GEOTHERMAL DEEP WELL DRILLING PRACTICES

- AN INTRODUTION

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ABSTRACT

An introduction to Geothermal Deep Well Drilling. The formation and reservoir conditions that characterise geothermal systems (typically higher enthalpy) require the adoption of drilling practices that differ from those utilised in conventional oil, gas, and water well drilling operations. Temperature, Geology, and Geochemistry are the principal areas of difference.
This paper outlines typical geothermal drilling conditions, and the drilling practices that have been developed to optimise the drilling processes in these conditions.

Keywords: geothermal, drilling,

INTRODUCTION

Although heat from geothermal sources has been used by mankind from the earliest days – for cooking and bathing, for instance - it's major development has taken place during the past 30 years. This has occurred in parallel with the significant advances made in deep drilling practices, and it's importance has risen dramatically during the last few years as the price of petroleum has soared, and awareness of the importance of 'renewable energy' has developed.

The equipment and techniques used in the drilling of geothermal wells have many similarities with those used in exploring and exploiting petroleum reservoirs. However, the elevated temperatures encountered; the often highly fractured, faulted, and permeable volcanic and sedimentary rocks which must be drilled; and the geothermal fluids which may contain varying concentrations of dissolved solids and gases have required the introduction of specialised drilling practices and techniques.

TEMPERATURE

The temperature of the earth's crust increases gradually with depth with a thermal gradient that usually ranges from 5° to 70° per kilometre. In anomalous regions, the local heat flux and geothermal gradients may be significantly higher than these average figures. Such anomalous zones are typically associated with edges of the continental plates where weakness in the earth's crust allow magma to approach the surface, and are associated with geologically recent volcanism and earthquakes. It is in such settings that the majority of geothermal resources are found and that the majority of geothermal wells have been drilled.

While a few wells have been drilled into temperature conditions that approach the critical point of water (374°C) and a number of fields produce dry and superheated steam, the majority of higher enthalpy resources are two phase – either vapour or water dominated, with temperature and pressure conditions controlled by the saturated steam / water relationship – 'boiling point for depth'.
For design purposes, where downhole pressures and temperatures are not known, 'boiling point for depth' (BPD) conditions are assumed from ground level as indicated in Figure 1.0.

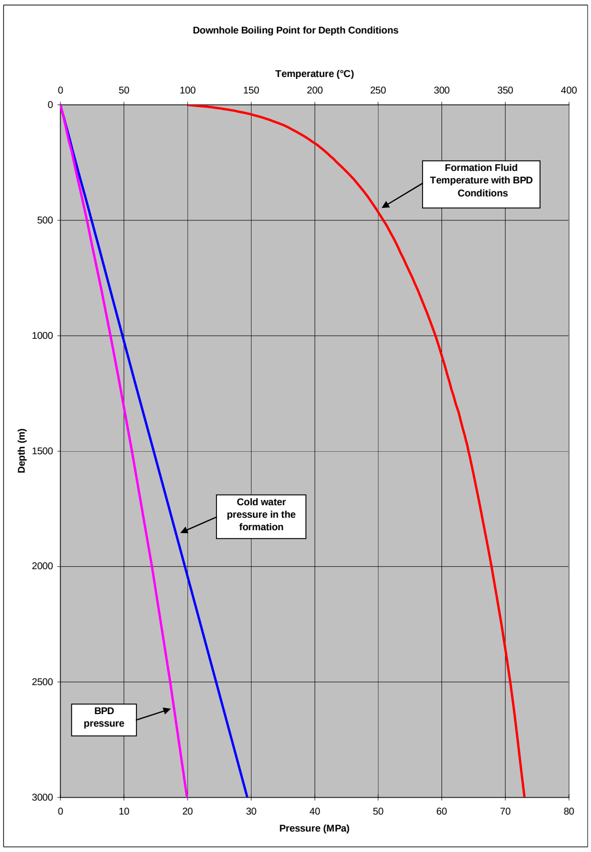

Figure 1.0 – Downhole fluid conditions - BPD.

Saturated steam has a maximum enthalpy at 235°C and consequently many geothermal fields are found to exist at temperatures approximating this value (dissolved solids and gases change this value somewhat).

Such elevated formation temperatures reduce drill bit and drilling jar performance and often precludes the use of mud motors and directional MWD instrumentation equipment; it adversely effects drilling fluid and cementing slurry properties; and reduces the performance of blow out prevention equipment. In addition it significantly increases the potential for reservoir fluid flashing to steam resulting in flowback or blowout from shallow depths.

The well, the downhole well components and the near well formations are subject to large temperature changes both during the drilling process and at the completion of drilling. The circulation or injection of large volumes of drilling fluid cools the well and the near well formation, but as soon as fluid circulation is ceased, rapid re-heating occurs. These large temperature differentials require special precautions to be taken:-

- to avoid entrapment of liquids between casing strings – which can exert extreme pressure when heated resulting in collapsed casing.
- to ensure casing grade and weight, and connection type is adequate for the extreme compressive forces caused by thermal expansion.
- to ensure the casings are completely cemented such that thermal stress are uniformly distributed.
- to ensure casing cement slurry is designed to allow for adequate setting times and to prevent thermal degradation.

GEOLOGY

Geothermal fields occur in a wide variety of geological environments and rock types. The hot water geothermal fields about the Pacific basin are predominantly rhyolitic or andesitic volcanism, whereas the widespread hydrothermal activity in Iceland occurs in extensively fractured and predominantly basaltic rocks. In contrast the Larderello steam fields in Italy are in a region of metamorphic rocks, and the Geysers steamfield in California is largely in fractured greywacke.

The one common denominator of all of these fields is the highly permeable, fractured and faulted nature of the formations in which the reservoirs reside. This high permeability being one of the fundamental and requisite components for any geothermal system to exist.

Typically, the permeable nature of the formations is not limited to the geothermal reservoir structure alone, but occurs in much of the shallower and overlying material as well.

In addition, a characteristic of most of these geothermal systems is that the static reservoir fluid pressures are less than those exerted by a column of cold water from the surface – the systems are "under-pressured". The high temperatures of the systems result in reservoir fluid densities which are less than that of cold water, and the majority of geothermal systems are located in mountainous and elevated situations – resulting in static water levels often hundreds of metres below the surface.

Drilling into and through these permeable and "under-pressured" zones is characterised by frequent and most often total loss of drilling fluid circulation.

Particularly in the volcanic geothermal systems, many of the shallow formations comprise low bulk density materials such as ashes, tuffs and breccias, which as well as being permeable, are often unconsolidated and friable, and exhibit a low fracture gradient, and thus provide low resistance to blowouts.

GEOCHEMISTRY

Geothermal fluids contain varying concentrations of dissolved solids and gases. The dissolved solids and gases often provide highly acidic and corrosive fluids and may induce scaling during well operations. Dissolved gases are normally dominated by CO_2 but can also contain significant quantities of H_2S, both of which can provide a high risk to personnel and induce failure in drilling tools, casings and wellhead equipment.

The presence of these dissolved solids and gases in the formation and reservoir fluids imposes specific design constraints on casing materials, wellhead equipment and casing cement slurry designs.

DRILLING PRACTICES:

In general, the drilling processes and equipment utilised to drill deep geothermal wells are substantially similar to those developed for petroleum and water well rotary drilling. However, the downhole conditions experienced in geothermal systems, as described above, require some significantly different practices to be adopted. Some of these differences are outlined below.

Well design

The thermal efficiency of converting geothermal steam/water to electricity is not particularly high (±20%), therefore large mass flows and therefore volume flowrates are required, particularly in vapour dominated systems. These large volume flowrate requirements necessitate large diameter production casings and liners.

Typically a 'standard' sized well will utilize standard API 9 5/8" diameter casing as production casing and either 7" or 7 5/8" diameter slotted liner in an 8½" diameter open hole section.

A "Large" diameter well will typically utilise standard API $13^3/_8$" diameter casing as the production casing, with either $9^5/_8$" or 10¾" diameter slotted liner in a 12¼" diameter open hole.

Casing sizes utilised for the Anchor, Intermediate, Surface and Conductor casings will be determined by geological and thermal conditions.

Figure 2 illustrates schematically the casing strings and liner of a typical geothermal well.

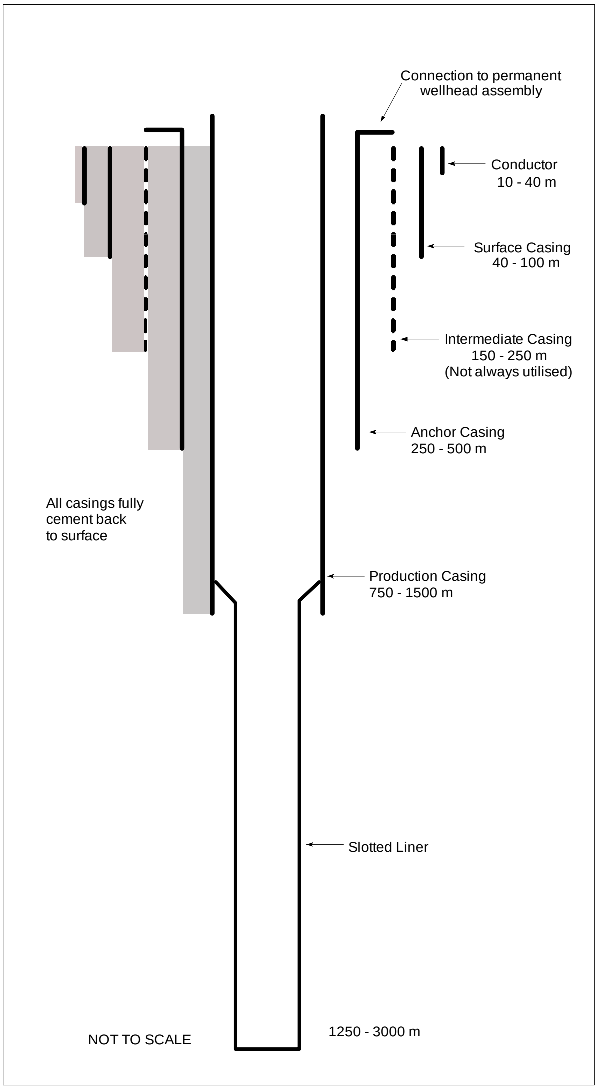

Figure 2. Casing strings and liner for typical well.

Casing Depths

The depths of all cemented casing strings and liners is determined such that the casings can safely contain all well conditions resulting from surface operations and from the characteristics of the formations and fluids encountered as drilling proceeds.
Casing shoe depths are determined by analysis of data from adjacent wells which will include rock characteristics, temperatures, fluid types and compositions and pressures. In particular fracture gradient data gathered from nearby wells. At any time the depth of open hole below a particular casing shoe should be limited to avoid exposure of the formations immediately below the casing to pressures which could exceed the fracture gradient at that depth and hence lead to a blowout. It is usual to assume worst case scenario's such as exposing the previous casing shoe to the saturation steam pressure at the total drilled depth of that section. Figure 3 illustrates how the shoe depths may be chosen using a somewhat simplistic and theoretical model with boiling point for depth fluid pressure condition from a nominal water level at 200 m depth; and a uniform formation fracture gradient from the surface to the total depth of 2400 m.

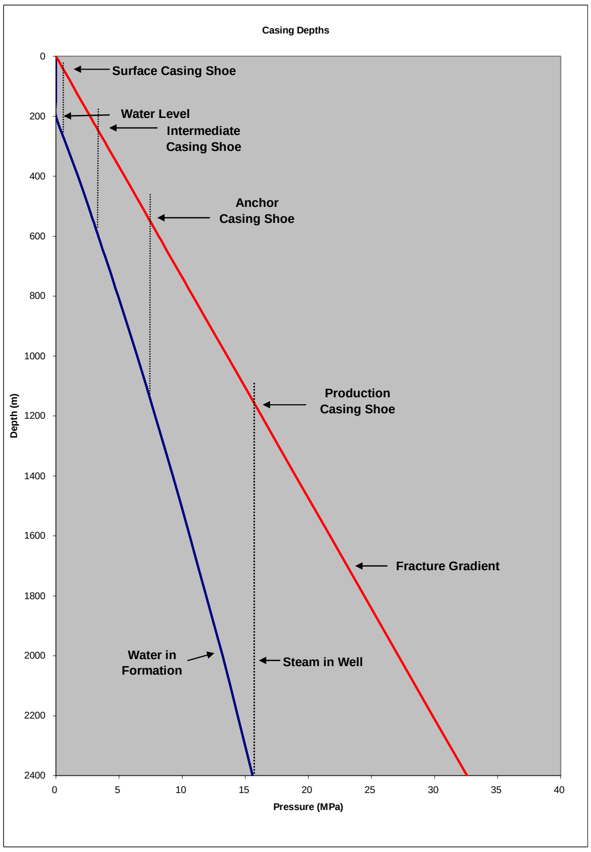

Figure 3. Casing Shoe Depths

This simplistic model suggests that the production casing shoe would need to be set no shallower than 1100m; the anchor casing shoe at approximately 550 m; an intermediate casing set at 250 m depth; and a surface casing set at around 40 m depth.
It is likely that with real data that this casing programme would be somewhat simplified, the production and other casings shoes somewhat shallower, and the intermediate casing eliminated.

Casing Diameters

Casing diameters will be dictated by the desired open hole production diameter – typically either 8½" or 12¼". Slotted or perforated liners run into these open hole sections should be the largest diameter that will allow clear running – there is an obvious advantage to utilise 'extreme line' casing connections from a diameter point of view, however this is often offset by reduced connection strength of this type of casing connection.

Casing internal diameters should not be less than 50 mm larger than the outside diameter of connection collars and accessories, to allow satisfactory cementing.

A typical well design would include:-

- Conductor:– 30” set at a depth of 24 metres, either driven or drilled and set with a piling augur.
- Surface Casing:- 20” casing set in 26” diameter hole drilled to 80 metres depth.
- Anchor Casing:- 13 3/8”casing set in a 17½” hole drilled to 270 metres depth.
- Production Casing:- 9 5/8” casing set in a 12¼” hole drilled to 800 metres depth.
- Open Hole – 7” perforated liner set in 8½” hole drilled to 2400 m –Total Depth.

Casing materials

Steel casing selected from the petroleum industry standard API Spec. 5CT or 5L.
In general the lowest tensile strength steel grades are utilised to minimise the possibilities of failure by hydrogen embrittlement or by sulphide stress corrosion. The preferred API steels are: Spec 5CT Grades H-40, J-55 and K-55, C-75 and L-80; Spec 5L grades A, B and X42.
In cases where special conditions are encountered, such as severely corrosive fluids, use of other specialised materials may be warranted.

Casing Connections

The compressive stress imposed on a casing strings undergoing heating after well completion is extreme. As an example, an 800 metre length of casing undergoing heating from the cement setup temperature of around 60°C to the final formation temperature of 210°C (a change of 150°C), would freely expand 1.44 m. If uniformly constrained over the full length, the compressive strength induced would be 360 MPa; the minimum yield strength of Grade K-55 casing steel is 379 MPa. As this illustrates, axial strength is critical and it is therefore important that the casing connection exhibits a compressive (and tensile) strength at least equivalent to that of the casing body.
It is usual that a square section thread form is chosen, and this is typically the API Buttress threaded connection.

Cementation of Casings

Unlike oil and gas wells, all of the casings down to the reservoir are usually run back to the surface, and are fully cemented back to the surface. The high thermal stresses imposed on the casings demand uniform cementation over the full casing length, such that the stress is distributed over the length of the casing as uniformly as is possible and such that stress concentration is avoided.

The objective of any casing cementing programme is to ensure that the total length of annulus (both casing to open hole annulus, and casing to casing annulus) is completely filled with sound cement that can withstand long term exposure to geothermal fluids and temperatures.

Of course, as suggested above, the permeable and under-pressured nature of the formations into which these casings are being cemented means that circulating a high density cement slurry with S.G.’s ranging from 1.7 to 1.9, inevitably result in loss of circulation during the cementing procedure.

The traditional method of mitigating this problem was to attempt to seal all permeability with cement plugs as drilling proceeded, however, this is usually an extremely time consuming process, and more often than not, circulation is still lost during the casing cementing process.

Many approaches to overcome this problem have been tried, and include:-

- Low density cement slurry additives – pozzalan, perlite, spherical hollow silicate balls
- Sodium silicate based sealing preflush
- Foamed cement
- Stage cementing
- Tie back casing strings – the casing is run and cemented in two separate operations.

Many of these options were tried but generally none have proven totally successful nor economic.

To date, in the experience of the author, the most successful procedure has been to utilise the most simple high density cement slurry blend, and to concentrate on the techniques of placing the cement such that a full return to the surface without fluid inclusions can be achieved. This nearly always involves a primary cement job carried out through the casing, and in the event of a poor or no return and immediate annulus flushing procedure, which is then followed by an initial backfill cement job through the casing to casing annulus, with sometimes repeated top-up cement jobs. Particular care must be taken to avoid entrapment of any water within the casing to casing annulus.

Perforated and Slotted Liner

Unlike the cemented casings discussed above, it is usual to run a liner within the production section of the well. This liner is usually perforated or slotted, typically, with the perforation or slots making up around 6% of the pipe surface area. As it is extremely difficult to determine exactly where the permeable zones within the production section lie, it is usual that the entire liner is made up of perforated pipe.

The liner is not cemented, but either hung from within the previous cemented production casing, or simply sat upon the bottom of the hole with the top of the liner some 20 to 40 metres inside the cemented production casing shoe, leaving the top of the liner free to move with expansion and contraction.

Drilling Rig and Associated Equipment

The drilling rig and associated equipment are typically the same as is utilised for oil and gas well drilling, however a few special provision are required.

- Because of the large diameter holes and casings utilised in the surface and intermediate (if used) casing strings, it is important that the rotary table is as large as practicable – typically a 27½" diameter rotary table is utilised, and even 37½" is sometimes seen.
- Again, due to the large hole diameters drilled in the upper sections, large diameter Blow Out Preventers (BOP's) are required, however only moderate pressure rated units are necessary – a typical set of BOP stacks would include:-

  - 30" (or 29½") 500/1000 psi annular diverter and associated large diameter hydraulically controlled diversion valve.

  - 21¼" 2000 psi BOP stack including blind and pipe ram BOP's and an annular BOP.

  - $13^5/_8$" 3000 psi BOP stack including blind and pipe ram BOP's and an annular BOP.

  (comparatively – oil and gas rigs would usually have 5000 psi and 10000 psi rated BOP's)

  For aerated drilling 21¼" and $13^5/_8$" rotating heads and a $13^5/_8$" 'Banjo box' is required.
- The use of a 'choke manifold' is not mandatory in geothermal operations, usually an inner and outer choke valve is sufficient.
- As the BOP stacks are relatively large and occupy a significant height above the ground level (in particular if aerated drilling is to be used) it is necessary that rigs are equipped with an 'extra' height sub structure – a clear height of at least 6 metres is necessary.
- All of the elastomeric parts of the BOP's must be high temperature rated.
- It is preferable, although not mandatory, that rigs are fitted with top drive units – allowing for drilling with a double or triple stand of drill pipe; for easy connection and circulation while tripping the drill string in or out of the hole; and for back reaming.
- Rig mud pumps – (usually tri-plex) must be capable of pumping 2000 to 3000 lpm on a continuous basis. Pressure rating is not as important as pumped volume, pumps must be fitted with large diameter liners (usually 7" diameter).
- Rig mud pumps must be piped to the rig such that fluid can be pumped to both the rig standpipe and to the kill line (annulus) at the same time. It is important that the pump sizes or quantity of pumps is such that sufficient fluid can be pumped for drilling purposes, while a secondary volume – say 1000 lpm can be simultaneously pumped to the kill line.
- The drilling fluid circulating system requires a fluid cooling unit – often a forced draft direct contact cooling tower, or chilling unit.
- Drilling water supply must be capable of providing a continuous supply of at least 2000 lpm and preferable 3000 lpm - backup pumps and often dual pipelines are utilised.
- Drillpipe should be lower tensile strength material to avoid hydrogen embrittlement and sulphide stress corrosion – usually API Grade E or G105. Drillpipe is now usually supplied with a plastic internal lining, it is important that this lining has a high temperature rating.
- A high temperature rated float valve, (non return valve), is always fitted immediately above the drill bit in the drill string to prevent backflow into the drill string which often results in blocking of the drill bit jets.
- Drill bits – usually tri-cone drill bits are utilised however the elastomeric parts of the bearing seals and the lubrication chamber pressure compensation diaphragm are particularly heat sensitive. It is important that while tripping the drill string into the hole, that the bit is periodically cooled by circulating through the drill string.
- PDC – polycrystalline diamond compact drill bits are now being used more often - initially they were found to be totally unsuitable for hard fractured rock drilling – improvements in materials are now making this type of bit a real option. With no moving parts, bearings and seals they are essentially impervious to temperature.
- Drilling tools – the high downhole temperatures limit use of mud motors and MWD instrumentation tools to the upper cooler sections of the hole.

Drilling Fluids

The upper sections of a well are usually drilled with simple water based bentonite mud treated with caustic soda to maintain pH. As drilling proceeds and temperatures increase, the viscosity of the mud is controlled with the addition of simple dispersants. If permeability is encountered above the production casing shoe depth, attempts will be made to seal these losses with 'Loss of Circulation Materials' (LCM), and cement plugs. If the losses cannot be controlled easily, then the drilling fluid is switched to either water 'blind' – that is drilling with water with no circulation back to the surface, or to aerated water.

Once the production casing shoe has been run and cemented, and drilling into the production part of the well commences, mud is no longer use as drilling fluid as it has the potential to irreparably damage the permeability and thus the production potential of the well.

Once permeability is encountered in the production section of a geothermal well, drilling was traditionally continued with water, 'blind' – with no return of the drilling fluid to the surface. The drill cuttings are washed into the formation, and periodic 'sweeps' with either mud or polymer assists in keeping the hole cleared of cuttings.

While this method alleviates the impractical and uneconomic loss of large volumes of mud, and the associated mud damage to the formation, the build up of cuttings within the hole often results in stuck drill strings, and the washing of cuttings into the formation causes damage to the permeability, although not on the same scale as bentonite mud.

Aerated water is now more commonly utilised for drilling this section of the well. To enable circulation of drilling fluids to be continued despite the presence of permeability and 'under pressured' reservoir conditions, the density of the drilling fluid must be reduced. The addition air to the circulating water allows a 'balanced' downhole pressure condition to be established, and the return and circulation of the drilling water and cuttings back to the surface.

Well Control

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. The pressures involved are not high, as they are controlled by the steam / water saturation conditions.

During such a 'steam kick' it is normal that some volume of non-condensable gas (predominantly CO_2) will be evolved. After the steam fraction has been quenched and cooled, it is usual that this usually small volume of non-condensable gas be bled from the well through the choke line. Some H_2S gas may be present, usually in small quantities, so precautions are required.

Running the Open-Hole Liner

One of the final tasks in completing the drilling of a geothermal well is the running and landing of the perforated or slotted liner. At this stage the drilling operations have been completed and hopefully permeability and a productive resource has been encountered. This operation is potentially critical as while a string of perforated or slotted liner (casing) is through the BOP stack, the functionality of the BOP stack is disabled. It is critical that a significant volume of quenching water is pumped to the well prior to and throughout the entire process.

In the event that a kick occurs in this condition, there are only two options available. A capped blank joint of pipe must be readily available so that it may be screwed in and run into the BOP stack so the well may be closed and then quenched. The alternative is that the liner is released and dropped through the BOP stack allowing it to then be closed and the well then quenched. Neither option a very satisfactory situation – it is crucial that a full understanding of the behaviour of the reservoir and the necessary quench volumes that are required to maintain the well in a fully controlled state.

The reliability of the water supply system for this process is of paramount importance.

Conclusion

The processes of drilling geothermal wells is very similar to those developed by the oil and gas and water well drilling industries, however the nature of a geothermal reservoir system; the temperature; the geology and the geochemistry require that some quite different practices be followed if the drilling process and the resulting well are to be successful.

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