored for directional drilling.

4.5.3. Shock subs

When drilling in hard or fractured formations, or those in which soft and hard stringers are inter-bedded, high vibration loads are common. A shock sub is a shock absorber, or damper, used to attenuate the vibrations transferred to the upper part of the BHA and drillstring.

4.5.4 Jars

If the drillstring is stuck in the hole, it can sometimes be released by the impact force produced by jars. When getting stuck while going down, the pipe needs to be jarred up. When getting stuck while going up, the pipe needs to be jarred down. The jars function by suddenly releasing energy stored in the drillstring by pulling up on it and

5. BIT TECHNOLOGY

The bit is usually either a roller-cone or a drag bit. The roller cone bit crushes and gouges the rock as the cones turn and their teeth successively come in contact with unbroken areas. The drag bit on the other hand, shears the rock in the same way that a machine tool cuts metal. Because of this shearing action, drag bits are inherently more efficient than roller-cone bits.

FIGURE 4: Roller cone bit

The great majority of roller-cone bits today have three cones, with either milled steel teeth that are part of the cone itself or hard-metal (usually tungsten carbide) teeth inserted into the body of the steel cone. Milled-tooth bits are less expensive but are suited only for softer formations. Insert bits are used in medium hard to harder formations, 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, and the bearings, seals, and lubricants should all be specified to withstand high temperatures 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 those reservoirs.

Because drag bits reduce rock with a shearing action, they are inherently more efficient than roller-cone bits. Drag bits with polycrystalline-diamond-compact (PDC) cutters began to be widely used in the early 1980's. A particular advantage of drag bits for geothermal drilling is that they do not have any moving parts, so temperature limitations on bearings, seals, and lubricants are not a factor. Historically, PDC bits have not had acceptable life in hard or fractured formations, and great deal of work was done to extend their use to harder rocks. Significant progress has been made, and these bits are slowly becoming accepted by the geothermal industry.

FIGURE 5: PDC bit

ROP with PDC bits has been similar to roller-cones in most wells but lifetime is much longer. If a single bit can now drill complete intervals, wear on other downhole tools (jars, stabilizers, drill collars and drill pipe) will become the limiting criteria rather than bit changes requiring tripping.

Wider use of these more efficient bits would be a significant technology advance.

6. DRILLING FLUIDS

Drilling fluid flows down the drill pipe, through nozzles in the bit, and back up the annulus between the pipe and wellbore wall, carrying the cuttings produced by the bit's action on the rock. The principal function of drilling fluid is to clean the hole of cuttings, but there are several other purposes (Chemwotei, 2011). They include:

- Cooling and cleaning the bit. Keeping the bit cool, especially if it has elastomer seals, is critical to its life.
- Lubricating the drill string. This can be a significant factor in deviated wells, where the drilling string is lying against the wellbore wall.
- Maintaining the stability of the borehole. The proper drilling fluid can help control swelling or sloughing formations, thus lessening the risk of stuck drill pipe. It is also important that the fluid hold the cuttings in suspension when circulation is stopped, so that they do not fall back and pack around the bit and BHA.
- Allow collection of geological information. The cuttings brought back to the surface by the fluid help to identify the formation being drilled.
- Form a semi-permeable filter cake to seal the pore spaces in the formations being penetrated. This prevents fluid loss from the wellbore into the formation.
- Controlling formation pressures. If high downhole pressures are present or expected, dense material can be added to the drilling fluid to increase its specific gravity, thus resisting the downhole pressure. Conversely, if low downhole pressures pertain then lower density drilling fluids may be used to minimize formation damage and reduce differential sticking pressures in particular.

7. CEMENTING

Cementing is the process of mixing and pumping cement slurry down to fill the annular space between the casing and formation and therefore establish a bond. The casings in geothermal wells are usually fully cemented back to the surface (Bett, 2010).

Portland cement is the most commonly used cement. Slurry is made by mixing cement with water and additives. Chemical additives are mixed into the cement slurry to alter the properties of both the cement slurry and the hardened cement making it more suitable for the geothermal environment.

The success and long life of well cementation requires the utilization of high-grade steel casing strings with special threaded couplings and temperature-stabilized cementing compositions. A hydraulic seal must be obtained 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 ensure the integrity of the well.

When primary cementing is not well executed using the right methods and materials and poor planning, remedial cementing might have to be done. This is done to restore a well's operation.

In general, there are five steps in designing a successful cement placement:

- Analysis of the well conditions; objectives of the well and then designing of placement techniques and cement slurry to meet the needs for the life of the well.
- Slurry composition and laboratory tests.
- Slurry volume to be pumped, use the necessary equipment to blend, mix and pump slurry into the annulus, backup procedures and contingency.
- Monitoring of the cement placement in real time: comparison is done with the first step, and changes are done where necessary.
- Post-job evaluation of results.

The objective of casing cementing is to ensure 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 borehole are:

- To prevent the movement (migration) of fluids from one formation to another or from the formations to surface through the annulus.
- To hold the casing string in the well.
- To protect the casing from corrosive fluids in the formations and buckling.
- To support the well-bore walls (in conjunction with the casing) to prevent collapse of formations.
- To prevent blowouts by forming a seal in the annulus.
- To protect the casing from shock loads when drilling deeper.

Cementing is also used to condition the well:

- To seal loss of circulation zones.
- To stabilize weak zones (washouts, collapses).
- To plug a well for abandonment or for repair.
- To kick-off side tracking in an open hole or past a junk.
- To plug a well temporarily before being re-cased.

8. DIRECTIONAL DRILLING

Directional drilling is a special drilling operation used when a well is intentionally deviated to reach a bottom location (Figure 6). It is the most widely used method of drilling geothermal wells due to its various advantages. Drilling multiple wells in the same well pad allows for fewer drill sites, less surface area disturbance as well as making it easier to exploit the resources being drilled for. Other benefits are as discussed below:

- Enhanced permeability – Possibility of intersecting many vertical or near vertical fracturing.
- Accessing targets from remote locations.
- Multi-well pads – Overall environmental impact is reduced since few well pads are prepared.
- Side tracking – In case of a stuck drill string which is not possible to fish, the well can be side tracked to bypass the fish in the hole and then drilled to the intended target.
- Relief well in case of uncontrolled blow out.
- Reduced earth works where the terrain is rough. The earth works involve access roads, sites, laying water pipelines, drilling water ponds, site rehabilitation, brine disposal, well testing, and road upgrading costs during power plant construction.
- Rig moving time and cost is reduced since the rig moves between well locations on the same pad.
- Reduced steam gathering system costs.

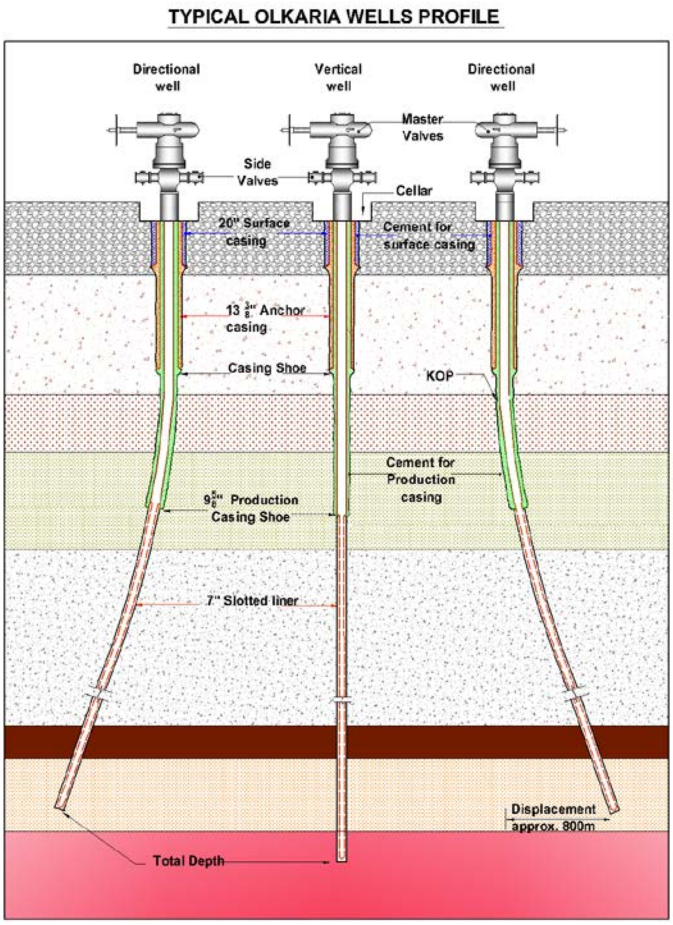

FIGURE 6: Typical regular diameter well profile

Centralized brine separation is largely achieved, which maximizes hot re-injection flexibility and also reduces the number of separators required. The collected centralized brine can be used for drilling wells on adjacent well pads.

There are however, a number of challenges experienced while drilling directional well. They include:

- Extra drilling cost due to the use of mud motor and directional surveys.
- Running in hole for angle correction BHA unlike for vertical wells where tripping out is only done for bit change.
- Time taken for angle measurements surveys which could be used for actual drilling.
- A higher drilling torque which translates to higher energy consumption

9. PROBLEMS

These are any occurrence which may cause a time delay in the progression of planned drilling operations. It includes the time required to solve that problem and the time it takes to bring the operation back to the point or depth at which the event occurred. It is very common to experience these problems when drilling geothermal wells. The ultimate goal of any drilling organization is to improve drilling performance by reducing unscheduled events and therefore reducing well costs. The most common down-hole problems when drilling geothermal well are discussed below.

9.1 Loss of circulation

This is one of the most expensive problem routinely encountered when drilling geothermal wells. It is the loss of drilling fluid to pores or fractures in the rock formation being drilled. Ideally the well should have no losses until the casings have been cemented but in the open hole section big losses indicate good future production potential and are thus highly desirable. Loss of circulation is quite harmful for the drilling process because of several reasons as discussed below.

- Drilling without returns can leave formation pressure unbalanced, which can allow the hole wall to fall in. Also the cuttings that do not enter the fracture accumulate inside the well cavities. At breaks in circulation for example when adding a new pipe and without much warning, the material can jam the drill string. This can cause stuck pipe, twist offs, or even loss of the well.

- Flow of the drilling fluid with cuttings into the formation can damage the formation permeability and reduce well productivity.

- Lost circulation that occurs during the cementing of the well can cause incomplete cement jobs that can in turn lead to casing failure.

- The drilling fluid used for example bentonite is usually quite expensive and losing it into the formation instead of re-circulating is costly.
- 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 to enter the wellbore causing loss of well control.
- Placement of cement plugs is made difficult because the top and bottom of the loss zone are often not well known.
- Placement of lost circulation materials (LCM) is difficult because the top and bottom of the loss zone are often not well known. The LCM or cement being used to heal the loss zone are especially likely to migrate away from the targeted placement zone if drilling has continued well past it into another loss zone, or if there is considerable rat hole below the original loss zone.

Combating lost circulation can be approached in different ways; drill ahead with lost circulation; drill with a lightweight drilling fluid that will have a static head less than the pore pressure in the formation; mix the drilling fluid with fibrous material or particles that will plug the loss apertures in the formation; or pause in the drilling and try to seal the loss zones with some material that can be drilled out as the hole advances.

9.2 Stuck pipe

This refers to the mechanical sticking of a drill string while drilling. It is caused by chips and cuttings collecting on top of the drill string. The pipe can also be held against the wellbore wall by differential between the drilling fluid pressure and the pore pressure. Differentially stuck pipe will not rotate nor can pulling move it, but the well can still be circulated. Differentially stuck pipe is usually combated with a lubricant that reduces the fluid loss and helps equalize the pressure around the drill pipe.

9.3 Fishing

Fishing operation is an attempt made to remove stuck or broken objects from the well that prevents further drilling. Fishing may take up to 20% of time when drilling a geothermal well. Each rig is equipped with various fishing tools. Fishing jobs require high skill and specialized equipment. Most companies find it more economical to rely on service companies to furnish the tools and specialized personnel when need arises. (Ngugi, 2008)

Other well problems may include twist-offs (broken drill sting), hole stability problems, well control problems, cementing, casing problems and directional drilling problems.

10. WELL COSTING

Some well cost drivers are uniqueness of the well, time spent on drilling, the well design, bit selection and technical challenges encountered.

9.1 Elements of well costing

Well costs are a major component of the total cost of developing any geothermal project. There are several factors that affect these well costs. They include the depth of the geothermal resource together with the nature, structure and hardness of the rock formation. These parameters automatically influence the initial and final well diameter, the number of casing strings required, the rate of penetration and drilling speed, and eventually the total time required to complete the well. Deeper wells also require larger and thus more expensive drilling rigs. Other factors that influence the well cost may include the geographical location of the drillsite, the downhole problems encountered and finally the well measurements and well logging types employed.

Well costs are divided into three major costs; the pre-spud, the drilling and the completion costs. The pre-spud costs are the costs incurred during the pre-spud phase. The drilling cost, on the other hand is the sum of the total cost incurred when making the hole. This includes the cost of drilling materials and consumables and the cost of services offered depending on the contract. The drilling cost although quite predictable can vary according to the drilling contract, the size and rating of the drilling rig being used, the well design and to a lesser extent the remoteness of the drillsite and proximity to suppliers.
Drilling costs are further categorized into four components, namely:

i. Daily operating costs: These are the costs incurred when operating the drilling rig on a day to day basis. It includes the daily rig rate which is the rental charges for the rig with crew and associated equipment.This rig rate varies depending on the type and size of rig, length of contract, supervision, and of course the market conditions. The well design will of course dictate the type of rig to be hired and not to mention the extra equipment that comes with it. It may also include the costs for the rig maintenance, water supply, catering and accommodation, drill site maintenance and waste disposal.

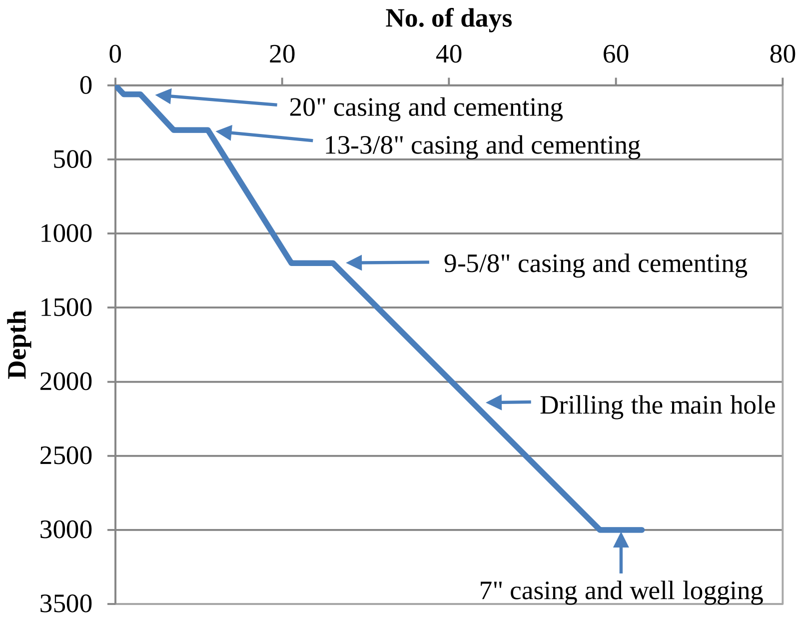

FIGURE 7: Depth vs. days

ii. Drilling consumables costs: These are the costs inclusive of VAT and transport and handling of the drilling consumables that are used when drilling a geothermal well. These consumables include the rock bits, the drilling detergent, diesel, lubricating oil, cement and cement additives and drilling mud. The quantity of these consumables will entirely depend on the well design.

iii. Casing and wellhead costs: These are the cost of the steel casing, casing accessories and wellhead equipment inclusive of VAT and transport to the drilling site. The cost of these drilling materials can be easily estimated. When calculating the cost of casings for a particular well for example, each casing string for each hole size is costed and the total added up to give the total casing costs for the well. The same applies to each item which requires selection and breaking into individual groups for example drill bits when calculating the drilling consumable costs.

iv. Services costs: There are several services offered during the drilling of a geothermal well. These services vary depending on the well design and the drilling contract in place. These services include drilling supervision, planning and logistics, civil engineering, geological services, cementing services, directional drilling, and well logging. The total cost of services is usually costed for each individual hole section and the total cost summed up.

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