

GEOTHERMAL WELL CEMENTING

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ABSTRACT

Perhaps the most critical component of the drilling process to the integrity and longevity of a Geothermal well is the cementation of the casings. The design of the cementing programme shall utilise materials and procedures which are most likely to ensure that the total length of both the cased annulus and the open hole annulus is completely filled with sound cement which will withstand long term exposure to geothermal fluids and temperature.

The cementing equipment, cementing materials, cement slurry designs and operational procedures are outlined and reviewed.

INTRODUCTION

Unlike oil and gas wells, the casings in Geothermal wells are all 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 concentrations are 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.

CEMENTING TECHNIQUES

The process of pumping cement to the annulus outside the casing being cemented may be carried out utilising one of three different techniques.

The traditional, and still often utilised technique of 'through the casing' cementing, involves pumping the cement slurry into the casing via a cementing head connected to the top of the casing; pumping a specific volume of cement slurry, then displacing the cement slurry from the casing into the annulus. Travelling plugs are utilised to separate the cement slurry from the fluid in the casing, and from the displacement fluid. The major disadvantage of this method is that usually the volume of the casing contents exceeds the annulus volume, and therefore a finite (calculated) cement slurry volume will be mixed and pumped, the top travelling plug released, and displacement commenced prior to any cement slurry reaching the annulus.

The 'Inner String' cementing technique requires a cementing string to be run inside the casing and 'stabbed' into a receptacle in the float collar, which is usually located at the top of the first or second joint of casing. The cement slurry is then pumped through the cementing string, through the 'shoe track' (the one or two joints of casing at the bottom of the casing string), and to the annulus directly. The small volume of the cementing string allows cement slurry to be mixed and pumped until good returns of cement slurry are returned to surface from the annulus. The volume to be mixed and pumped does not have to be finite.

While this technique is more elegant with respect to mixing and pumping the cement slurry, the procedure requires that as soon as the casing has been run and the annulus circulated clear, the casing must be set in the rotary table and circulation ceased while the cementing 'inner' string is picked up and run into the hole. This is not usually a problem for shallow casings, but for the deeper production casings, the time required to pick up and run the cementing 'inner' string is such that, in wells with unconsolidated formations, the risk of the hole packing off against the casing, or the well kicking is high.

The third technique, 'reverse circulation', involves pumping the cement slurry directly to the annulus, with the displaced fluid being forced back through the casing shoe and through the casing to the surface. This technique is rarely utilised, as in the event of a loss of circulation there is no positive means of ensuring a cemented casing shoe.

CEMENTING EQUIPMENT

In Hole Equipment - Casing Accessories

When the casing is run into the hole it is fitted with a number of accessories specifically designed to enable the cementing procedure to be carried out.

- Casing Shoe (or Float Shoe) – is fitted to the bottom, or pin end of the first joint of casing, and is a heavy walled, rounded profile unit designed to guide the casing into the hole. It is fitted with a non-return valve which allows fluid (cement slurry) to flow from the casing into the well, but prevent flow from the well back into the casing. The internal structure is made from cement or some other easily drillable material.
- Float Collar - is fitted between either the first and second, or the second and third joint of casing and incorporates a non-return valve to

ensure one way flow only from the casing out into the annulus.

It is usual to utilise non-return, or float valves in both the shoe and the float collar for redundancy purposes.

The float collar is also typically fitted with a ‘stab in – latch down’ receptacle to allow the ‘inner string’ cementing process to be utilised which will be described below.

- Casing centralisers - are fitted periodically on the casing string to keep the casing concentric within the drilled hole.
- Travelling plugs – when utilising the ‘through the casing’ cementing process these plugs are utilised to separate the cement slurry from fluids in the well and from the displacement fluids.
- Cementing head – when utilising the ‘through the casing’ cementing process, the cementing head is attached to the top of the casing string and allows for connection of the cementing pipeline from the cement slurry mixing and pumping unit to the casing. The cementing head is usually designed to contain and release the travelling plugs.
- Tag-in adaptor and string centralisers – when utilising the ‘inner string’ cementing process, a tag in adaptor is fitted to the bottom of the cementing string (drillpipe) to allow the string to be ‘stabbed in’ to the ‘stab-in – latch down’ receptacle in the float collar.

Surface Equipment

It is usual that the cement mixing and pumping equipment are provided by a specialised oilfield cementing services contractor.

At significant contrast to the equipment utilised even 10 years ago, the equipment available from cementing services contractors today usually includes an automated computer controlled recirculating slurry mixing and pumping unit which can mix and pump uniform density slurries at rates of around 800 lpm at high pressures. These units are typically constructed with two independently powered triplex plunger type downhole pumps, and an independently powered recirculating mixing system with electronic density control.

Dry cement is typically stored in bulk pressure silos that allow pneumatic transfer of the dry cement to the mixing unit. Cement additive chemicals are either dry blended with the dry cement, or are added in liquid form to the mix water, which is delivered to the mixing unit automatically via the control system.

Cementing systems can mix and pump cement slurry volumes of up to 65,000 litres continuously within the allowable cement pumping time – sufficient for most geothermal well cement jobs.

CEMENTING MATERIALS

The petroleum industry has developed a wide range of highly sophisticated, and expensive materials specialised for the cementing of casings in oil and gas wells. Very few materials have been specifically developed for geothermal application, and many of the petroleum industry materials are inappropriate for geothermal environments.

Cement

During the ‘early days’ of geothermal well drilling, standard construction grade Portland cement was utilised, often successfully, for the cementing of casings. However, Portland cement, manufactured to API specification – typically API Class A or API Class G cements are now most commonly utilised. The quality control requirements of the API standards provides for cement slurries of highly reliable consistency.

Cement Blends

The high temperature environments of geothermal reservoir systems require blending of additional materials to ensure longevity of the cement used for cementing casings. API specifications recommend the blending of up to 40% by weight of cement (BWOC) of silica flour to prevent strength retrogression and increasing porosity as is seen with neat cement slurries exposed to elevated temperatures. However, work carried out by N. Milestone, Department of Scientific and Industrial Research, New Zealand, in the 80’s showed that carbonation of the silica caused cement with higher concentrations of silica to rapidly develop high porosity. This work determined that the addition of between 15% to 20% of silica flour (BWOC) provided thermal stability sufficient thermal stability but was not susceptible to attack by the CO₂ rich fluids commonly found in all geothermal systems.

More recently, the use of blast furnace slag with Class A Portland cement blended in the ratio of 30 : 70 has been found to provide a highly corrosion resistant cement, along with enhanced mixing and pumping properties.

This blend produces a slurry with more thixotropic properties, making it more suitable for use in permeable formations – a characteristic of nearly all geothermal systems. In addition the early and final compressive strengths of this blend are significantly higher than those of the standard API cements.

Additives

In addition to silica flour or blast furnace slag materials mentioned above, a selection of additives are included in the slurry blend.

- Retarders – when high bottom hole circulating temperatures are expected, a retarder is added to prevent set-up prior to completion of pumping of the slurry. Careful estimation and testing, where possible, of the maximum and minimum circulating temperatures is required

such that the correct retarder and concentration is utilised to avoid flash setting, or very long setup times of the slurry in cooler sections of the well.

- Friction reducers – are added to the slurry to reduce slurry shear stress and hence pumping pressures.
- Fluid Loss control agents - the requirement to cement the total length of each casing in 'under pressured' reservoirs results in a tendency for the water fraction of the cement slurry being lost to the formation. This dehydration process can result in annular bridging with high water loss slurries. The addition of fluid loss agents binds the water fraction within the slurry, reducing this tendency.
- Free water additive – Wyoming bentonite and /or a specialised free water agent is added to the slurry to ensure no free water evolves during cement setup.
- Mica - Loss of circulation during the cementing process is a persistent problem. It is critically important that organic LCM materials, traditionally utilised in drilling mud formulations, is not used for cementing casings. Organic LCM materials may achieve the objective of sealing the permeable zones by accumulating and blocking the permeability, but after the well is completed and has heated up, this organic material will be carbonised, leaving high porosity within the loss zones providing a flow path for possibly corrosive formation fluids. The use of medium to finely ground mica flakes, which are completely inert and non-sensitive to temperature, dry blended into the cement has been found to be very effective.

Mix Water

It is important that the mix water to be used in the cement slurry is tested by the cement laboratory to ensure suitability. Water contaminated with geothermal brine fluids, or with dissolved organic materials can significantly alter the behaviour of the cement slurry, and the final properties of the cement.

CEMENTING PREPARATIONS

Slurry Design Laboratory Tests

Prior to drafting a cementing programme, including calculating cement slurry volumes and materials requirements, it is important that estimates of the bottom hole circulating and bottom hole static temperatures at the programmed casing depths are estimated on the basis of experience from adjacent wells or, if there are no nearby wells, on the basis of the scientific survey information of the field.

The cementing laboratory will carry out slurry design tests that will provide the best estimate for quantities of additives, slurry yield, mix water requirements, slurry gelling times and allowable pumping times.

Cementing Programme Preparation

Utilising the laboratory slurry design data, and the physical data of the casings in place, the new hole drilled, and casing to be cemented, a cementing programme detailing each step of the cementing procedure is prepared and issued. This programme will detail volumes of pre flush, scavenge slurry, main slurry, and displacement to be pumped, pumping rates and pressure limitations.

Hole and Casing Volume Calculations

It is usual to break the well volume calculations into a series of volume components:-

- Casing contents – the volume of fluid contained within the casing from the surface down to the float collar.
- Shoe track – the volume of fluid contained within the casing from the float collar down to the casing shoe.
- Rat hole – the new open hole volume from the depth of the casing shoe to the total drilled depth – typically a 'rat hole' of 2 to 3 metres is left from the depth of the bottom of the casing shoe to final drilled depth – this rat hole is left such that any cuttings or debris can settle on the hole bottom without interfering with the casing shoe.
- Casing to open hole annulus – the volume of the annulus between the new casing and the open hole from the casing shoe depth up to the previous casing shoe depth.
- Casing to casing annulus – the volume of the annulus between the new casing and the previous casing, from the previous casing shoe depth to the surface.

Excess Volume to be Pumped

The calculation of slurry volumes to be pumped must include allowances for displacement of contaminated slurry, over gauge hole and losses to the formation. It is usual that an excess of between 100% and 150% is applied to the rat hole volume plus the casing to open hole annulus volume.

Total Slurry Volume = Shoe track volume + (Rat hole volume + casing to open hole Volume) x (1 + 'excess') + casing to casing annulus volume.

Where 'excess' = 1.0 to 1.5 - depending on hole conditions.

CEMENTING PROCEDURES***Pre – Cementing***

Prior to picking up the final joint of casing to run in, it is usual that a circulating swage and circulation hose is made up to the top of the joint of casing. When this joint is made up, circulation of fluids through the casing is commenced and the final joint washed down to the final setting depth. This procedure is carried out to ensure any settled cuttings or debris is washed away from the casing shoe as it is lowered toward the bottom of the hole, preventing possible blockage of the casing shoe port.

Circulation to Cool the Well

Once the casing is down to depth, pumping of fluid is continued to cool the hole down as much as is possible. This process may take a period of a few hours. During this period the casing should reciprocated continuously.

Reduce Mud Gel Strength

It is usual that bentonite mud will have been used as drilling fluid to production casing shoe depth. Prior to cementing it is desirable that the mud viscosity and gel strength be reduced as much as is possible, and that wall cake that may have built up on the hole wall and casing be stripped away. The addition of mud thinners and deflocculants will aid in this process.

If the formations drilled have proven to be non-sensitive to water, and no swelling clays have been encountered, once the gel strength has been fully reduce, the mud is displace from the well, and water circulated in its place.

If water sensitive formations have been encountered then this step of displacing the mud to water is omitted.

Pressure Test

When the circulating fluid return temperatures have fully stabilised, indicating the well has been cooled, and the circulating drilling mud has been thinned or displaced from the hole with water, the drilling mud pumps are disconnected from the casing, and the cementing unit line connected up and pressure tested.

Pre-Flush

A volume of water or proprietary pre-flush fluid is pumped to the casing. This pre-flush is typically just water, but may include mud stripping agents, or a sodium silicate based pre-flush fluid to aid in blocking permeable formation zones. Typically the volume of this pre-flush will be in the order of 5,000 litres.

Scavenge Slurry

Immediately after the pre-flush has been pumped, a bottom travelling plug will be released if the 'through the casing' cementing technique is being used. A volume of lightweight scavenge slurry is then pumped. This scavenge slurry typically has a specific gravity of around 1.2, and is pumped to scour any remaining mud

and mud cake from the annulus. The dilute cement slurry rapidly flocculates any remaining mud allowing it to be easily washed with the scavenge slurry. Typically a volume 5,000 to 20,000 litres of scavenge slurry is pumped, depending the hole and casing sizes and depth, and on whether the mud has been previously displaced from the hole or not.

Main Slurry

After the scavenge slurry has been pumped, the slurry weight will be increased to the main slurry design weight which is typically a specific gravity of 1.87. The main slurry is pumped at flow rates of around 800 litres per minute to ensure turbulent flow occurs within the annulus – this flow rate is also typically the practical maximum flow rate that most cement mixing and pumping units utilised on geothermal wells can operate at satisfactorily. During mixing and pumping of the main slurry, samples are periodically collected weighed and stored such that the slurry setup can be monitored.

Displacement

When the specified slurry volume has been pumped, the top travelling plug is released, and water or drilling mud pumped into the casing behind the travelling plug to push the cement slurry out of the casing and up into the annulus.

During displacement, and as long as returns of circulation are maintained, the returned fluid is carefully monitored and samples of returned cement slurry weighed and stored. While displacement proceeds, the casing continuously reciprocated until it begins to 'stick' (which usually occurs at some point during the displacement), reciprocation is stopped and the casing set to height.

Displacement is continued until the top travelling plug is 'bumped' onto the float collar.

Inner String Cementing

Exactly the same procedures, in principal, are followed if the inner string method is used. When the casing has been run in to depth, washed to bottom; the annulus circulated for a period, then the casing is set in the rig rotary table, and the inner cementing string picked up; run into the casing; and stabbed into the float collar receptacle.

Circulation is then commenced through the cementing string, to cool the well, reduce the gel strength of the mud, displace the mud from the hole if appropriate and continue with the procedures as detailed above.

Annulus Squeeze

If displacement is completed with full returns, and the quality of the returned cement is good, the final procedure is to wait for a period of about 30 minutes for the cement to 'settle', and then to top up the annulus and apply a slight 'squeeze' to ensure cement is forced slightly into the formation and to ensure a good bond with the casing.

The cementing line is flushed to ensure only good quality cement is in the line, which is then connected up to one of the side outlets on the casing head – typically the ‘kill line’ outlet, the other ‘Choke line’ outlet is open and cement is pumped slowly until slurry flows from the open choke line valve indicating that the annulus has been ‘topped up’. The choke line valve is then closed, and the annular BOP is ‘soft closed’ around the casing (with a lowered closing pressure to ensure the casing is not deformed by the annular BOP). Cement is then pumped very slowly until a pressure of around 0.35 MPa can be held. This ‘squeeze’ pressure is held for a period of 30 minutes, then released.

The cementing process is now complete and operations halted while the cement slurry sets up – waiting on cement (WOC).

Loss of Circulation

Of course, the permeable and under-pressured nature of the formations into which the casings of a geothermal well are being cemented means that circulating a high density cement slurry with specific gravities 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 – pozzolan, perlite, ceramic spheres
- 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 have been and are still being 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.

Flushing the Annulus

In the event that while pumping the cement, or the displacement, returns to the surface stop partially or totally, this indicates that circulation has been lost. The cement slurry is flowing out into the formation rather than up the annulus. This is a very common occurrence when cementing casings in geothermal wells.

Pumping of the cement and displacement is continued, without stopping until the programmed cement slurry and displacement volumes have been pumped and the top travelling plug has been ‘bumped’.

A line from the cementing unit is then immediately connected to the kill line outlet on the wellhead, and the annular BOP soft closed around the casing. Water is then immediately pumped to annulus to flush any cement that may have moved up into casing to casing annulus out. A volume of at least 1.5 times the casing to casing annulus volume is pumped. When pumping of the volume of flush water to the annulus by the cementing unit is complete, the rig pumps are then connected to the kill line valve, and water is pumped slowly and continuously to ensure the flow path to the loss zone is maintained in an open condition. While the rig is pumping this water, the cementing unit prepares to pump the primary back fill cement slurry.

Primary Back Fill

As soon as pumping the annulus flush volume is completed, and the drilling rig pumps have taken over pumping top the annulus, a cement slurry of the same constituency as the main cement job, but without retarders, is mixed and made ready for pumping. When ready, pumping of water to the annulus by the rig is ceased, the cementing unit is reconnected to the kill line outlet. A volume of approximately the sum of the casing to casing annulus volume plus the open hole annulus volume is then pumped to the annulus. The density of this slurry is to be as for the main cement slurry – specific gravity of 1.87.

It is important that the entire programmed volume of this primary backfill is pumped, even if the annulus begins to build pressure – however, ensuring that the collapse pressure of the casing being cemented, and the burst pressure of the outer casing are not exceeded. Usually the annulus does not pressure up in this situation.

If, when the total programmed primary backfill volume has been pumped, the annulus remains pressured and the annulus is full of cement and remains so, then the procedure of applying a ‘squeeze’, as detailed above is carried out.

If on the other hand no pressure is evident and the annulus is not filled with cement, which is normally the case, the kill line valve is shut in; the cementing line disconnected; and the cementing unit and flow line flushed and cleaned up. All entries to the casing annulus must remain closed and absolutely no water is to be used near the wellhead to avoid any water entering the annulus.

The primary backfill cement is left for a period of 4 to 6 hours to begin setting up.

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Top Up and Hesitation Cementing

After samples of the primary cement slurry indicate that the cement has gelled and begun setting up, the annulus is to be topped up and a squeeze applied.

When the top up cement slurry, (which is to be the same consistency as the main cement slurry, but without retarders), is ready to be pumped, the choke line valves are to be opened, the cementing line flushed with good quality cement slurry, and then connected to the kill line valve. A volume of no more than 2500 litres of slurry is to be pumped. If returns are achieved then the 'Annulus Squeeze' procedure as detailed above is to be commenced. If no return is achieved when the 2500 litres has been pumped, the valves to the annulus are to be closed, the cement line broken off and the cementing unit cleaned up.

The top up cement is to be left to gel for a period of around 4 hours, and then this top up procedure repeated until a return to the surface is achieved.

Typically, returns are achieved on the first or second top up. The completion of the final top up and squeeze marks the completion of the casing cementing programme.

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