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CEMENTING PROCESSES IN GEOTHERMAL WELL DRILLING: APPLICATION AND TECHNIQUES

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ABSTRACT

During drilling of deep high temperature geothermal wells, zones of weak or fractured formations are encountered. These zones pose a challenge to the quality and effectiveness of the cementing process. Losses are encountered during cementing which require top jobs to complete and anchor the various casing strings back to surface with cement. The cement sheath should be able to withstand the cyclic thermal-induced loading through the operational life of a geothermal well. Cement is also used to plug zones of large circulation losses and to stabilize collapsing weak zones which slow down the drilling process. Well cementing is one of the operations which impacts the overall cost of well drilling process.

In deciding the type of cement slurry to be placed for each of the casing strings in the well's profile, adjustments are made on cement properties as per the strength of the open borehole walls (lithology). The open borehole wall's strength is dependent on geological conditions of the section to be cemented. Cement properties such as viscosity, thickening time and strength are of prime consideration when engineering for the highest probability of successful primary cementing operations (Lecourtier and Cartalos, 1993). The viscosity and thickening time must be optimized so that the slurry remains pumpable long enough to place the cement across the desired zones and achieve the top of cement (TOC). Additionally, cement should set as quickly as possible after pumping is stopped to minimize the wait on cement (WOC) time while achieving necessary structural integrity for retaining zonal isolation throughout the life of the well. The physical properties of cement need to be customized for the specific attributes of each well. Each well is unique in regard to pore pressure and the fracture gradient, bottom-hole temperature, bottom borehole pressure, physical properties of the formation, properties of the fluids already in the wellbore, wellbore deviation and annular space clearance. It is critical to perform cementing operations with cost and integrity of the operation in mind. With proper cementing procedures, drilling time and cost can be optimized (Halliburton, 2005).

Cement manufactured to API specification class A is usually utilized in Kenya, and additives are added to improve its properties and customize it to a particular well environment. This report gives an outline of different cement placement methods, both for plugging large circulation losses, and for casing cementing under certain conditions. The methods will be compared to the method applied in Olkaria, Kenya for primary casing cementing and remedial top cementing of casing at eight hour intervals. Quality assessment of the cementing process, through laboratory tests and post cementing assessment, through the use of cement bonding logs and temperature logs, is also discussed.

1. INTRODUCTION

One of the major challenges experienced during the drilling of geothermal wells in Olkaria, Kenya is cement losses during the cementing of casings, often requiring top jobs (backfills) to complete. Deep geothermal well drilling involves the installation of several casing strings of different sizes which are cemented fully back to the surface using different placement methods. A primary cementing job is planned with the objective of achieving the desired top of cement (back to surface) and reducing the number of cementing top jobs (backfills).

Other than cementing casings, cement is used to seal zones of large circulation losses and weak collapsing sections of the well, encountered during drilling of the casing sections, except for the production section of the well which is lined with slotted liners. Use of cement as a lost circulation material (LCM) is not only effective but it guarantees durable results and the best possible cementing of the casings. It also lowers the risk of stuck drill pipes and assists in circulation of drilling cuttings back to the surface (NZS, 1991).

Cementing operation processes mainly involve the components shown in Table 1 (Thórhallsson, 2014).

TABLE 1: Components of cementing process operation

No	Component	Function
1	Expertise	• Cementing engineer • Service company/Self cementing service • Suppliers • Drilling contractor
2	Modelling	• Calculation of slurry volumes, materials requirements, displacement volume, time • Temperature and pressure during cementing
3	Placement methods	• Open ended • Plug method • Inner string method • Reverse circulation method • Use of casing packer • Two stage cementing
4	Casing hardware	• Casing guide shoes • Cementing heads • Collars • Plugs • Centralizers • Dope and thread compound
5	Cement and additives	• Type of neat cement • Additives to be added- retarders, fluid loss, friction reducer and accelerator • Density control
6	Testing and quality control	• Cement laboratory test-rheology, thickening time, strength, water loss and density • Density measurement during mixing • Cement bond logs (CBL), temperature logs and pressure testing.
7	Reporting	• Cementing program • Casing tally • Cement report

The cementing method used in Olkaria, Kenya is the single stage plug method, which involves pumping a calculated volume of cement into the casing, placing a movable top 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 through the casing shoe at the bottom of the casing string and up the annulus between the casing and the wellbore. Top job (backfills) cementing through the annulus is required in most casing cementing to completely fill the cement to the surface. The cement is blended with retarder, anti-fluid loss, friction reducer, loss circulation materials and a light agent (Wyoming bentonite) to improve its properties and make it pumpable through the casing and up the annulus. Top job cementing is carried out through the annulus using neat (un-blended) cement in eight hour intervals till the casing is fully cemented. Cement samples collected during cementing are observed for hardening before drilling is continued. A summary in Tables 2 and 3 shows a typical cementing job analysis and casing data in Olkaria for well OW-43A.

TABLE 2: Cementing job summary of well OW-43A

Casing size	**Casing weight (lb/ft.)**	**Setting depth (m)**	**Average specific weight (ASW) (kg/l)**	**Materials and data**	**Remarks**
20"	94	58.73	1.68	**Primary** Cement used = 19.4 tons ASW= 1.682 kg/l	Cement received on surface
			Total Cement Used in 20" casing **= 19.4 tons**		
13-3/8"	68.0 & 54.5	300.75	1.68	**Primary** Cement used = 36.8 tons ASW = 1.681kg/l	No cement received on surface
			1.63	**Backfills** 1st backfill = 13.0 tons ASW = 1.68 kg/l	No cement received on surface
			1.63	2nd backfill = 19 tons ASW = 1.63 kg/l	No cement received on surface
			1.67	3rd backfill = 6.20 tons ASW= 1.67 kg/l	Cement received on surface but dropping
			1.65	4th backfill = 4.3 tons ASW= 1.65 kg/l	Cement received on surface
			Total cement used in 13-3/8"**= 89.4 tons**		
9-5/8"	47	756.25	1.65	**Primary** Cement used = 28.7 tons ASW = 1.65 kg/l	No cement received on surface
			1.68	**Backfills** 1st backfill =12.40tons ASW = 1.68 kg/l	No cement received on surface.
			1.65	2nd backfill=12.1 tons ASW = 1.65 kg/l	No cement received on surface.
			1.60	3rd backfill = 6.9 tons ASW = 1.6 kg/l	Cement returns received on surface.
			Totals cement used in 9-5/8" casing **= 60.2 tons**		
Total cement used in OW-43A				**168.9 tons**	

TABLE 3: Casing data of well OW-43A in Olkaria

Casing Size	Weight (lb/ft.)	Grade	No. of joints	Length (m)	Casing shoe depth (m)
20"	94.59	K55	4	45.03	58.73
13-3/8"	54	K55	26	265.72	300.75
	68	K55	2	23.21	
9-5/8"	47	K55	66	730.41	741.79
7" Slotted liners	26	K55	205	2272.42	3001
7" blank liners	26	K55	2	22.18	

Assessment of the adequacy of casing cementing involves continual monitoring and recording of the returns and materials consumed with respect to time, during the course of every casing cementing operation. Correlation of such information with theoretical volumes of casing and annuli being filled provides information on the quality of the final casing cementation (e.g. premature return of a fluid may indicate inadequate mud removal or collapsed borehole; late returns may be caused by partial losses or an over-gauge hole). The correlation is necessary to optimize remedial cementing operations and to evaluate the integrity of the final cementation (NZS, 1991).

The geology of Olkaria area is generally characterized as follows:

0-100 m: Pyroclastic: This is a thick layer of unconsolidated clastic materials consisting of soils, volcanic ash and lithic rock fragments including pumice, tuff, obsidian, rhyolite and trachyte. This is a zone of soft and incompetent formation where caving-in is expected.

100-300 m: Rhyolite: This stratum consists of slightly altered rhyolitic lavas with minor intercalations of tuff. This formation is medium hard and is generally massive, though fractured. Minor losses during drilling are expected to occur.

300-650 m: Rhyolite and Trachyte: This zone is characterized by trachytic and rhyolitic lava flows. The formation is quite compact and massive and is expected to be medium hard. Alteration and oxidation intensities vary with depth and minor intercalations of tuff and rhyolite are expected. Minor losses are expected at fracture zones.

650-1400 m: Trachyte, tuff and basalt: This zone is generally massive but slightly fractured, characterized by trachyte, tuff, rhyolite and basalt intercalations. This zone is moderately altered and fractured and circulation losses are expected at fracture zones.

1400-2100 m: Trachyte with rhyolite and basalt: This zone is generally characterized by the trachytic and rhyolitic lava flows with minor basalt intercalations. The rock is expected to be moderately altered and fractured, but medium hard. Circulation losses are expected at fault or fracture zones.

2100-2500 m: Trachyte and rhyolite: Trachyte dominates this lower part of the well with occasional rhyolite. Thin intrusives are also expected to start appearing in this zone. The formation is medium hard to hard and is competent, therefore, not many problems are expected except minor losses or partial losses, especially at fracture or fault zones.

2500-3000 m: Trachyte with Syenitic and doleritic intrusions: This zone is composed of trachyte with occasional Syenitic and doleritic dyke intrusives. The formation here is compact and is expected to be hard and competent. Minor or partial losses are expected at fracture or fault zones.

The cemented casings are set as follows: Surface casing between 60 and 100 m, anchor casing between 300 and 400 m, and production casing between 750 and 1200 m, depending on the area being drilled. Figure 1 shows the well design and the depths of the casing strings.

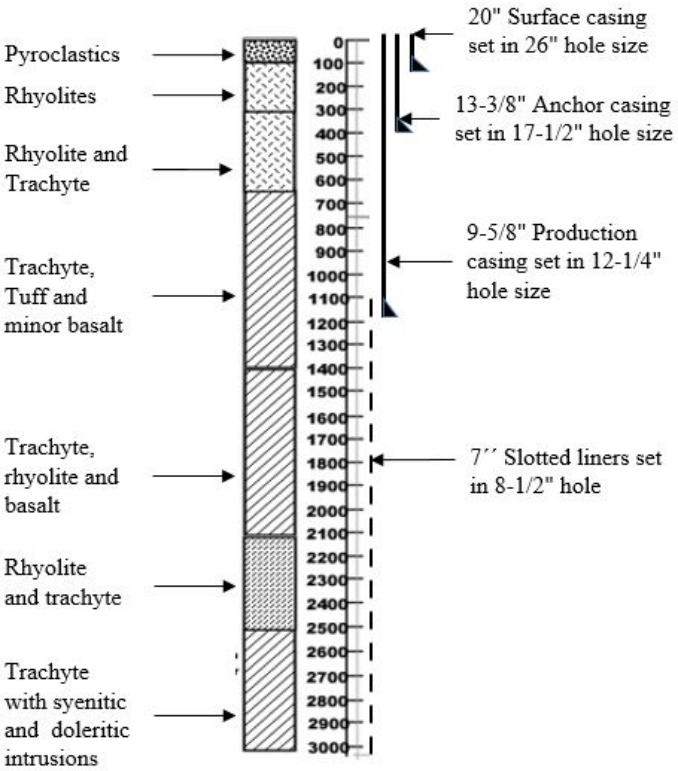

FIGURE 1: Well design in Olkaria Kenya (Kengen)

2. WELL DESIGN AND CEMENTING

2.1 Geothermal well design

Well design is a detailed program of work to be undertaken during drilling of a well and it defines the desired final status. The design steps which are necessary to drill a deep well safely include (NZS, 1991):

a) Geological and reservoir conditions of the area to be drilled;
b) Determination of the casing depths and well completion;
c) Selection of casing diameters, thicknesses, cementing material and programmes;
d) Deciding the drilling fluids, drill string assemblies and wellheads; and
e) Selection of the necessary equipment, tools, materials, support facilities and site requirements.

2.2 Functions of cementing

Cement plays a key role in the integrity of a geothermal well and is a critical component of the well designing process (Nelson, 2012). The wells act as a high pressure containment vessel at elevated temperature which should resist failure by deformation, fatigue, fracturing, and corrosion during its operating life (Agapiou and Charpiot, 2013). The two main functions of the casing cementing process are:

a) To restrict fluid movement between the formations (zonal isolation); and
b) To bond, anchor and support the casing together with associated wellhead equipment.

In addition cement assists in:
a) Protecting the casing from corrosion;
b) Preventing blowouts by quickly forming a seal; and
c) Protecting the casing from shock loads in deeper drilling.

For open borehole condition and repairs, cement is used to:
a) To seal off zones of high loss of circulation during drilling;
b) Stabilize weak and collapsing wellbore sections;
c) Plug (seal off) a well for abandonment;
d) Plugging and side tracking/ directional drilling a hole around a non-retrievable fish or due to geological reasons; and
e) To plug a well temporarily for re-casing (Hole, 2008a).

2.3 Casing equipment

Casings are connected together, either by screwing or welding, to form a casing string, which is then lowered into the drilled borehole. As the well deepens, the diameter of each casing string is usually smaller than the preceding one. The accessories fitted to a casing string to enable the cementing process to be carried out include (Hole, 2008a):

1. Guide shoe (float shoe) – fitted to the bottom of the first casing and is usually tapered in order to guide the casing toward the centre of the wellbore during installation, minimizing contact with the wellbore walls. It may contain a non-return valve to restrict fluid flow into the casing. Figure 2 shows two types of guide shoes commonly used;
2. Float collar-fitted between the first and the second casing or between the second and the third casing. It contains a non-return valve to prevent reverse flow of cement slurry. For the inner string cementing method, the float collar has a stab-in or latch receptacle to take in the drill pipe end fitted with a tag in adaptor. Figure 3 shows float collars commonly used;
3. Centralizers, fitted along the casing string at pre-determined intervals. They assist in preventing sticking of the casing while lowering them into the well and keeping the casing in the centre of the wellbore. Centralizing the casing ensures uniform placement of cement sheath in the annulus between the casing and the borehole wall. Figure 4 shows a bow centralizer;
4. Bottom plug - usually elastomer, used to separate cement and the drilling fluids in the well during the casing cementing method. It has a membrane which ruptures when it lands at the stop collar under the cement pressure in order to allow the flow of cement through;
5. Top plug - elastomer (rubber) separating cement slurry and the displacing fluid during the casing cementing method. Figure 5 shows top and bottom plugs; and
6. Tag in adaptor and string centralizers - used when utilizing the inner string cementing method to adapt the drill pipe into the float collar receptacle. The centralizer (usually optional) aligns the drill pipe string to the centre of the casing for ease of stabbing or for latching the drill pipe cementing string to the float collar, depending on the type of inner string adaptation method used (Hole, 2008a).

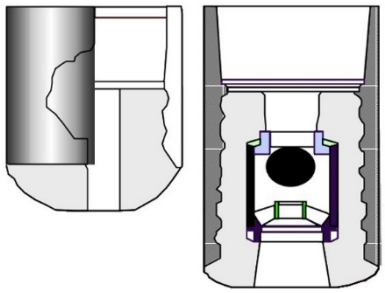

FIGURE 2: Guide shoes (Rabia, 2001)

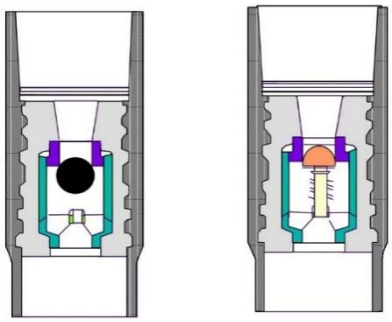

FIGURE 3: Float collars (Rabia, 2001)

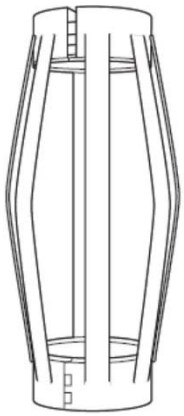

FIGURE 4: Bow centralizer (Bett, 2010)

FIGURE 5: Top plug-solid, and bottom plug-hollow (Rabia, 2001)

2.4 Cementing materials

Portland cement, used as the bonding compound between the casing and the formation, consists of mainly anhydrous calcium silicate and calcium aluminate compounds, which hydrate when added to water to provide strength and low permeability for zonal isolation. Other special grades/ formulations of cement are produced as per the API10 specification for well cementing, and are divided into classes A to H depending on the properties (Rabia, 2001). Cement additives are used to make different cement blends, depending on the wellbore conditions, and are classified according to the functions they perform (Nelson, 2012). They include:

1. Silica flour - this is fine-ground quartz which prevents strength retrogression and increases the porosity of cement in a high temperature environment (Guerra, 1998). According to the New Zealand code of practice for deep geothermal wells, silica flour of over 20% by weight of cement may result in the deterioration of the cement in the presence of carbonating ground waters (NZS, 1991);
2. Accelerators - they reduce the cement setting time and increase the rate of compressive strength development. Inorganic chloride salts are mainly used with calcium chloride being the most commonly used cement accelerator (Nelson, 1990);
3. Retarders - they are used to delay the setting time and extend the pumping time of cement slurry by slowing down the cement hydration process. They are added to counter the effects of high temperatures in the wellbore, especially in the anchor and production casing sections. Common retarders used include sugar and lignosulphonates (Rabia, 2001);
4. Extenders (light weight agent) - they reduce the amount of cement per unit volume (slurry density) and also increase the slurry yield. Water-based extenders, such as Wyoming bentonite, allow the addition of excess water to achieve slurry extension, while maintaining a homogeneous slurry, and prevent the development of excess free water (Nelson, 1990);
5. Fluid loss control agents - they control leakage (loss) of water from cement slurry into the formation, preserving the design properties of the cement slurry. Fluid loss agents decrease cement filtration by decreasing cement permeability or by increasing the viscosity of the aqueous phase of the cement. Finely divide particulate materials, such as bentonite, and water-based polymers, such as hydroxyethylcellulose (HEC), are the two main classes of anti-fluid loss agents (Nelson, 1990);
6. Lost circulation control agents - they limit the flow of cement slurry out of the well into the weak fractured formation and ensure that the cement slurry is able to fill the entire annular space. Medium coarse grade mica flakes are commonly used as loss of circulation agents (Nelson, 2012);
7. Dispersant (friction reducers) - they reduce slurry viscosity, which allows a lower pumping pressure during placement. Dispersants are negatively charged polymers which absurd onto the positively charged particles, thereby reducing particle interaction and making them more mobile (Nelson, 1990); and
8. Antifoam agent - used to reduce air entrapment and foaming during mixing by altering the surface tension of the mixing water and the way cement solids disperse during mixing.

3. TYPES OF CEMENTING OPERATIONS

3.1 Casing cementing

There are three main casing cementing operations conducted during the drilling of a deep geothermal well, namely: surface casing, anchor casing and production casing. Cement has to support the casing uniformly to the surface as the thermal expansion stresses the steel beyond the yield point. It also has to block any fluid movement up the annulus, either from the formation or through a casing leak. When the casing to casing annulus has water entrapped by good cement, heating and expansion of the trapped water can lead to collapse of the inner casing (Thórhallsson, 2014).

Proper centralization of the casing, especially in a deviated well, and taking into account the hole's profile (kick off and build up) are essential for effective casing cementing. The other important factor is borehole cleaning of the drilling fluid prior to cementing, which should be continued even with all the casing downhole (last circulation). The last circulation improves borehole cleaning and, at the same time, cools the wellbore which is critical in geothermal well cementing. The casing string should be reciprocated periodically during circulation to avoid differential sticking, while also checking on the returns for cutting and circulation temperature (Lecourtier and Cartalos, 1993; NZS, 1991).

3.2 Cement plugging and loss of circulation control

3.2.1 Loss of circulation control

One of the major challenges in drilling a geothermal well is loss of circulation during drilling of highly fractured zones. Adequately cementing the casing through lost circulation zones is a major challenge and a major cost (Finger and Blankenship, 2010). If the loss of circulation cannot be regained through the use of loss circulation materials (LCM), the alternative is to use cement plugs for non-productive zones of the well that are to be cased off. Lost circulation plugs are used to isolate the fractured zones and create a seal between the zone and the wellbore. Open drill pipes positioned near the suspected loss zone are used to place the calculated quantity of cement slurry. A whole series of plugs is often required before a satisfactory result is obtained (Rickard et al., 2012).

In addition to the drilling time and material costs, loss of circulation plugging risks drilling pipes being filled with cement or, worse still, getting cemented in the well. To decrease the risks of difficulties, the tubular equipment that runs through the mixtures containing cement should be re-drillable (fibreglass or aluminium) (Lecourtier and Cartalos, 1993). Two main methods are normally used to seal loss circulation zones using cement plugging, namely the balanced plug method and the drift plug method.

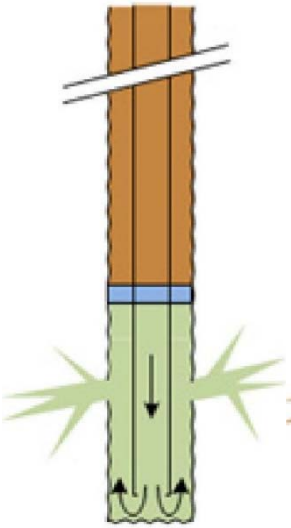

FIGURE 6: Balanced plug method (Rickard et al., 2012)

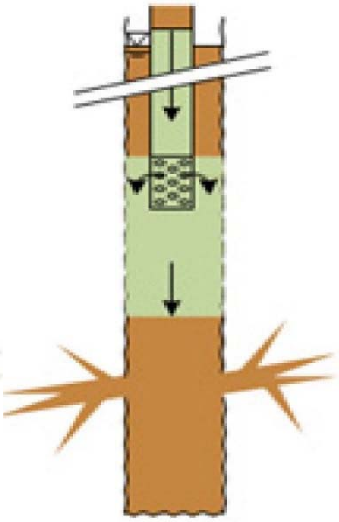

FIGURE 7: Drift plug method (Rickard et al., 2012)

The balanced plug method consists of pumping the desired quantity of cement slurry through the drill pipe or tubing until the level of cement outside is equal to that inside the string. Figure 6 shows the placement of the balanced plug method in a well. This process involves running the drill pipes past the loss zone and displacing cement as a balanced plug into and above the loss zone. Balanced plugs are effective when the loss rate is low enough that cement stops going into the formation long before it sets (Rickard et al., 2012).

Drift cement plug method involves placing the cement slurry above the loss zone and allowing it to flow (drift) downwards towards the loss zone as one single mass of cement. This method is effective for plugging severe loss of a circulation zone but is not suitable for partial loss of circulation. The method uses a diffuser to divert the cement flow in a lateral direction, instead of vertical as in the balanced plug method. A cement diffuser is a piece of drill pipe plugged and bull-nosed on the bottom with several cut holes around the circumference. The lateral flow creates a piston-like plug in the borehole. The cement slurry is displaced to create a hydraulic head inside the drill pipe (Rickard et al., 2012). Figure 7 shows the placement of a drift plug in a well.

3.2.2 Cement plugging for repairs and abandonment

When side tracking a hole around a stuck bottom hole assembly, or changing the direction of drilling for geological reasons, a cement plug is placed at the required depth to change the wellbore direction or to help support a mechanical whipstock so that the bit can be guided in the desired direction. Cement plugging is used to seal off the well bore in a case of complete abandonment, due to drilling challenges or a producing well that has been damaged (Remedial Cementing, 2013).

4. CEMENTING PROCESS AND SLURRY DESIGN

4.1 Geothermal wellbore conditions

Effective cleaning of the wellbore prior to cementing through removal of the drilling fluid improves the quality of the bond between cement, casing and formation. One way of cleaning the wellbore is by the use of chemical washes which help remove the drilling mud through dilution, thinning (preventing mud flocculation and gelling) and dispersing it. Chemical washes are fluid with density and viscosity higher than the drilling fluid but lower than that of cement (containing dispersants and surfactants), which are pumped ahead before cementing to help remove the drilling mud through dilution, thinning and dispersing (Devereux, 1998).

Wellbore conditioning during the last bit run before tripping out helps in cleaning the wellbore before running the casings. After running the casings, circulation of water at least 110% of the casing internal volume is usually continued to further clean and condition the wellbore before cementing. This should be accompanied, where possible, with reciprocating the casing string up and down to scrape mud from the wall of the wellbore to ensure flow around all portions of the well (Bett, 2010).

4.2 Calliper logs

In preparing a well for cementing, it is important to measure the diameter of the borehole in order to estimate the volume of the cement slurry required. This is done by measuring the size and shape of the borehole (open hole) along its depth using a calliper logging tool. Multi-finger calliper tools utilize either mechanical or sonic means to measure the diameter of the well at numerous locations simultaneously, accommodating all the irregularities in the wellbore diameter. Other uses of calliper logs include detecting deformations, build up in case of scaling, and metal loss due to corrosion in casings. Even with a calliper log, it is advisable to have excess (allowance) volume (120%) to cover for losses and fill up the cavities in the wellbore (Schlumberger, 2014).

Figures 8 shows a calliper log and Figure 9 shows cement volume estimates from the logs for 9-5/8´´ casing of well HE-53 in Hellisheidi geothermal field in Iceland. The anchor casing of 13-3/8´´ was set at 300 m, while the production casing of 9-5/8´´ was set at 846 m. The total cement estimate was 34.89 m^3.

4.3 Casing design

The main functions of the casing strings are:

1. Prevent borehole collapse in weak and fractured formations;
2. Allow safe drilling of the well; support and anchor the wellheads;
3. Fluid pressure control;
4. Protect and control contamination of subsurface aquifers;
5. Counter circulation losses during drilling;
6. Protect the integrity of the well against corrosion, erosion or fracturing; and
7. Define the production zone if the reservoir has more than one production zone (Rabia, 1987; Hole, 2008b).

Casings are characterized by three measurements, namely: diameter (nominal outside diameter), weight (weight per unit length-material thickness), and grade (materials tensile strength); their selection is guided by API (American Petroleum Institute) or equivalent ISO standards. Determination of casing depths depends on rock properties, formation fluid, surface casing setting, well control requirements and

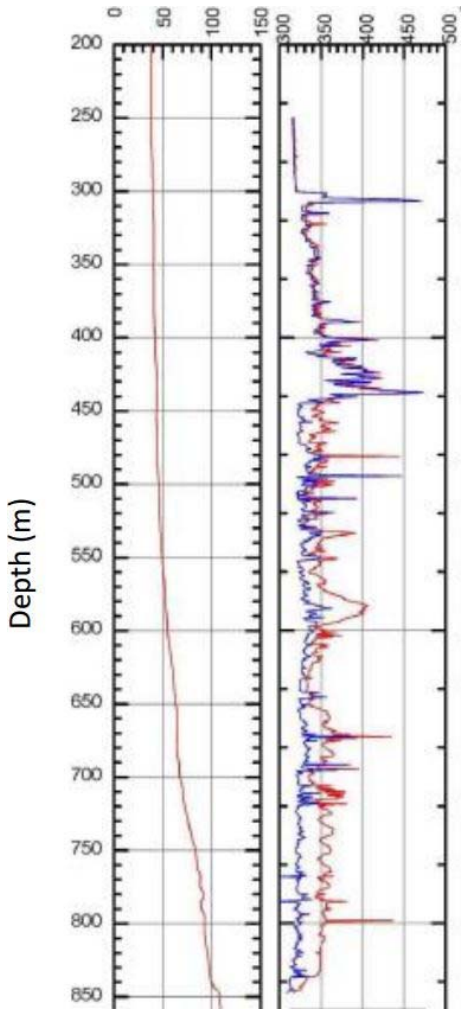

FIGURE 8: Calliper logs of well HE-53 in Hellisheidi, Iceland (Sveinbjornsson, 2014)

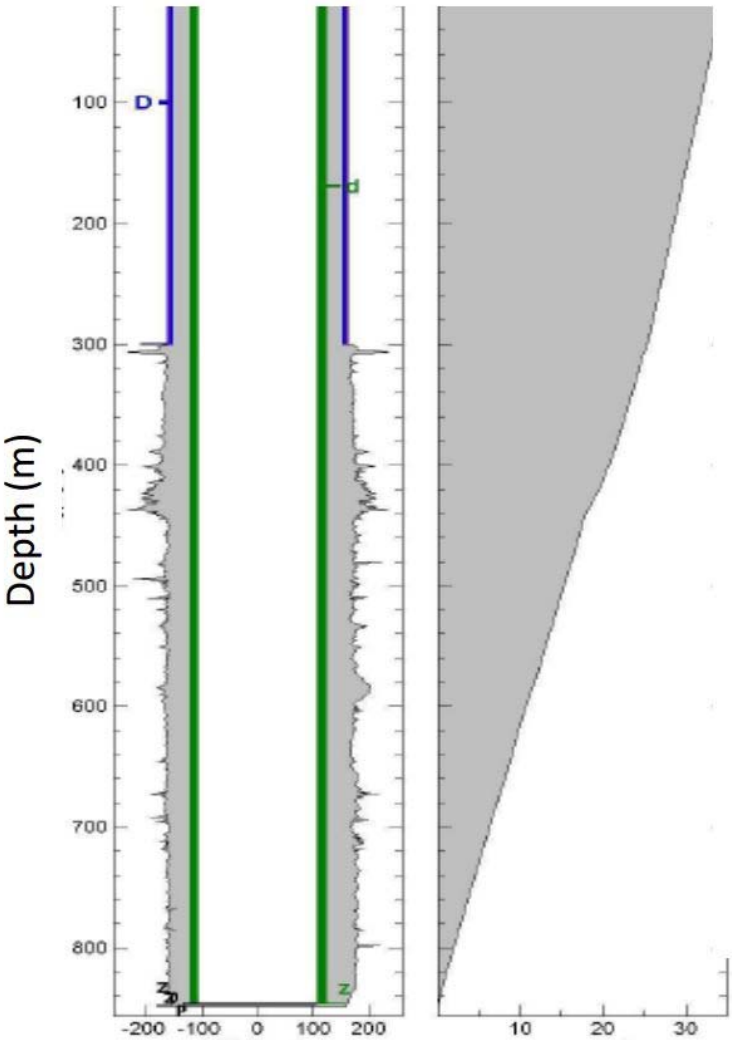

FIGURE 9: Cement estimate using calliper log of well HE-53 in Hellisheidi, Iceland (Sveinbjornsson, 2014)

regulatory requirements (Finger and Blankenship, 2010). Selection of casing depths is guided by the available drilling and well data but, in absence of the data, casing depths can be approximated using the boiling point depth curve (a column of water at boiling temperature throughout its depth) and the water table level (depth to be taken below the water table level). The pressure inside the well at the casing shoe for each casing string shall not exceed the overburden pressure (formation fracture pressure), assuming the well is filled with steam (NZS, 1991). Another criteria used in Iceland is to consider the pressure from a column of water or heavy mud inside the casing exceeding the pressure in the well at the casing shoe for two phase flow (Thórhallsson, 2014). Figure 10 shows casing selection using the New Zealand standard.

The following cemented casing strings are used in geothermal well drilling in Kenya:

1. Surface casing - this is run to prevent caving of weak near-surface formations, support initial drilling wellheads and to contain circulating drilling fluid. A typical size of this casing is 20" K55 94 lb/ft. in Kenya;
2. Anchor casing - protects the surface aquifers, prevents circulation losses during deeper drilling and supports the drilled wellhead and, later, the permanent wellhead after well completion. Typical casings utilized are 13-3/8" K55 54 lb/ft. and 68 lb/ft; and

3. Production casing - seals off low temperature aquifers, conveys geothermal fluids to the surface and supports drilling to the total depth of the well. Typical casings utilized are 9-5/8" K55 40 lb/ft. and 47 lb/ft. Casing strings and a liner commonly used in a geothermal well are shown in Figure 11.

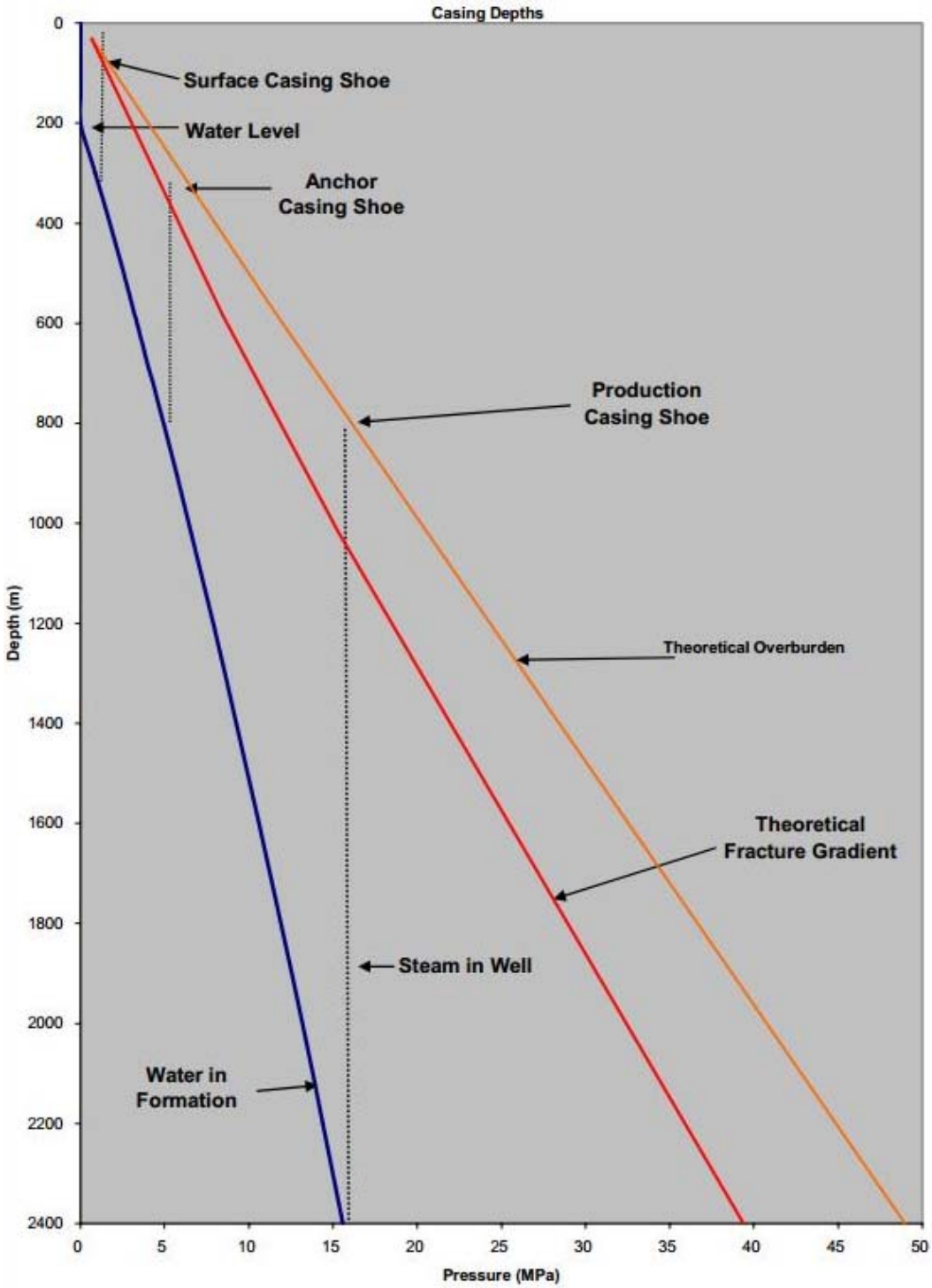

FIGURE 10: Theoretical casing selection (Hole, 2008b)

In well casing design, three types of loading are considered, namely: burst pressure, collapse pressure and axial loading, which are functions of the casing grade, wall thickness and tensile strength. The effects of pressure, temperature, and temperature changes which may occur during drilling and operation of a geothermal well should be considered. Casing string axial loading before cementing is a result of a casings' own weight less the buoyancy effect of the fluid in the well and the drag for deviated wells. However, after cementing the casing cannot expand freely and, therefore, compressive and tensile loading are induced due to temperature changes (Hole, 2008b). Internal fluid pressure can result in a casing bursting, especially before and during cementing, while external fluid pressure can result in casing collapse while displacing cement to the annulus and due to the column of cement after cementing. Safety margins are usually added while designing for the different casing loading situations.

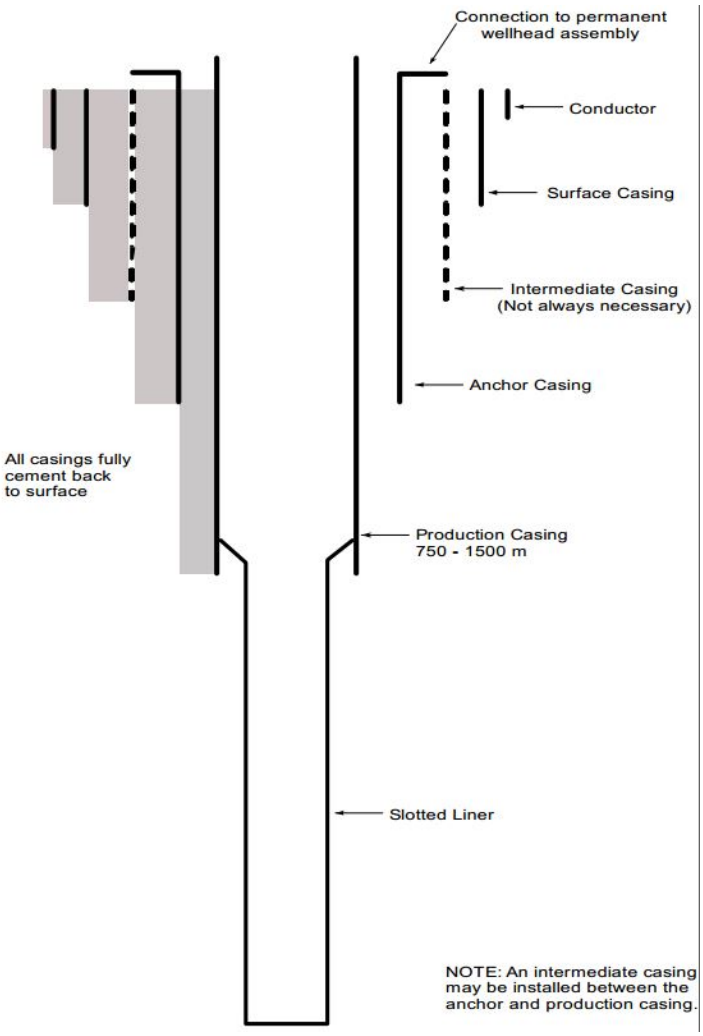

FIGURE 11: Casing strings and a liner for a typical geothermal well (Hole, 2008b)

4.4 Cement blending

Portland cement in Olkaria, Kenya is usually mixed with other additives to make a cement blend to be used for casing cementing. Neat (without additives) cement is mainly used for plugging a loss zone and is sometimes mixed with accelerators to shorten the setting time. Typical composition by weight of cement (BWOC) includes:

- Cement class A;
- Silica flour (proposed) - 15% to 20% (BWOC);
- Mica (LCM) - 3% BWOC;
- Wyoming Bentonite - 2% BWOC;
- Retarder - 0.3% BWOC;
- Fluid loss control - 0.3% BWOC; and
- Friction reducer (dispersant) - 0.3% BWOC.

Other additives added in new cement slurry designs are perlite, hollow microspheres and nitrogen gas for foamed cement slurry, all of which are aimed at lowering the cement density for improved geothermal casing cementing (Bett, 2010). Latex is also added to cement to improve on corrosion resistance, fluid loss control and high temperature solid-suspension properties. Slurries blended with latex have better wetting properties, low viscosities and increased resiliency resulting in increased bonding strength and a tighter annular seal. Advantages of foamed cement slurry include:

- Low density which makes it easier to cement weak formations without exceeding the fracture pressure of the formation;
- Foamed cement develops very high compressive strength which enhances protection against gas invasion and reduces chances of casing corrosion; and
- Foamed cement is more ductile and can withstand thermal expansion and contraction without cracking and compromising the sealing effect (Hernández and Nguyen, 2009). Figure 12 shows schematic cement preparation.

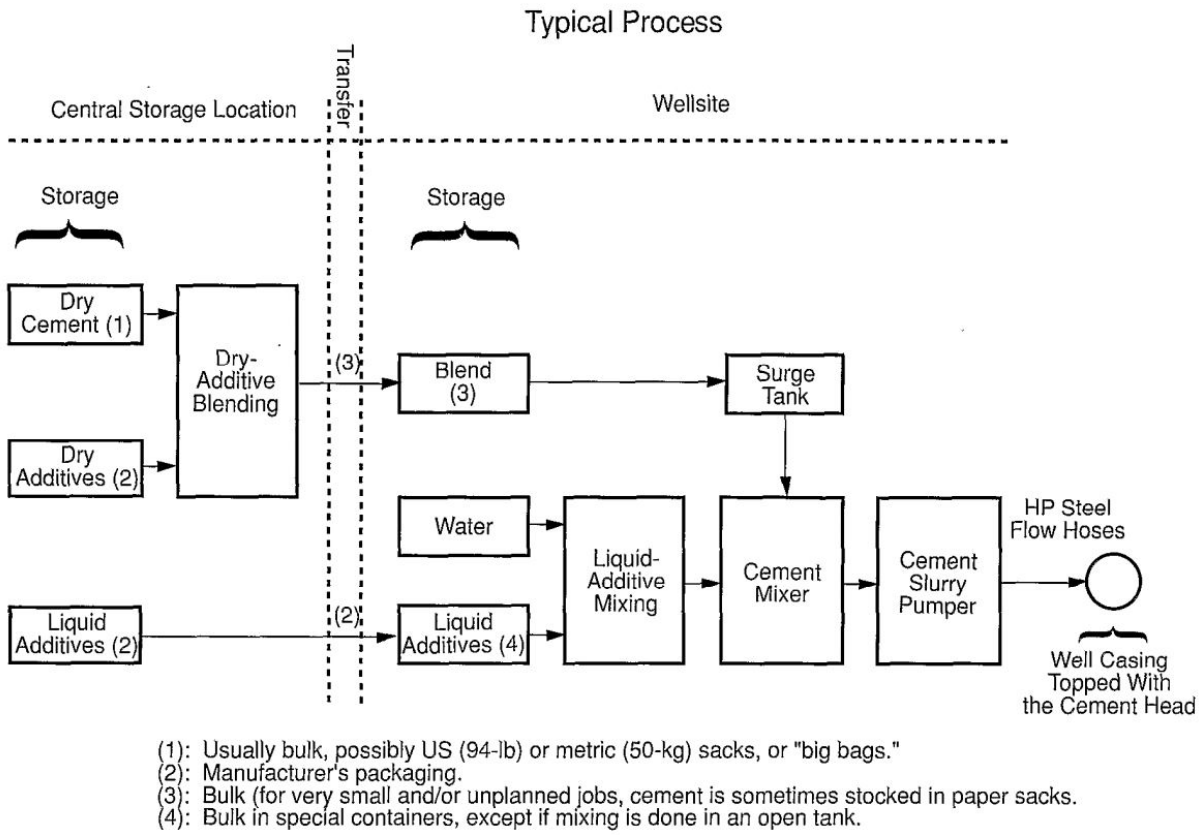

FIGURE 12: Cement mixing process (Nelson, 1990)

4.5 Cement mixing and pumping equipment

Cement and cement additives are usually handled in bulk for ease of blending and transportation to the rig site. Cement and dry additives are combined in a blending tank where they are weighed, depending on the blending recipe, and then are thoroughly mixed together to make the blended cement. The mixer is then blown, using compressed air, to the storage tanks. Blended and neat cement is stored in air tight steel silos (tanks) with capacities of up to 50 m^3, aerated with compressed air during loading and offloading. Pneumatic transport tanks are used to transfer cement from the blending and storage site to the rig site in preparation for cementing.

During cementing, cement is mixed with water to form cement slurry, either by a jet mixer or a recirculation mixer. A jet mixer consists of a hopper, which controls dry cement flow, a mixing bowl where water is injected at high pressure to mix with dry cement, a discharge goose neck to control the slurry density, and a slurry tub contain the cement slurry for pumping. Slurry density is adjusted by controlling the rate of water and cement flow from the jets and hopper. A recirculation jet mixer re-circulates some of the slurry through the mixing system, using a centrifugal pump feeding the displacement pump, thereby improving on the slurry homogeneity and viscosity. Density in the

recirculation jet mixer is controlled by opening or closing the sliding gate between the hopper and the mixer (Nelson, 1990).

Modern cementing units use recirculation mixer without jets; they are mainly composed of a high energy mixer (injector), a cement control valve which is either manual or computer controlled, an expanding tank to remove entrapped air and dust in the first mix, a mixing tank which acts as the measuring tank with stirrers to thoroughly mix the slurry, a circulation pump, a booster pump and a water pump. The centrifugal pump re-circulates the already mixed slurry and, at the same time, feeds the downhole displacement pumps. The booster pump boosts the suction pressure of the pumps, though it is not always used. The mixing process is computer controlled, with the computer using the water flow rate signal, the dry cement flow rate, the slurry pumping rate and the density signal to adjust the water-cement mixing ratio and, therefore, automatically adjust slurry density (Serva, 2011). Cementing units use a recirculation mixer with automatic density control for continuous mixing and pumping; they mainly come in three configurations: truck mounted, semitrailer mounted and skid mounted (Nelson, 1990). Figure 13 shows the schematic diagram of a recirculation mixer.

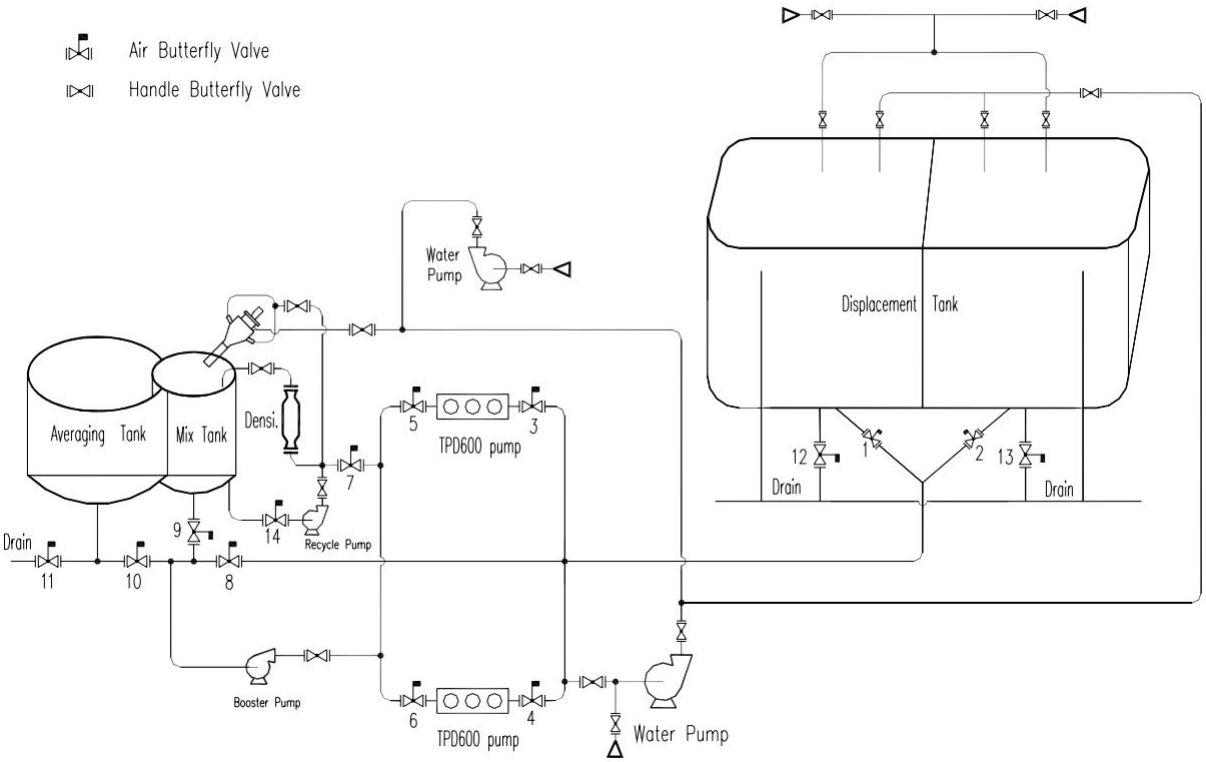

FIGURE 13: Recirculation mixing and pumping unit (Serva SJS, 2011)

5. CEMENTING TECHNIQUES

5.1 Inner string (stinger) cementing

This cement placement method involves pumping slurry through a drill pipe string attached to either the casing shoe or the float collar through a stab-in receptacle. The bottom end part of the drill pipe has a stab-in sub with seals to fit in the collar receptacle, and the lower part is fitted with centralizers, adapted to the size of the casing being cemented (Devereux, 1998). An inner string method is commonly used to cement large size casings run below 1000 m and has the following advantages:

- Reduces cement contamination;
- Eliminates the need for large cementing heads and plugs;
- Reduces the amount of cement to be drilled out;
- Decreases cement displacement time and pressure;
- Reduces slurry placement time;
- Reduces cement waste; and
- Cement is discharged outside the casing much faster (Halliburton, 2005).

The main disadvantage of an inner string method is the time taken to run in with the cementing string and the time taken to pull it out after cementing for long casing strings. Figure 14 shows stab in shoe, collar and stab in adaptor. Figure 15 shows different inner string methods (Halliburton, 2005).

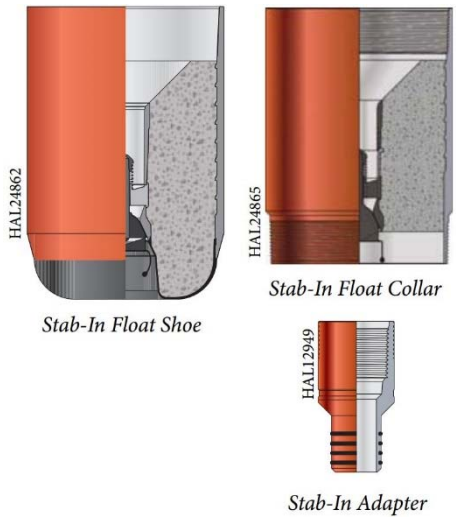

FIGURE 14: Stab-in shoe, collar and adaptor (Halliburton, 2005)

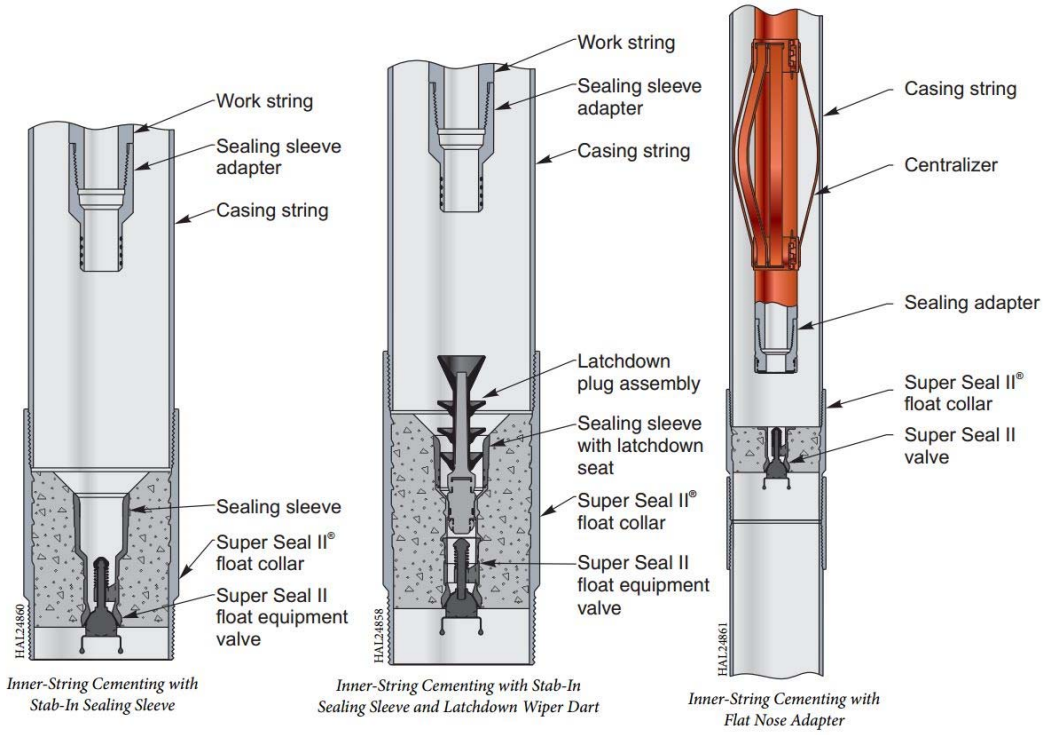

FIGURE 15: Inner string methods (Halliburton, 2005)

5.2 Single stage cementing

In this method, a calculated volume of cement slurry is pumped into the casing and is displaced out to the annulus through the casing shoe. The method uses two plugs, a bottom plug (optional) which displaces the drilling fluid and a top plug which displaces cement and separates it from the displacement fluid. The bottom plug has a membrane which ruptures, allowing cement slurry to flow through. But the top plug is solid in order to withstand high pressures, and it limits mixing of the displacement fluid with cement slurry. The top of the casing string is fitted with a cementing head which has compartments for holding the bottom and top plugs and allows cement to be pumped inside the casing. The bottom plug is optional, especially if the drilling fluid used is water, which is a common occurrence in geothermal well drilling. The major drawback of this placement method is that it is not flexible in adjusting the volume of cement to be pumped, even if there are no cement returns to the surface (Guerra, 1998). Figure 16 show the single stage casing cementing process.

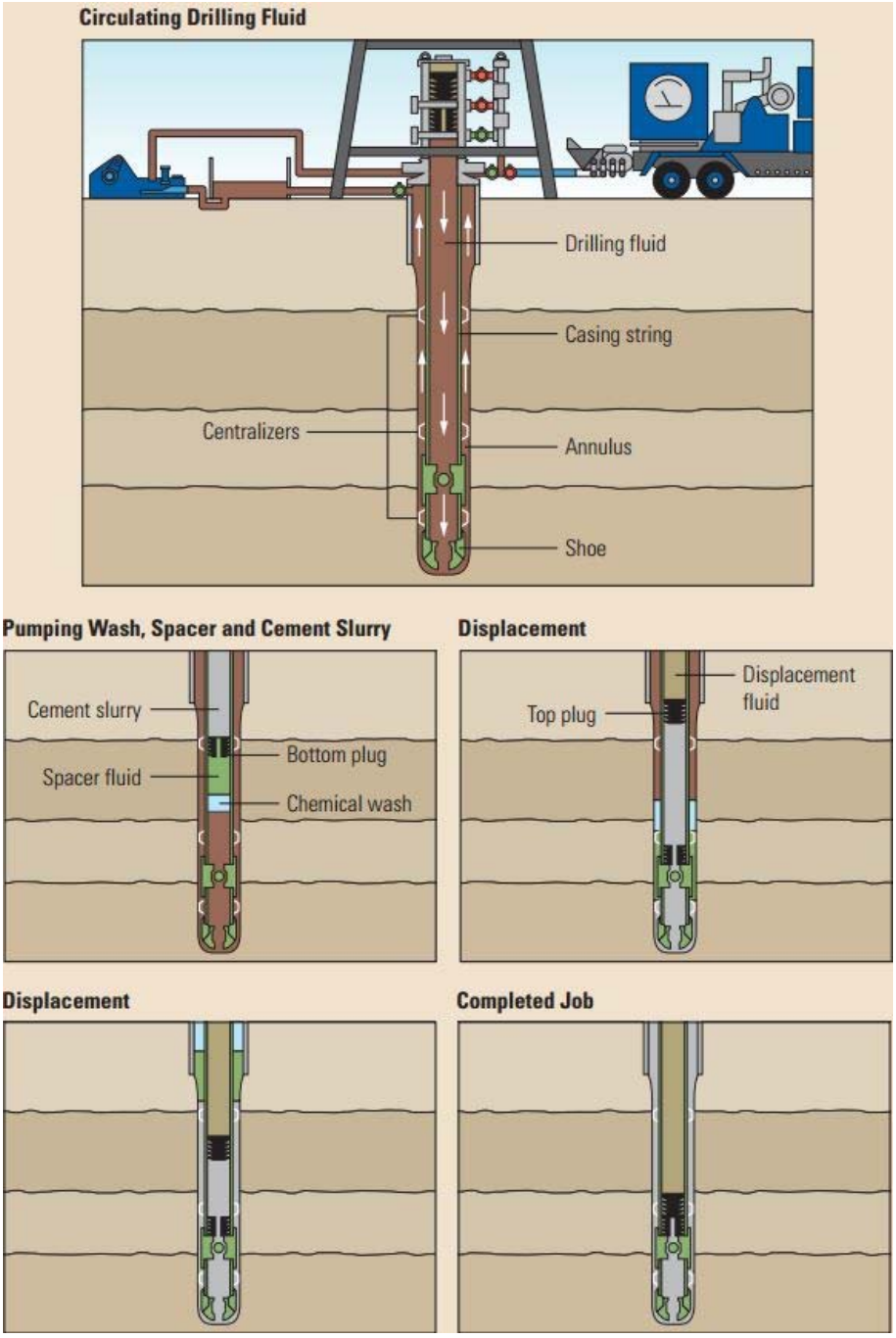

FIGURE 16: Single stage cementing process (Nelson, 2012)

5.3 Multiple stage cementing

The multiple stage cementing method is used to place cement slurry around the casing in stages at selected intervals. Two stage cementing is the most common of the multi stage cementing method and is used when (Halliburton, 2005):

- The hydraulic pressure head of cement is too high for the formation or casing;
- There is limited pumping time, especially in hot wells, to pump the desired quantity and quality of cement;

- Downhole conditions require different blends of cement slurry;
- Only certain portions of the wellbore require cementing; and
- In horizontal wells in oil drilling, where the bend radius of the well requires cementing.

The first stage is cemented using the conventional methods, while stage cementing collars (differential valves) designed to allow cement flow into the annulus when they are opened either by the use of a plug or hydraulic pressure, are used for stage cementing. After cementing, a closing or shut-off plug is deployed to block the casing side ports. Other stage cementing valves have a single sleeve which is opened by a special tool (sleeve positioner) run in after heavy packing. This method is used without limiting the number of stages and the plugs are not re-drilled. Also used together with a stage cementing valve is a multi-stage packer, located below the stage cementing valve which is inflated during the opening of the valve to minimize over-pressuring the zone below the stage valve (Lecourtier and Cartalos, 1993). Figure 17 shows a stage cementing collar.

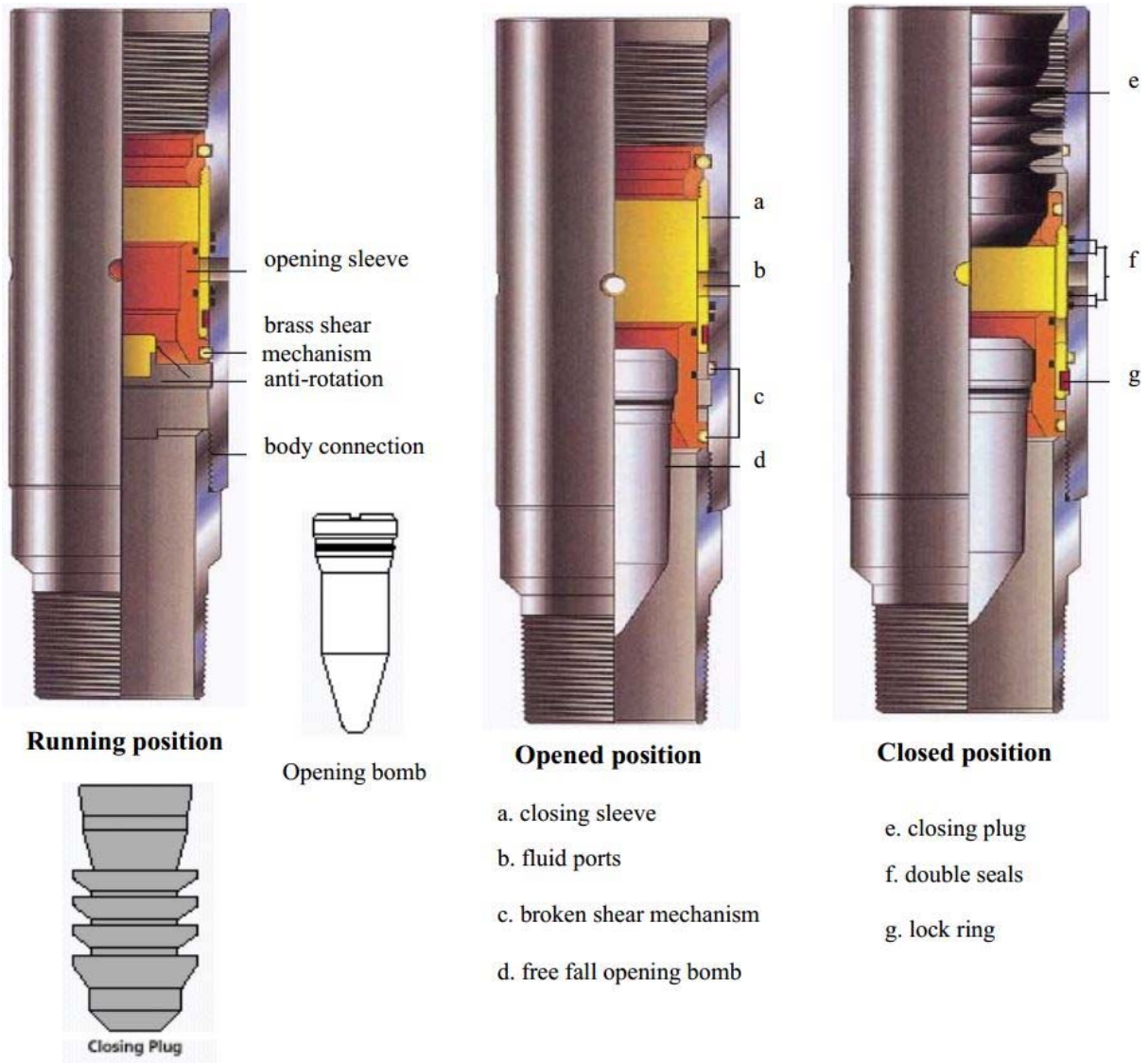

FIGURE 17: Stage cementing collars (Rabia, 2001)

5.3.1 External casing packers (ECP)

These are elastomeric elements (packers) used to isolate zones in the annulus when inflated with mud, cement or viscous fluid and can be incorporated when running casings. They are inflated through valves operated with shear pins, which break when the set pressure is reached, allowing fluid to enter; the closing valve shear pin breaks when the packer is fully inflated to the set pressure. The packers can be positioned above a loss zone to prevent cement slurry loss into the zone while the lower portion is cemented using other methods; they can also be used to cement sections of slotted liners which need to be isolated. The major disadvantage of packers is that they are the weak point areas and are susceptible to leakage, breaking the casing cement bond (Lecourtier and Cartalos, 1993). Figure 18 shows an external casing packer in running and inflating positions.

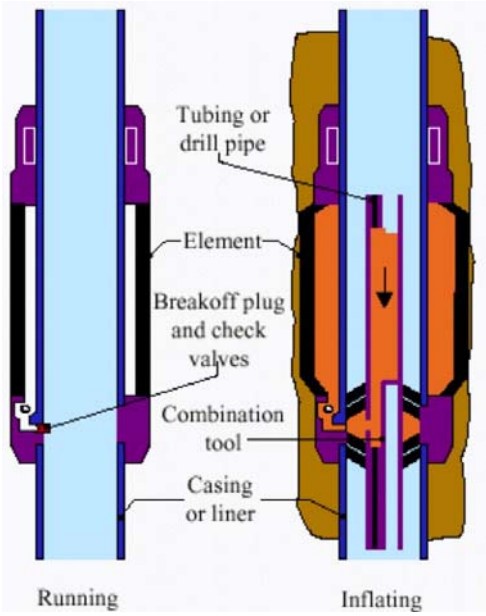

FIGURE 18: External casing packer during running and inflating (Rabia, 2001)

5.4 Reverse circulation cementing method

Reverse circulation cementing involves pumping cement slurry through the annulus, displacing the drilling fluid in the wellbore through the casing. The method is aimed at reducing the circulating bottom hole pressure (BHP), thus lowering the risk of cement slurry loss during cementing and eliminating the need for top jobs in order to complete cementing process. The major advantages of reverse cementing method are:

- It reduces the pressure applied to the formation during cementing since the fluid ahead of the cement has a lower density than the cement (lower effective circulating density);
- It minimizes the excess cement required for a cementing job since once the cement slurry reaches the bottom, mixing and pumping are stopped;
- It is possible to lower or stage manage retarder loading in cement slurry and, therefore, reducing the wait on cement time;
- The top cement in the annulus can be accelerated to reduce wait on cement time;
- Reduces cement pumping time since flow is by gravity and there is no displacement required; and
- Small top up job may be required to complete the cementing process in case the top of cement drops during setting.

The main challenge of reverse cementing is in knowing when competent cement has reached and circulated the bottom of the well. The main method used is the use of a tracer with a logging tool to indicate when cement enters the casing. Other methods include the use of stab in collars with a drill pipe for circulation of returns through the casing, if a marker (dye) is used, or to actuate a non-return valve when pulled out. Figures 19 and 20 show the reverse cementing process, using tracer and a drill pipe (Rickard et al., 2011; Spielman et al., 2006; Bour and Hernández, 2003; Hernandez, 2009).

5.5 Remedial casing cementing

The main objective of primary casing cementing is to fill up the annulus with cement back to the surface. However, in not all occasions are cement returns received on the surface due to loss of cement to the formation; then remedial cementing is required. The main method used to complete the cementing process is to fill cement though the annulus, sometimes with repeated top up jobs. This method poses

the danger of having water trapped between two top up jobs in the casing to casing annulus, if the remedial cementing is not well executed, leading to casing failure (Hole, 2008a).

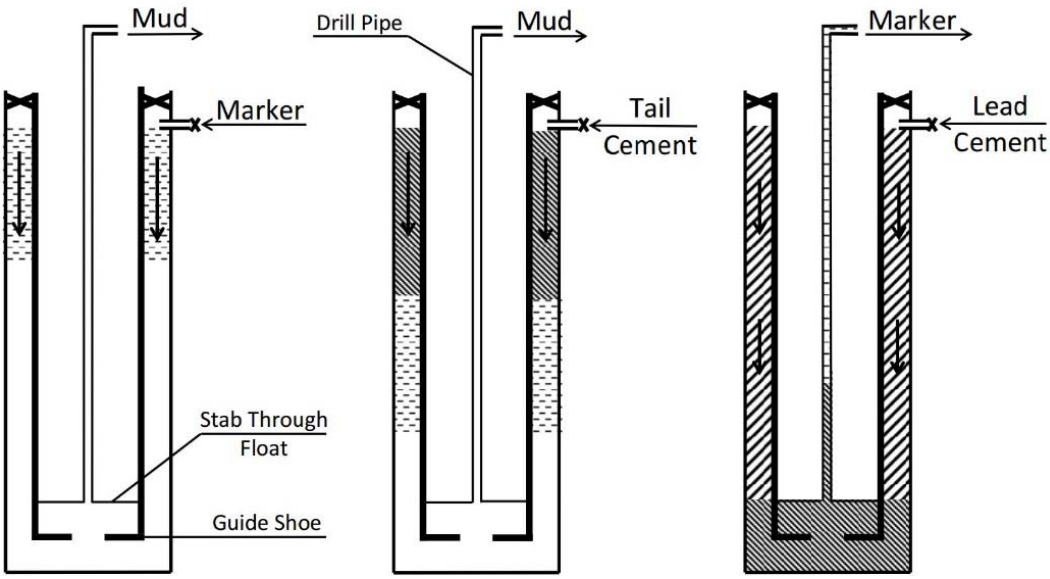

FIGURE 19: Reverse cementing process using drill pipe (Rickard et al., 2011)

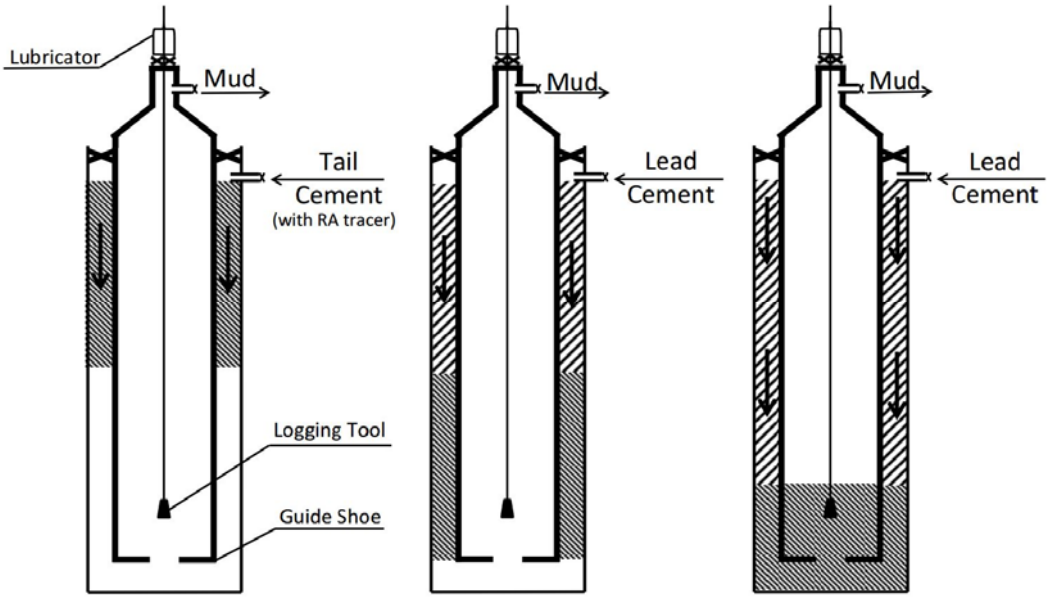

FIGURE 20: Reverse cementing process using tracer and logging tool
(Rickard et al., 2011)

Other methods used include:

a) *Squeeze cementing* where cement is forced into the annulus with the casing being perforated. This method is mainly used to repair poor primary cementing. Figure 21 shows squeeze cementing using an internal casing packer (Rabia, 2001);
b) *Tie back cementing* which is mainly used for repairing production casing by cementing the liner back to the surface from the top liners;
c) *Spaghetti cementing* which employs small diameter pipes to pump cement into the annulus. The pipes are run to the top of cement for shallow casing strings; and
d) *Using gravel and sand* for shallow surface and conductor casing with large circulation losses: sand and gravel are placed first, then the cement slurry is pumped (Guerra, 1998).

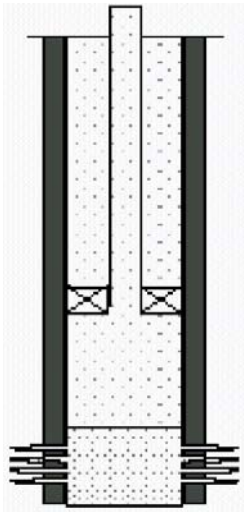

FIGURE 21: Squeeze cementing (Rabia, 2001)

6. QUALITY CONTROL AND POST CEMENTING LOGGING

6.1 Pre-cementing tests

Cement slurry formulations (design) are adjusted to suit wellbore conditions expected to be encountered during drilling. These conditions are simulated in a cement testing laboratory; cement blending recipes are adopted, based on the analysis results, to provide the best estimate for quantities of additives, slurry yield, mix water requirements, slurry gelling time and allowable pumping time. In geothermal, the main controlling factor in cement formulation is temperature, which affects the thickening time, setting time, rheology and compressive strength development.

Bottom hole circulation temperature (BHCT) represents the temperature at the bottom of the well after several hours of circulation; bottom hole static temperature (BHST), which is the undisturbed (natural) temperature (formation temperature) at the bottom of the well, is key in formulating cement slurry to be pumped downhole (Hole, 2008a). Parameters tested in cement slurry formulations include: thickening time, slurry density (specific gravity), fluid loss, free water, compressive strength, and rheology. These tests are conducted to determine the quantities of cement additives, such as retarders, accelerators, anti-friction materials, fluid loss control, lighting agents, free water control and silica flour, needed to prevent strength retrogression.

Thickening time test - is used to determine the time during which the cement slurry will remain in fluid state and be pumpable. Slurry thickening time should be enough to be pumped and displace cement back to surface. It is measured using a consistometer, in accordance to API 10B, which plots the viscosity (consistency) of cement slurry over time at the expected downhole temperature and pressure, and is expressed in Bearden units of consistency (BC) over a scale of 1 to 100 (Schlumberger, 2014). This test is used to determine the amount of retarder to be used to avoid over or under retardation of cement slurry. Figure 22 shows the output curve from a consistometer testing cement in Olkaria, mixed with 0.3% BWOC anti-fluid loss agent, 0.3% BWOC retarder and 0.3% BWOC dispersant.

Slurry density - is the measure of the mixing proportions of the dry cement blend and water to form the cement slurry. An increase in the cement slurry density favours displacement of drilling fluids during slurry placement but, at the same time, it increases the risk of circulation losses due to formation fracture. To modify slurry density, additives such as bentonite are added to soak extra water (extenders) for lighter slurry, or weighting agents such as barite are added to increase the density. Other methods include the use of hollow microspheres in the slurry or the use of foamed cement to lower the slurry density (Devereux, 1998).

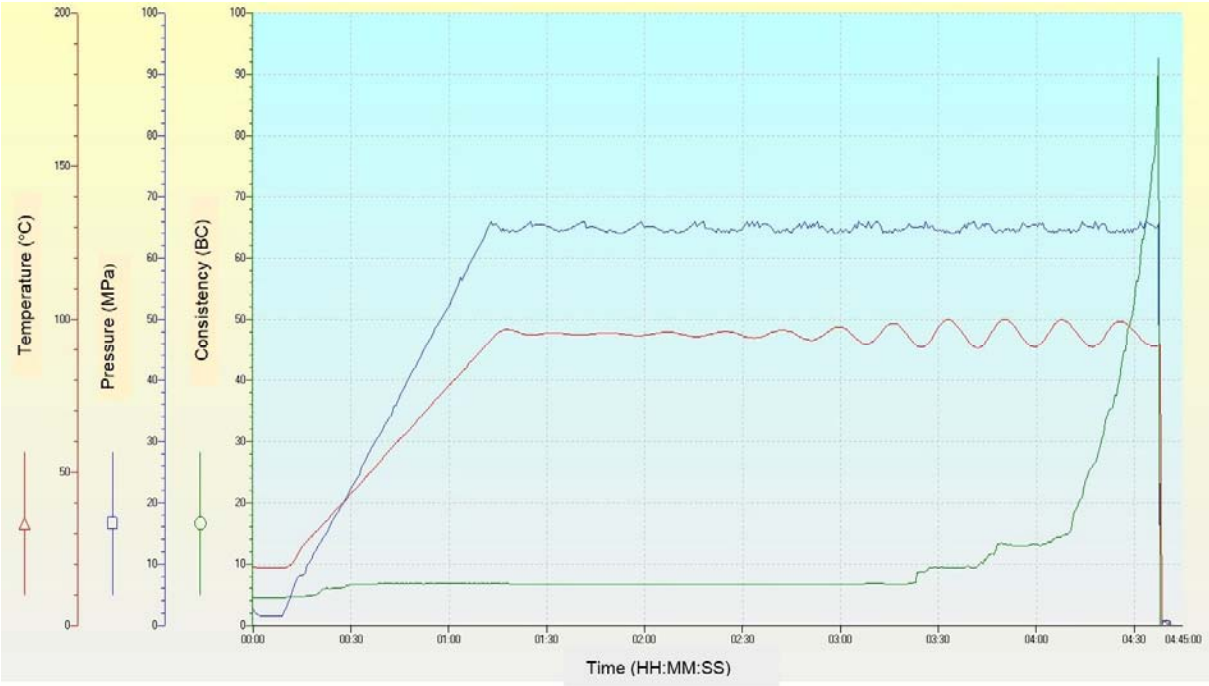

FIGURE 22: Thickening time output from a consistometer (Kengen, 2014)

Measurement of slurry density is done to determine the mix water required to yield the desired density during cementing. Cementing units have automatic density controls during mixing and pumping. Mud balance is used to confirm slurry density at the rig site during cementing (Guerra, 1998). Figure 23 shows a mud balance used to measure cement slurry density during cementing.

FIGURE 23: Mud balance (Fann, 2012)

Free water - is a measure of the excess water in the cement slurry not required to fully mix the dry cement blend (Schlumberger, 2014). When cement is setting, free water separates from the slurry, settling at the top of the cement column or in small water pockets if the well is deviated. This water can create channels while moving at the top of cement, resulting in a poor cement bond or casing failure, if the water pockets are between the casing to casing annulus. Testing of free water involves mixing (homogenization) cement slurry in an atmospheric consistometer with a rotational speed of 150rpm at a temperature of 88°C. The mixer is then transferred to a settling 250 ml cylinder where it stays for two hours. The segregated free water settled on the top of the cement mixer after two hours is measured to determine the amount of free water. Cement additives (free water control agents) such as Wyoming bentonite are usually added to control free water in cement slurry. The maximum free water allowable for cementing slurry is 0.5% or less, especially for geothermal casing cementing (Bett, 2010; Guerra, 1998; Devereux, 1998).

If cement is placed across a permeable formation, loss of filtrate will dehydrate the slurry, affecting its setting time, set strength and may lead to channelling. High fluid loss builds a thick filter cake that narrows the annulus, leading to increased annular pressure drop and possibly induced losses or fracturing (Devereux, 1998). The testing of fluid loss is done under simulated wellbore conditions in a stirring apparatus with a heating jacket to give the circulation temperature. The pressure differential between annular and formation pressure is simulated by pressurized nitrogen at 69 bars for 30 minutes. A screen and a filtration chamber simulate the permeable zone, and fluid loss is measured as filtrate volume per unit of time. The testing is done using API 10B guidelines which specify the size of the mesh to be used. It also recommends a maximum fluid loss of 100cc/30min for casing cementing, but lower values below

50cc/30min are recommended for permeable zones and directional wells (Devereux, 1998; Halliburton, 2005; Bett, 2010).

Compressive strength testing - is performed on cement slurry samples cured for 8, 12, 16 and 24 hours under simulated downhole temperature and pressure to determine the initial set time and the wait on cement time. Testing can be done by crushing the samples, using a hydraulic press, or using a sonic analyser to determine the compressive strength. Compressive strength failure pressure from the hydraulic press is used for comparison, since the testing is not done under downhole conditions, and the cement cube is unconfined in all directions, unlike in a well where cement is confined by formation and casings. Ultrasound compressive testing is non-destructive and the compressive strength development is monitored continuously during curing (Halliburton, 2005; Guerra, 1998, Devereux, 1998). Figure 24 show the output curve from a compressive strength test.

Rheology testing - is the measure of how cement slurry flows (viscosity) with respect to bottom hole circulation temperature, using a viscometer in order to properly predict pumping pressure during cementing. The slurry is first measured at ambient temperature and later conditioned to bottom borehole circulation temperature where viscosity readings at various rotational speeds are taken. A viscometer consists of a spring loaded shaft with a bob at the bottom in a rotating cylinder. The cylinder is rotated at variable speeds (200, 100, 60, 30, 6 and 3 rpm), creating a gap in which slurry flows deflect the bob due to increased drag. The drag in the shaft is transmitted to a precision spring where its deflection is measured and used to calculate the slurry viscosity (Halliburton, 2005).

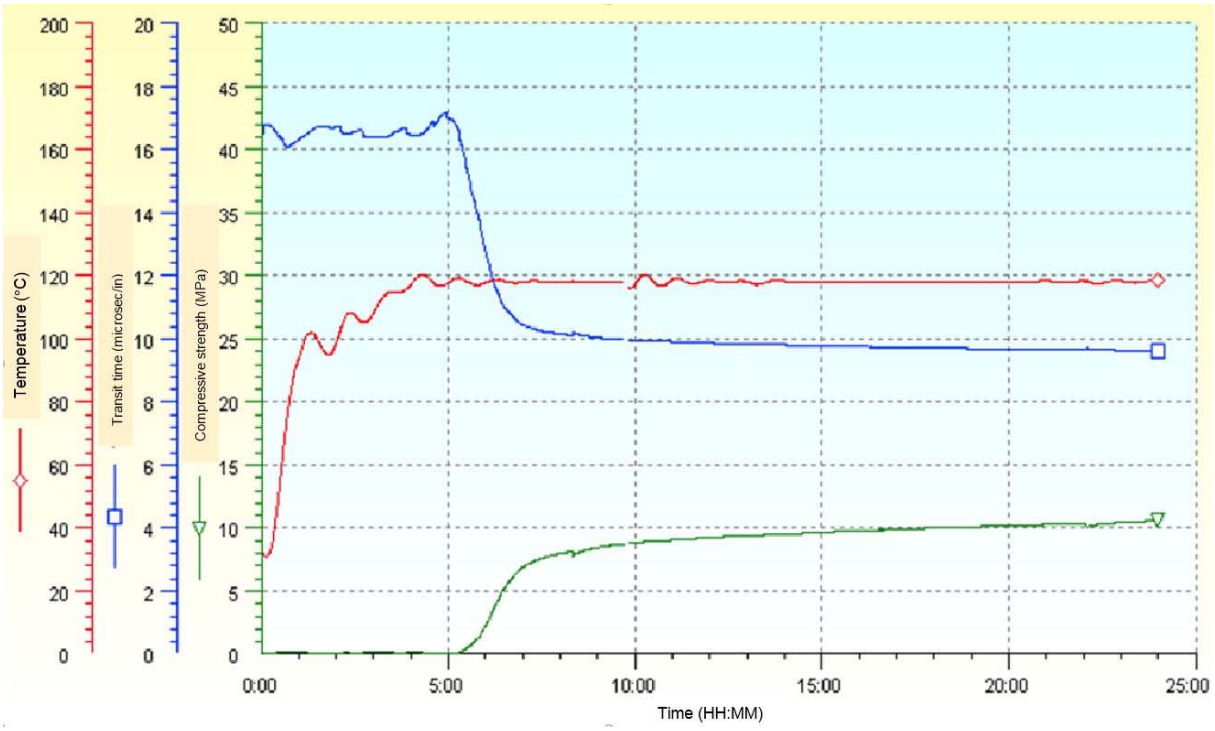

FIGURE 24: Compressive strength test (Kengen, 2014)

6.2 Post cementing evaluation

After casing cementing, there is need to establish the top of cement if there are no cement returns, confirm if the cement has cured before the next drilling operation, verify whether the whole casing string is uniformly covered with cement, and whether cement has bonded to the casing and formation. All

these can be established by running logging tools to assess the effectiveness of the cementing job. The most common methods are:

1. *Temperature logs for top of cement*: cement curing process is exothermic, thereby generating heat when it is setting. A temperature logging tool can be used to establish the top of cement if there are no cement returns to the surface. A sharp increase in temperature from the ambient will indicate the top of cement. Temperature logging needs to be done during the cement curing period (within 24 hours) as the reaction causing the temperature anomaly will fade with time. Figure 25 shows a temperature log indicating top of cement (Steingrímsson, 2011).

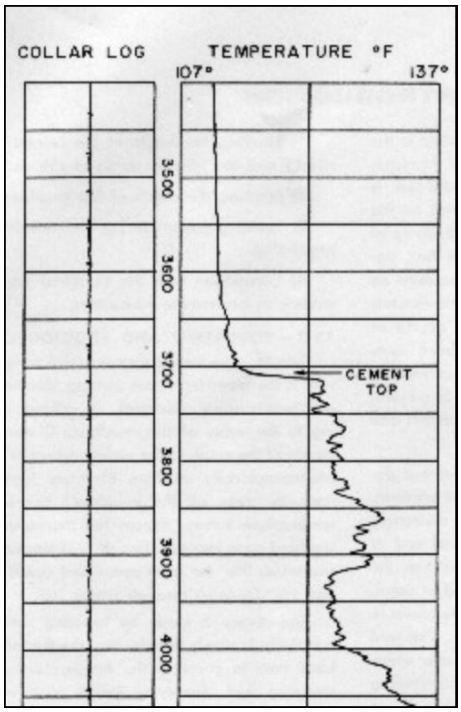

FIGURE 25: Temperature log showing top of cement (Crain, 2000)

2. *Cement bond log (CBL)*: is used to evaluate the quality of the cement bond between casing to cement and cement to formation, and also indicate the top of cement. The travel time and amplitude of the continuous sound pulses generated by a transmitter are measured by the receiver, placed at a distance (usually 3ft) from the transmitter as a function of depth. The amplitude will be at maximum where there is no cement or poorly cemented sections, and at minimum where the casing is well cemented (Steingrímsson, 2011).

3. *Variable density log (VDL)*: this provides the full wave signal (graphical representation) of the sound pulses as they are received at the receiver as a function of depth. The wave form of the variable density log corresponds to the sound signal that has travelled through the casing, cement sheath and is reflected back from the formation to the receiver. If there is no cement or the section is poorly cemented, the waveform will be in the form of parallel black and white lines, indicating that the sound pulse did not reach the formation, while wavy grey lines indicate a good cement bond. This should correspond to the cement bond logs (Bridge7, 2014; Rabia, 2001).

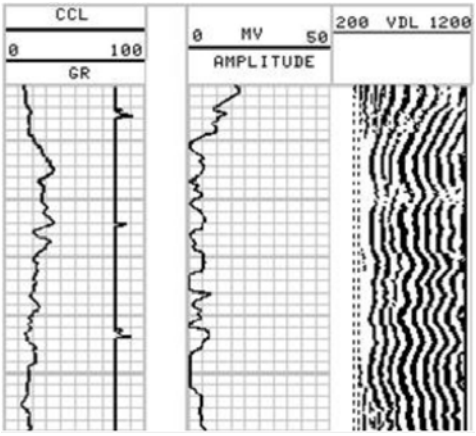

FIGURE 26: Cbl/vdl showing good cementation (Bridge7, 2014)

In addition to locating the top of cement and the quality of the cement bond logs (CBL), variable density logs (VDL) can be used to monitor the rate at which the cement is setting and to locate water pockets in the cement column. Both the CBL and VDL are observed from the sonic or ultrasonic logging tools. Gamma-gamma and neutron-neutron logging tools can also be used to determine the quality of casing cementation (Steingrímsson, 2011). Different models of cement bond log interpretation are shown in Figures 26, 27, 28 and 29. Figure 30 shows a cement bond log for well OW-33 in Hellisheidi, Iceland.

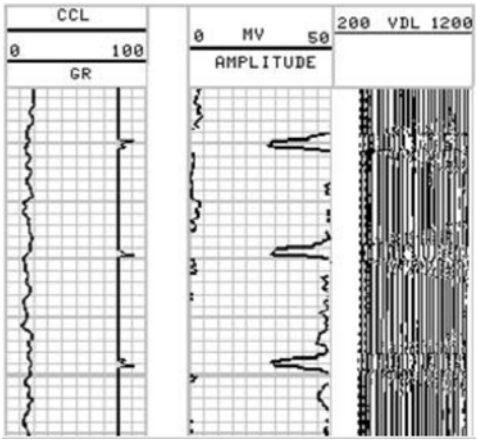

FIGURE 27: Cbl/ vdl showing no cement in the annulus (Bridge7, 2014)

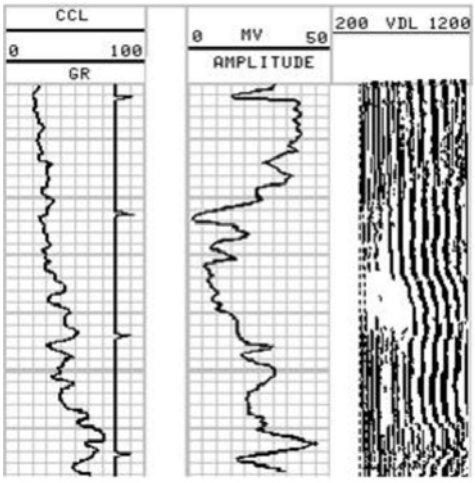

FIGURE 28: Cbl/ vdl showing partial cementation (Bridge7, 2014)

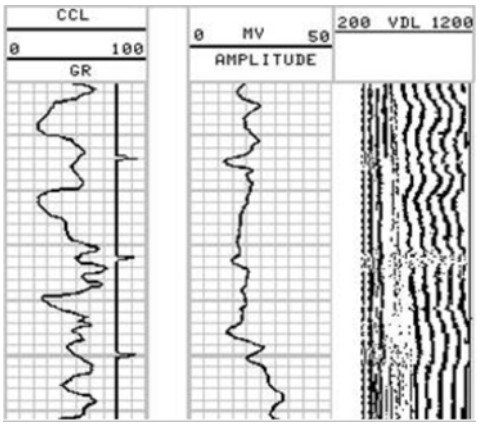

FIGURE 29: Cbl/vdl showing micro gap between casing and cement (Bridge7, 2014)

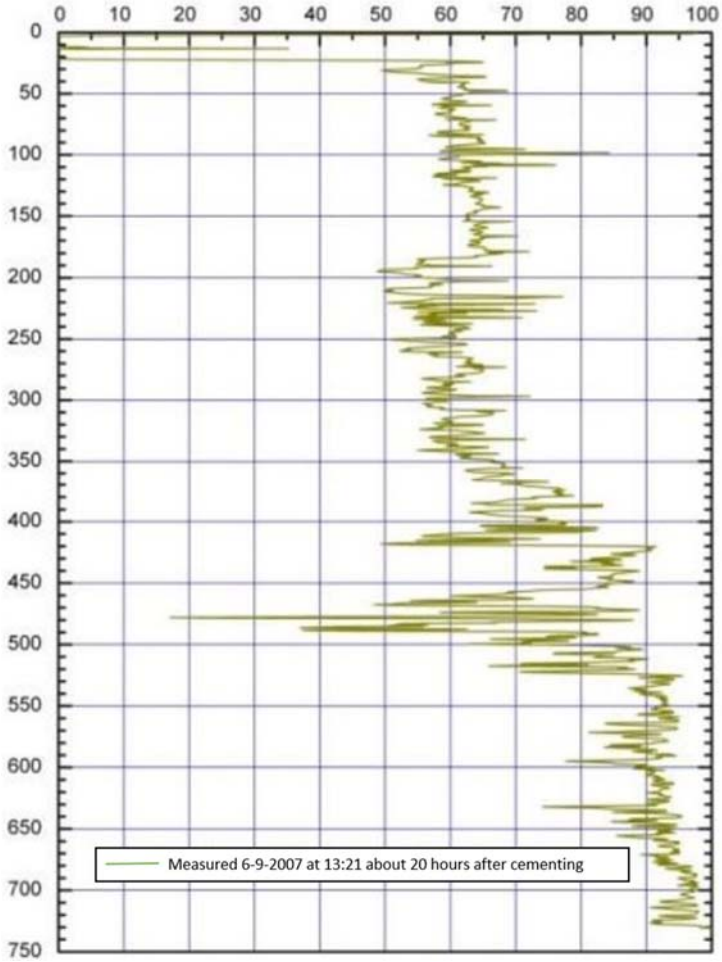

FIGURE 30: 20" Surface casing cementing

6.3 Shoe integrity pressure test (leak off test)

After the wait on cement time elapses, preparation for drilling the next section of the well starts with the installation of the blow out preventers. A pressure test is usually conducted to confirm the strength of the cement bond around the casing shoe and to ensure that there is no leakage to the formation above the casing shoe or to the previous annulus. It is also conducted after drilling a few metres (usually 3 m) into the new formation below the casing shoe to confirm the capability of the wellbore to withstand drilling fluid pressure for safe drilling of the next hole section. The casing cement bond is tested first by closing the blow out preventers and hydraulically pressurizing the cemented casing to 300 psi and observing any pressure drop for ten minutes. If the bond is holding, drilling out of cement then proceeds to three metres below the casing shoe into the new formation. The wellbore is closed and incremental fluid pressure from 200 psi to 1000 psi is applied for ten minutes. If there is no pressure drop, drilling ahead continues. If there is pressure leakage noted, the leakage point is cemented (Bett, 2010, NZS, 1991; Schlumberger, 2014).

7. CASING AND PLUG CEMENTING ANALYSIS

7.1 Casing cementing of wells OW-43A, OW-40V and OW-731A

The cementing of surface, anchor and production casings of wells OW-43A, OW-40V and OW-731A in Olkaria, Kenya were analysed for the calculated cement volume required in the single stage cementing method. During casing cementing, the calculated cement volume is pumped into the casing and then displaced, using water into the annulus in the primary (first) cementing job. In cases where cement did not return to the surface in the primary cementing, backfills (top up) through the annulus were required to completely fill up the cement and complete the casing cementing. All the wells except well OW-43A's surface casing did not receive cement returns to the surface during primary cementing and required top up jobs to fully cement the casings. The cement volume used in the primary cementing was based on the casing size, drilled hole size and drilled depth. Extra (excess) volume was also added to cater for losses during cementing and cavities in the well bore.

Cement volume calculation for surface, anchor and production casing strings was compared with the actual cement used to complete the cementing jobs. Cement volume calculation was based on the Drilling Data Hand Book (DDH) casing and annular volume data, and by considering all the annular volumes which needed to be filled with cement during cementing (Gabolde and Nguyen, 2014). For annular calculation of the casing to the open borehole volume and the rat hole (open hole below the casing shoe), 100% excess cement was added to cater for losses into the formation. The calculations, together with the actual cement volumes used, are shown in Table 4 for 20" casing, Table 5 for 13-3/8" casing, and Table 6 for 9-5/8" casing. The well sections are shown in Figures 31, 32 and 33.

TABLE 4: Cement volume calculation for 20" surface casing

Casing size	**20" Surface casing 94 lb/ft. K55**		
Well number	**43A**	**731A**	**40V**
Rig floor height from the cellar H (m)	11.9	11.9	11.9
Drilled depth L (m)	59.2	56	56.8
Casing depth L_1(m)	58.7	55.6	56.3
Casing shoe track length (length below the float collar) L_2 (m)	11.8	11.8	11.8
Rat Hole (open hole below the casing shoe) length L_3=L-L_1 (m)	0.5	0.4	0.5
26" drilled hole capacity in litres per metre (l/m)	342.5	342.5	342.5
Annular capacity between 20"casing and 26"drilled Hole in litres per metre (l/m)	139.8	139.8	139.8
20" casing internal Capacity in litres per metre (l/m)	185.3	185.3	185.3
Annulus Cement between 20"casing and 26" drilled hole $\mathbf{V_1}$ (m^3)= (Length L_1 x Capacity)/1000	6.55	6.11	6.21
Shoe Track Cement Volume $\mathbf{V_2}$ (m^3)= (Length L_2xCasing capacity)/1000	2.19	2.19	2.19
Rat hole volume $\mathbf{V_3}$ (m^3)= (length L_3 x 26" drilled hole capacity)/1000	0.17	0.14	0.17
Total Cement Volume=$\mathbf{V_1}$+$\mathbf{V_2}$+$\mathbf{V_3}$ (m^3)	8.90	8.43	8.56
Total Cement Volume With Open Hole Excess 100% (V_1+V_3) (m^3)	15.62	14.68	14.94
Plug cementing during drilling m^3	0	0	6
Primary cementing m^3	11.54	14.5	7.38
Backfills m^3	0	1	22.2
Actual volume used m^3	11.54	15.5	35.6
Number of backfills	0	1	3
Number of plug jobs	0	0	1

TABLE 5: Cement volume calculation for 13-3/8" anchor casing

Description	**13-3/8" Anchor casing 54 lb/ft. K55**		
Well number	**43A**	**731A**	**40V**
Rig floor height from the cellar H (m)	11.9	11.9	11.9
Drilled depth L (m)	302.0	294.5	301.5
13-3/8" Casing Depth L_0 (m)	300.7	293.5	300.5
20" Surface casing depth L_1 (m)	58.7	55.6	56.3
17-1/2" Drilled hole depth (m)=L-L_1	243.3	238.8	245.2
Casing shoe track length (length below the float collar) L_3 (m)	11.8	11.8	11.8
Rat Hole (open hole below the casing shoe) length L_4=L-L_0 (m)	1.3	0.8	1.0
17-1/2" Open hole capacity in litres per metre (l/m)	155.2	155.2	155.2
13-3/8" Casing internal capacity in litres per metre (l/m)	80.64	80.64	80.64
Annular capacity between 13-3/8" casing and 17-1/2" open hole in litres per metre (l/m)	64.5	64.5	64.5
Annular capacity between 13-3/8" casing and 20" casing in litres per metre (l/m)	94.66	94.66	94.66
20" casing and 13-3/8" casing annular cement volume $\mathbf{V_1}$ (m^3)= (Length L_1x Annular capacity)/1000	4.43	4.14	4.20
Annular volume between 13-3/8" casing and 17-1/2" open Hole $\mathbf{V_2}$ (m^3)= (Length L_2x Annular capacity)/1000	14.84	14.59	14.98
Shoe Track Cement Volume $\mathbf{V_3}$ (m^3)= (Length L_3x 13-3/8" casing internal capacity)/1000	0.95	0.95	0.95
Rat hole volume $\mathbf{V_4}$ (m^3)= (length L_4 x 17-1/2" drilled hole capacity)/1000	0.19	0.13	0.16
Total Cement Volume (m^3)=$\mathbf{V_1}$+$\mathbf{V_2}$+$\mathbf{V_3}$+$\mathbf{V_4}$	20.42	19.81	20.29
Total Cement Volume With Open Hole Excess($\mathbf{V_2}$+$\mathbf{V_4}$) 100% (m^3)	35.46	34.52	35.43
Plug job during drilling	0	0	0
Primary cementing volume m^3	33.2	20.9	18.2
Backfills cement m^3	47.3	168.1	168.3
Actual volume used m^3	80.7	183.0	186.5
Number of backfills	4	15	12
Number of plug jobs	0	0	0

TABLE 6: Cement volume calculation for 9-5/8" production casing

Casing	**9-5/8" Production casing 47 lb/ft. K55**		
Well number	**43A**	**731A**	**40V**
Rig floor height from the Cellar H (m)	11.9	11.9	11.9
Drilled Depth L (m)	742.5	754.0	752.0
9-5/8" Casing Depth L_0 (m)	742.0	753.0	751.0
13-3/8" anchor casing depth L_1 (m)	300.7	293.5	300.5
12-1/4" Drilled Hole depth (m)=L-L_1	442.0	460.34	451.5
Casing shoe track length (length below the float collar) L_3 (m)	11.8	11.8	11.8
Rat Hole (open hole below the casing shoe) length L_4=L-L_0 (m)	0.71	1.1	1
12-1/4" drilled open hole capacity in litres per metre (l/m)	76.04	76.04	76.04
9-5/8" Casing internal capacity in litres per metre (l/m)	38.18	38.18	38.18
Annular capacity between 9-5/8" casing and 13-3/8" casing in litres per metre (l/m)	33.7	33.7	33.7

Casing	**9-5/8" Production casing 47 lb/ft. K55**		
Well number	**43A**	**731A**	**40V**
Annular capacity between 9-5/8" casing and 12-1/4" open hole in litres per metre (l/m)	29.1	29.1	29.1
13-3/8" casing and 9-5/8" casing annular cement volume $\mathbf{V_1}$ (m^3)= (Length L_1x Annular capacity)/1000	9.73	9.50	9.73
Annular volume between 9-5/8" casing and 12-1/4" open Hole $\mathbf{V_2}$ (m^3)= (Length L_2x Annular capacity)/1000	12.83	13.36	13.11
Shoe Track Cement Volume $\mathbf{V_3}$ (m^3)= (Length L_3x 9-5/8" casing internal capacity)/1000	0.45	0.45	0.45
Rat hole volume $\mathbf{V_4}$ (m^3)= (length L_4 x 12-1/4" drilled hole capacity)/1000	0.05	0.08	0.08
Total cement volume (m^3)=$\mathbf{V_1+V_2+V_3+V_4}$	23.07	23.39	23.36
Total cement volume with open hole excess($\mathbf{V_2+V_4}$) 100% (m^3)	35.96	36.84	36.55
Plug cementing during drilling m^3	0	316.7	0
Primary cementing m^3	25.85	16.70	17
Backfills m^3	28.3	31.40	21.00
Actual volume used m^3	54.15	364.80	38.00
Number of backfills m^3	3	2	4
Number of plug jobs	0	23	0

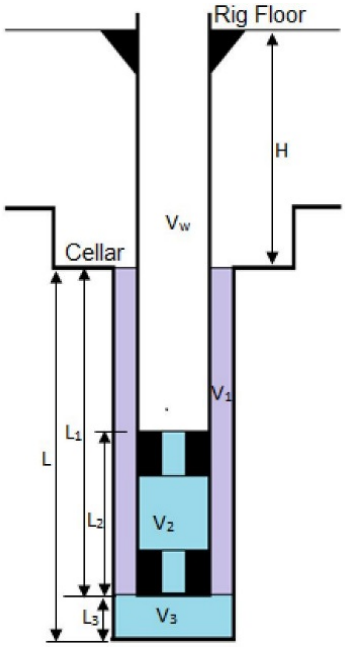

FIGURE 31: 20" Surface casing cementing

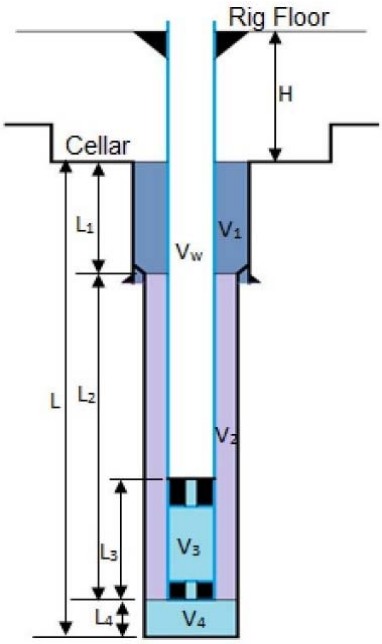

FIGURE 32: 13-3/8" Anchor casing cementing

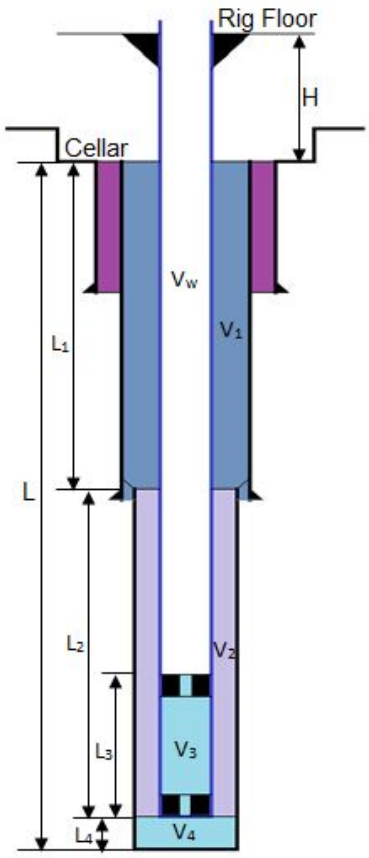

FIGURE 33: 9-5/8" production casing cementing

The calculated cement volume was compared to the actual cement used for the three casing strings in these three wells and is summarized in Table 7. The values were then compared, as shown in Figure 34.

TABLE 7: Comparison of calculated and actual cement used

Casing size	Calculated volume m^3	Actual volume used m^3	Extra volume used m^3
20" casing	45.3	62.6	17.3
13-3/8" casing	105.4	450.2	344.8
9-5/8" casing	109.4	140.3	30.9

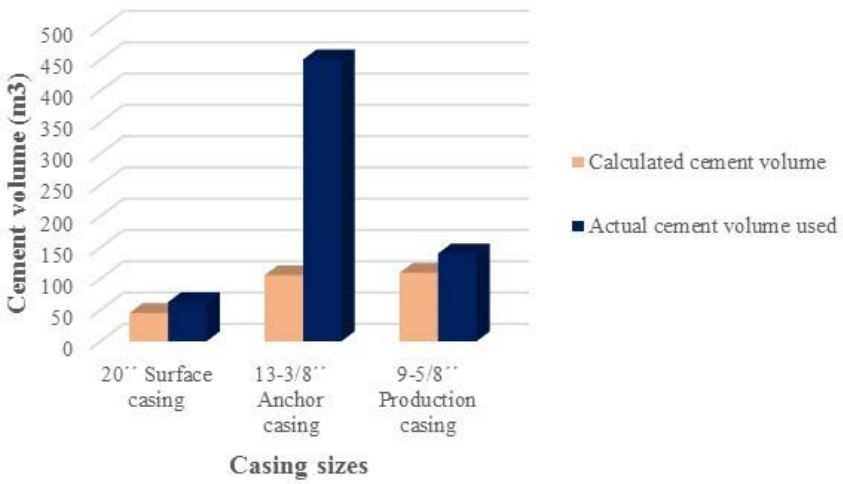

FIGURE 34: Comparison of calculated cement and actual cement used

After cementing, the wait on cement time is eight hours from one cementing operation to another either primary to backfill or backfill to backfill, and twenty four hours if cement is received at the surface. For cement plugs, the wait on cement time is twenty four hours between one plug and another or between a plug and the next drilling operation. The drilling days versus depth for the three wells are shown in Figures 1, 2 and 3 in Appendix I. The total wait on cement time, both for casing cementing and a cement plug placed during drilling for the three wells is summarized in Table 8, then compared to the total drilling days in Figure 35.

TABLE 8: Wait on cement time in days and percentage of total drilling time

Well	Drilling days	Cementing days	Percentage %
OW-43A	154	5.3	3.5
OW-40V	61	9	14.8
OW-731A	96	33	34.4

7.2 Well OW-731A cement plugs

A total of twenty four plug jobs were conducted during drilling of the production casing section of well OW-731A. The volume of cement used, depth and wait on cement time after each plug are summarized in Table 9. The well was completed in 96 days but 24 days were used as wait on cement time, which is equivalent to 25% of the total drilling days.

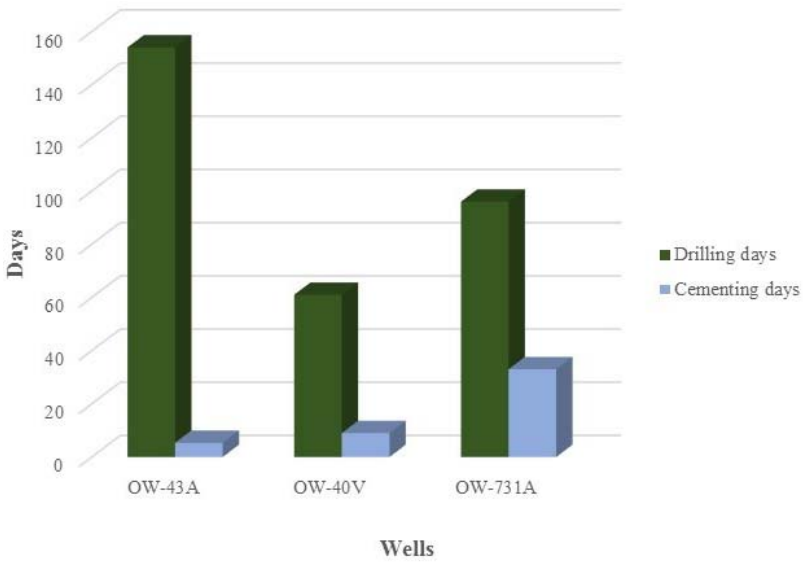

FIGURE 35: Comparison of total drilling days and wait on cement time

TABLE 9: Summary of plug cementing for well OW-731A

No.	Cement volume used (m^3)	Depth (m)	Wait on cement (hours)
1	14.20	204.00	24
2	15.00	204.00	24
3	15.00	200.00	24
4	15.00	235.00	24
5	14.00	233.00	24
6	20.00	233.00	24
7	15.00	203.00	24
8	10.16	203.00	24
9	15.60	201.00	24
10	20.50	199.00	24
11	16.00	371.00	24
12	10.25	371.00	24
13	12.09	371.00	24
14	10.27	309.00	24
15	15.02	302.00	24
16	6.02	293.00	24
17	9.02	293.00	24
18	15.07	365.00	24
19	15.05	391.00	24
20	15.21	377.00	24
21	6.60	383.00	24
22	15.43	383.00	24
23	10.00	383.00	24
24	6.20	396.00	24
Total	**316.69**		**576 (24 Days)**

7.3 Analysis of top up (backfill) cement volume used

Casing cementing using single stage cementing was analysed for sixty eight wells in Olkaria in order to compare the total cement volume placed through backfill cementing and the total cement volume used to fully cement the casing strings back to the surface. The summary of the backfill cement is shown in Table 10 and the results are compared in graph 3 (Figure 36). The complete cement volume analysis is shown in Table 11 in Appendix II

TABLE 10: Backfill cement volume comparison

Description	**20" surface casing**	**13-3/8" anchor casing**	**9-5/8" production casing**
Total backfill cement volume m^3	620.2	3167.8	1800.9
Total cement volume used m^3	1676.1	4638.5	3324.5
Percentage %	37.0	68.3	54.2

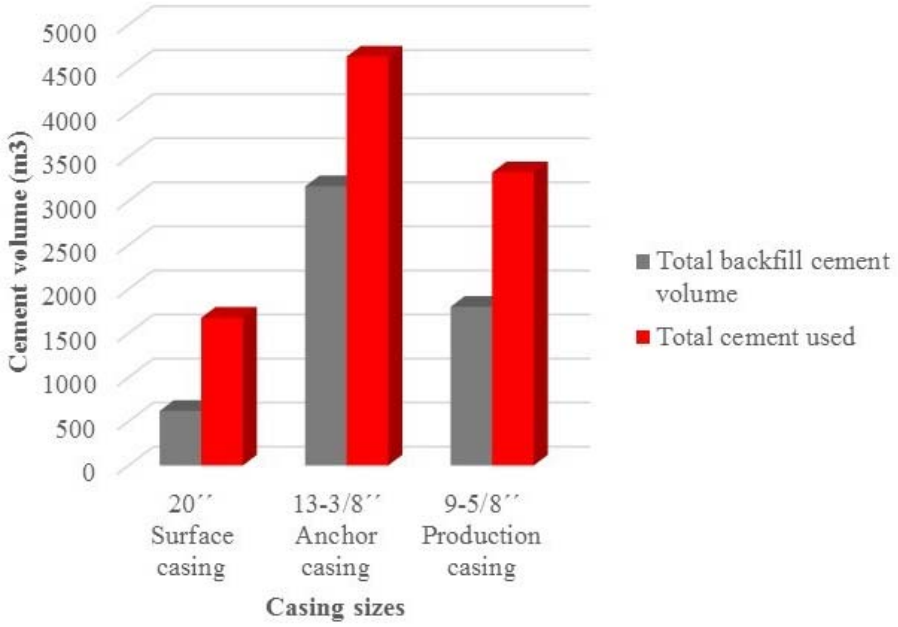

FIGURE 36: Comparison of backfill cement volume and total cement for casing cementing

8. CONCLUSIONS

The main conclusions drawn from this work are as follows:

a) There is need to explore other viable cement placement techniques for both casing cementing and healing of lost circulation based on the challenges encountered during drilling.
b) It is important to carry out calliper logging to assess wellbore conditions before running casing for casing cementing. Temperature/pressure logs can also assist in making the right decision on the wellbore conditions, the correct depth for cement plug placement during loss of circulation, and the expected challenges during running and cementing casings.
c) Carrying out cement bond logging or temperature logging to locate the top of cement will help in the calculation of the cement volume to be placed during backfills and in reducing small backfill cementing and wait on cement time.
d) There is need for immediate backfill cementing, especially for surface casing cementing since, in most cases, the cement volume involved is relatively small.
e) Explore the use of inner string cementing or reverse circulation cementing, especially for anchor casing cementing which has the most backfill cementing jobs and large volume requirements.
f) Review of the slurry design is necessary, aiming at lowering the cement slurry density to reduce pressure on the formation, and the best placement technique for the casing strings involved.
g) Analysis of the viability of using light cement slurry, without compromising on the cement compressive strength and the additives to be used to lower the density, needs to be carried out, including the best placement techniques using the available cementing equipment.
h) Introducing silica flour to a blend with Portland cement will improve on cement compressive strength retrogression at elevated temperatures, especially for production casing which is set in high temperature deeper sections of the geothermal wells. Another option is using other API classes of cement, e.g. class G cement, which is sulphate resistant in high temperature casing cementing.
i) Analysis of the wait on cement time and the quantity of cement additives such as retarder, accelerators and anti-friction materials in the cement blend for casing cementing is important in adjusting the wait on cement time. Also, if temperature logging is used or there are good returns during drilling, the wait on cement (WOC) time can be adjusted according to formation temperatures. It is also critical to review the use of cement accelerators during placement of cement plugs.

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NOMENCLATURE

ASW - Average cement slurry weight in kilograms per litre (Kg/l)
Lb/ft. - Casing weight in pounds per foot
Casing diameter - inches (")
BWOC - By weight of cement
V_w - Volume of water in the casing cubic metres (m^3)
TOC - Top of cement
WOC - Wait on cement

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APPENDIX I: Drilling progress diagrams for wells OW-43A, OW-731A and OW-40V

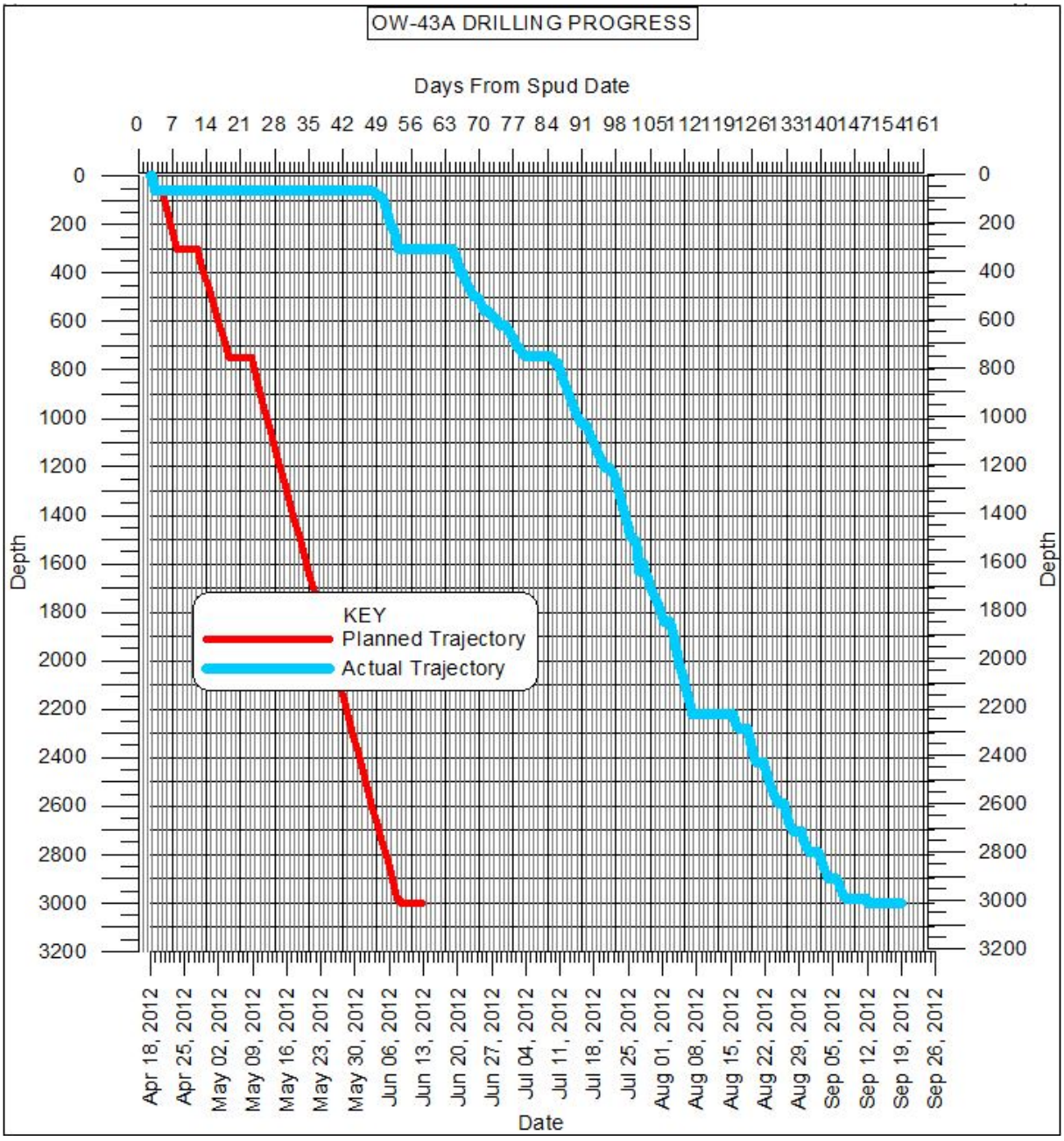

FIGURE 1: Drilling progress well OW-43A (Kengen, 2014)

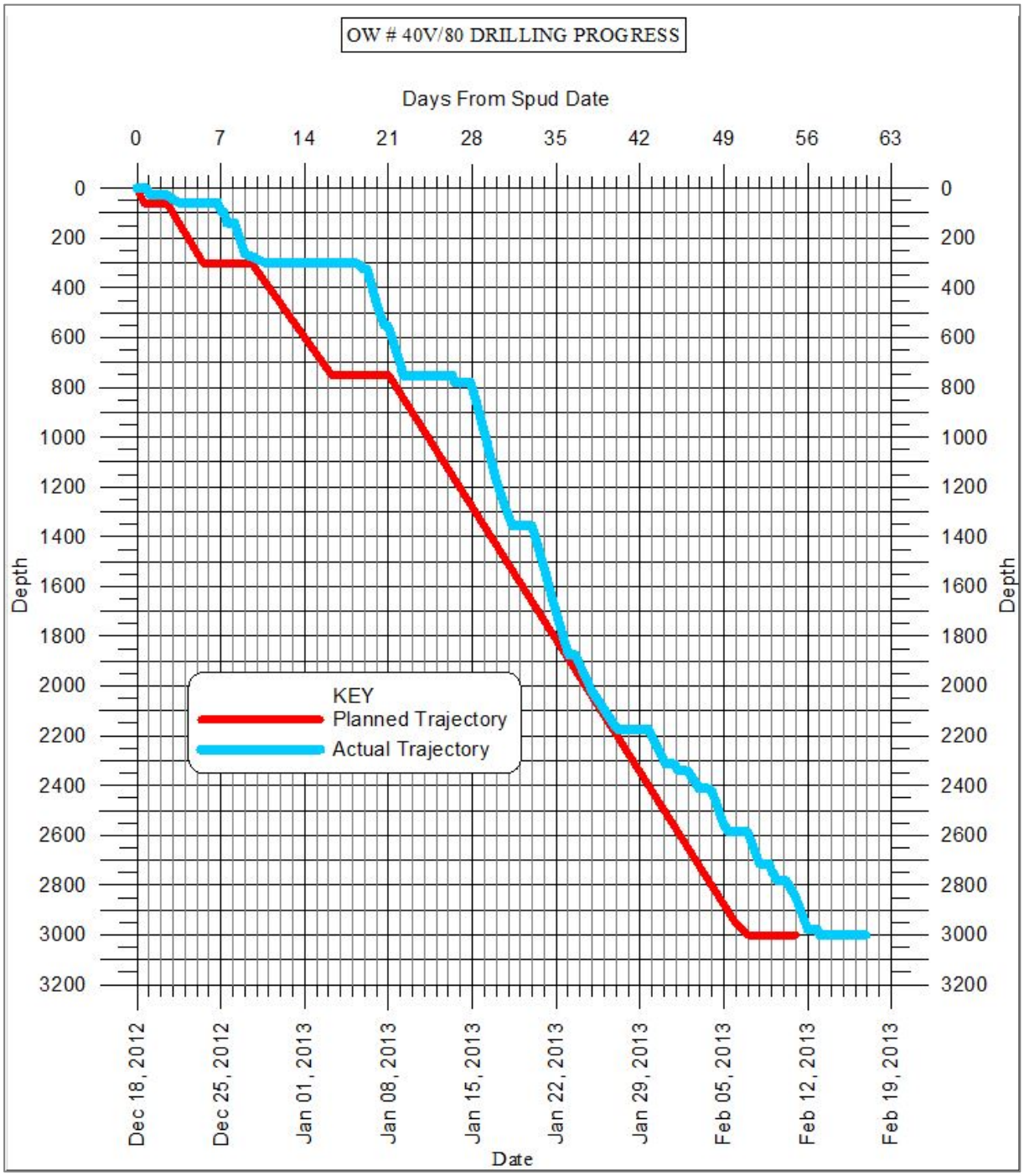

FIGURE 2: Drilling progress for well OW-40V (Kengen, 2014)

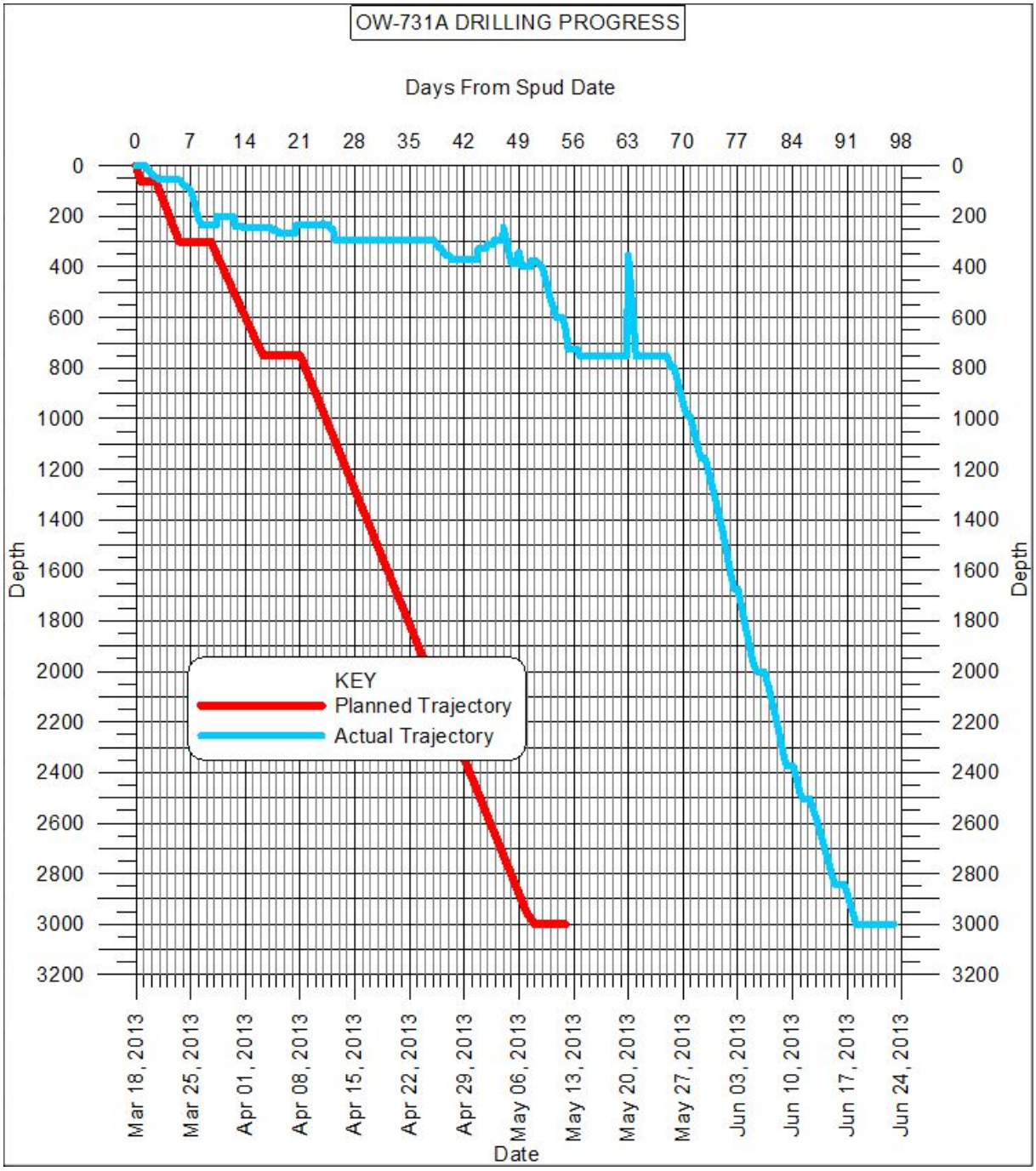

FIGURE 3: Drilling progress for well OW-731A (Kengen, 2014)

APPENDIX II: Summary of primary and backfill casing cementing

TABLE 1: Summary of the primary and backfill casing cementing in Olkaria, Kenya

No	20" surface casing		13-3/8" anchor casing		9-5/8" production casing	
	Total backfill cement volume (m^3)	Total cement volume used (m^3)	Total backfill cement volume (m^3)	Total cement volume used (m^3)	Total backfill cement volume (m^3)	Total cement volume used (m^3)
1	0.00	17.70	22.32	42.37	18.41	38.47
2	1.50	15.15	35.97	60.75	41.21	61.86
3	14.05	19.67	32.97	45.92	20.34	70.24
4	0.00	19.45	29.75	45.68	19.60	37.05
5	3.10	16.85	27.77	51.44	25.11	45.41
6	27.63	43.16	8.89	36.34	35.20	72.14
7	12.24	31.95	8.00	22.01	28.89	67.51
8	0.60	16.06	40.69	58.15	37.90	65.34
9	0.00	13.26	25.34	44.81	23.00	51.05
10	18.64	32.48	22.10	45.77	24.95	58.63
11	0.00	14.71	17.22	37.06	37.70	62.46
12	22.17	29.55	168.34	186.52	20.99	38.01
13	0.00	15.76	37.51	55.96	23.10	44.87
14	0.00	14.64	41.63	63.17	21.97	44.34
15	0.00	12.40	45.35	68.32	21.60	44.37
16	0.00	15.45	23.67	43.72	21.40	41.77
17	16.47	26.55	50.12	75.17	23.81	50.18
18	0.99	16.89	162.09	182.97	31.40	48.12
19	84.58	101.28	82.09	102.86	14.39	37.88
20	0.00	15.80	27.06	47.34	22.61	55.05
21	0.00	17.50	14.80	34.75	28.30	47.97
22	0.00	18.45	24.90	40.47	38.85	54.87
23	45.60	54.76	20.59	37.64	21.00	39.87
24	3.40	19.11	22.19	44.64	52.42	71.73
25	4.01	15.75	74.83	91.70	18.86	36.59
26	0.00	19.37	39.74	58.19	46.83	63.31
27	3.60	18.76	24.61	36.05	22.29	43.46
28	4.40	20.35	31.02	52.27	41.96	62.52
29	5.58	24.08	13.05	32.10	22.30	40.08
30	9.41	25.15	44.60	68.72	17.06	39.59
31	6.90	25.43	46.80	72.05	15.20	32.60
32	8.90	25.15	44.00	58.25	97.54	121.33
33	36.24	52.39	11.12	32.10	18.06	31.33
34	0.00	15.95	27.59	50.74	43.93	55.90
35	0.00	13.75	36.80	58.97	47.21	62.51
36	7.70	22.81	18.21	37.66	29.60	48.75
37	129.00	144.60	130.72	151.77	15.40	34.97
38	3.00	18.16	54.08	70.18	23.29	43.07
39	4.73	20.13	18.59	40.13	34.00	55.07
40	0.00	13.41	43.99	64.40	27.06	41.62
41	15.83	31.13	51.00	73.46	27.70	43.37
42	4.01	19.71	32.09	53.14	17.40	39.87
43	0.00	16.20	30.90	51.64	21.76	47.53

No	20" surface casing		13-3/8" anchor casing		9-5/8" production casing	
	Total backfill cement volume (m^3)	**Total cement volume used (m^3)**	**Total backfill cement volume (m^3)**	**Total cement volume used (m^3)**	**Total backfill cement volume (m^3)**	**Total cement volume used (m^3)**
44	27.35	43.41	86.96	113.21	22.25	43.14
45	6.57	22.57	33.23	65.30	15.60	43.85
46	0.00	18.04	32.09	52.54	14.30	33.92
47	0.00	17.30	22.01	42.79	26.20	89.97
48	20.01	36.25	80.51	102.87	17.30	49.35
49	2.96	21.50	70.39	100.06	25.71	52.17
50	2.96	17.06	9.00	33.44	10.00	31.44
51	7.17	20.48	167.00	195.15	11.97	41.82
52	0.18	17.27	98.14	128.09	36.65	61.54
53	0.00	17.24	44.63	66.64	69.98	84.22
54	14.30	26.71	52.90	72.05	41.52	66.89
55	0.00	17.45	47.27	80.42	28.30	54.14
56	0.00	14.50	27.14	54.28	23.22	45.50
57	3.47	20.26	6.50	37.70	17.66	44.33
58	0.00	16.85	40.65	58.84	28.31	59.52
59	0.45	16.50	35.99	55.59	72.05	100.90
60	8.19	25.74	122.66	156.68	1.08	17.58
61	5.40	25.55	29.75	39.20	6.74	19.67
62	1.00	16.69	19.71	41.27	30.06	60.00
63	0.00	13.64	15.40	39.97	27.00	46.94
64	4.73	23.37	160.81	185.06	2.30	16.70
65	2.60	19.04	12.90	33.99	6.61	23.06
66	0.90	15.75	25.30	42.60	24.50	45.24
67	11.57	31.02	23.71	53.77		
68	6.16	21.11	138.08	159.69		
Total	**620.24**	**1676.14**	**3167.79**	**4638.52**	**1800.87**	**3324.54**
Percent.	37%		68.29%		54.17%	