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Principal Points in Cementing Geothermal Wells

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Abstract

Geothermal energy is becoming an important source of energy and its importance will be increasing in the future. When we drill geothermal wells, we encounter high temperature zones and may also encounter high pressure areas. Cementing in high temperature environments such as geothermal wells is very challenging. The survey that was sent to High-Pressure-High-Temperature (HPHT) professionals at the HPHT Summit meeting in 2012, showed Cement Design is one of the biggest concerns for HPHT operations and it is one of their technology gaps. Temperatures as high as 200 °C-400 °C could destabilize the setting of the cement. If the well has both high temperature and high pressure, the cementing process becomes much more complex. This article discusses various aspects of cementing procedures and considerations for geothermal wells including cements design considerations, crucial problems, and some technology solutions.

Key words: Geothermal energy; HPHT; Geothermal well

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INTRODUCTION

World population growth continues to soar. The World Factbook (CIA, 2011) listed annual population growth rate in percent as shown in Figure 1 (Wikipedia, Population Growth Rate).The United States Census Bureau (2012) estimates the world population has currently surpassed 7 billion. Other estimates from the United Nations Population Fund revealed a population of 7 billion was achieved in 2011. Figure 2 shows the world population history in the year 2000 to be less than 6 billion people (Wikipedia, World Population History).It can be concluded from these different sources that special attention is required to sustain the growth of various sectors, such as food supply, environmental integrity, and sufficient energy resources. Some of the energy sources can be extracted from geothermal energy. Worldwide electricity production from it has increased, and direct use could displace millions of barrels of oil. On the other hand, drilling geothermal wells are a very small number comparable with drilling oil and gas well. Just as in the United States (U.S) in the year 2008, 100 geothermal wells were drilled, while for oil andgas,there were more than 50,000 wells drilled (Finger and Blankenship, 2010).

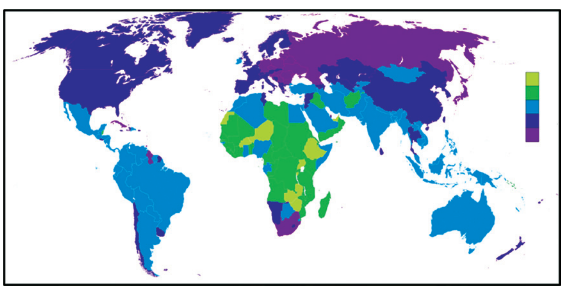


Figure 1
Annual Population Growth Rate (2011 Estimate)

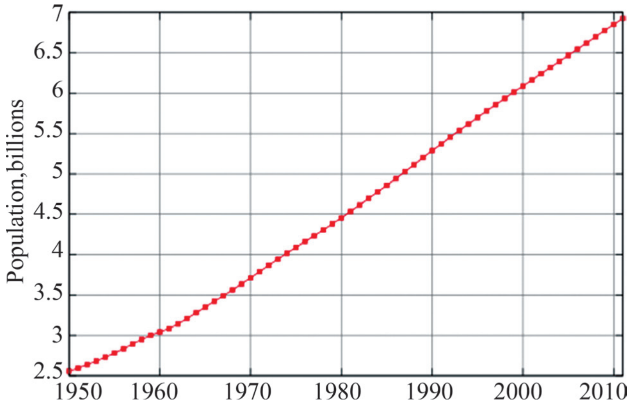


Figure 2
World Population History

Geothermal wells can be found in the United States, Philippines, Indonesia, Mexico, Italy, New Zealand, Iceland, Kenya, Japan, and other locations. Countries that have installed the power renewal can be seen in Table 1 (International Geothermal Association, 2011). Finger and Blankenship 2010 mention some geothermal power sources in the US produce temperatures as low as 200 °C at a depth of 330 m, however, locations such as geysers produce temperatures above 240 °C at a depth of 2500 m.Even in Japan we could find a well with a 500 °C bottom hole temperature at a depth of 3350 m. Saito and Sakuma (2000) recorded experimental wells in Hawaii and Iceland with temperatures above 980 °C. Figure 3 displays a map of high temperature geothermal locations worldwide.

Table 1
Installed Geothermal Power

Country	2011 (MWe)	Share (%)
Austria	1.4	0.01%
Australia	1.1	0.01%
China	24	0.2%
Costa Rica	208	1.9%
El Salvador	204	1.9%
Ethiopia	7	0.1%
France (Guadeloupe)	16	0.1%
Germany	8	0.1%
Guatemala	52	0.5%
Iceland	665	6.0%
Indonesia	1189	10.8%
Italy	863	7.8%
Japan	502	4.6%
Kenya	170	1.5%
Mexico	887	8.0%
New Zealand	769	7.0%
Nicaragua	88	0.8%
Papua New Guinea	56	0.5%
Philippines	1967	17.9%
Portugal (The Azores)	29	0.3%
Russia (Kamchatka)	82	0.7%
Thailand	0.3	0.003%
Turkey	114	1.0%
US	3112	28.3%
Total World	11014	100.0%

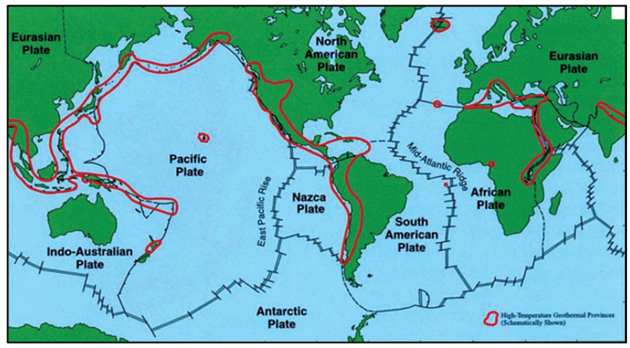


Figure 3
High Temperature Geothermal Location Worldwide

Geothermal energy is used for heat pumps, bathing, space-heating, greenhouses, aquaculture and industrial processes (Lund and Freeston, 2001). It is an endless energy source that does not need fuel, thereby reducing pollution. Figure 4 shows the basic geothermic well's operating principle (BBC, Geothermal Energy); a thermal well was drilled to high-temperature formations then the cold water was pumped down. As the water flows through the hot fracture formation, the temperature rises make it become heated water and at the surface formed steam. The steam is used to drive a turbine, usually for electrical power generation. Since 1970, another technology has been found to aim the heat (Ghori, 2006). It is by extracting the energy from dry hot rock, deep in the earth crust. Sometimes heat can be obtained from the movement of magma in cracks or water circulation in the area of the fault.

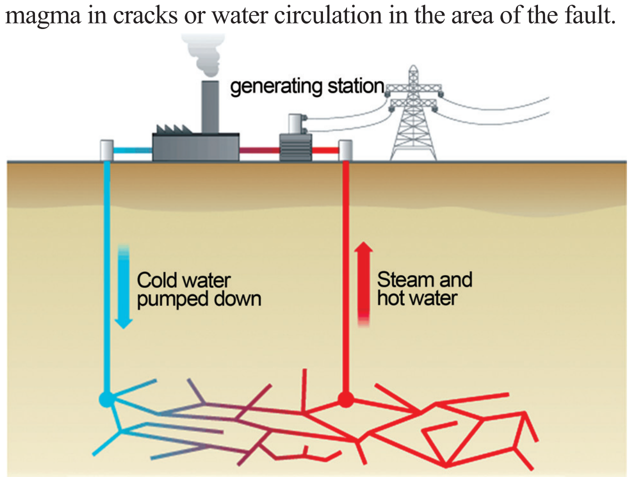


Figure 4
Geothermal Basic Principles

Based on Finer and Blankenship (2010), temperature in the earth will rise approximately 25 °C for each kilometer of depth. Direct use of geothermal energy such as water heating or recreational use requires a minimum temperature of 35 °C. However, electric power generation requires temperature of at least 135 °C. This means that when the surface temperature is 20 °C, then only a 5 km hole is needed to reach the formation that can produce heat for electrical power. Geothermal wells are sought in the areas of heat flow that have above average subsurface temperatures. There were also studies conducted by A.G.

Geohil about the Earth›s crust temperature profile at different places, as shown in Figure 5.

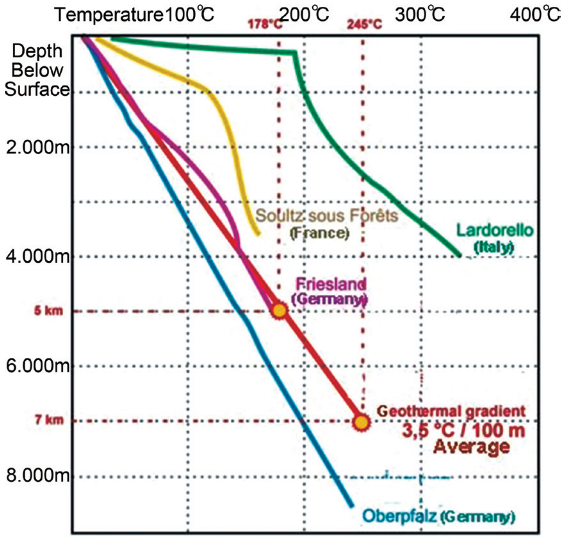


Figure 5
Earth'S CRUST TEMPERATURE PRofile at Different Location

1. CRUCIAL PROBLEMS IN GEOTHERMAL WELLS

1.1 High Temperature

Normally, cementing in geothermal will need 6.9 MPa compressive strength and water permeability less than 10^{-4} m^2 (API Task Group on Cements for Geothermal Wells, 1985). Cement will lose its strength over its particular temperature, approximately 110 °C. Calcium Silicate material, with addition of water will generate a Calcium Silicate Hydrate (CSH phase) which will decrease compressive strength and increase permeability, this is known as *strength retrogression.* One way to prevent this phenomenon is by partially replacing bulk lime with silica; that is, substitute Portland cement with at least 35% silica BWOC. The recommended cement composition for the geothermal environment by Nelson, Eilers and Spangle (1981) is shown in Table 2.

Table 2
Recommended Cement Composition for Geothermal Environment

Recommended cement composition for geothermal environment						
1	Class J	44% H_2O				Normal density
2	Class B	54% H_2O	35% Silica Flour			
3	Class G	54% H_2O				
4		91% H_2O		15% Diatomaceous Earth		Low density
5		116 % H_2O		2% Bentonite	8.5% Perlite	
6		136% H_2O	100% Silica Flour	2% Sodium Silicate Extender		

Specifically, in geothermal wells, a cement job conducted not at a geothermic temperature, with a circulation of drilling mud in colder conditions, will reduce the temperature of the well. However, retarder agent must be added into the cement system, in order to have enough placement time at a maximum temperature. Cement of the upper part has a longer placement time, then sometimes more retarder was added, causing a very long drying time. At least two to three hours pumping time are required to allow adequate placement time (Gaurina *et al.*, 1994).With extreme temperature, the thickening time was measured initially with ± 10% of the retarder concentration (North *et al.*, 2000).

In some cases since there will be a water flow, it could cause an increased water cement ratio, and cement will crack as the thermal cycle continues to recur. Portland Class G cement and Class J cement are used to persist in high temperatures, together with silica flour and omit extender, expected to withstand for 30 years. However, if the cement is applied to the environment that reaches 400°C, Portland cement should not be used;high alumina cement will provide more stability. Drastic temperature change could decrease cement and casing bond. Cement with calcium aluminate phosphate shows increasing bond strength between 0 to 100 cycles, and Portland cement shows declining bond strength in the first 70 cycles (Berard *et al.*, 2009).

1.2 Lost Circulation

To increase the amount of production, geothermal drilling is most likely influenced by oil and gas drilling technology. The integrity of the formation ranges from poorly consolidated up to highly fractured, and the fracture gradients tend to be low (Nelson and Eilers, 2006). Consequently, the most common problem encountered in geothermal wells is lost circulation. Often it is in a very large amount, either during drilling or cementing. If the losses happen during the cementing job, not rare that cement return cannot be found on the surface, especially when using normal cement design. In geothermal wells, water traps should be avoided between two casings, because the casings can fail while discharging after the wells heat up. The first loss zone depth should be recorded and designed as the cement top; excess slurry volume should be less than 30% (Fen *et al.*, 2012).

Low density cement is used to overcome this problem, while an extender is added in order to lower the density of the mixture without the settling issue. Fly ash, bentonite, and perlite are the types of extender (Gaurina *et al*., 1994). For Portland or Class J cement, if the temperature is above 232 °C,it's better to use bentonite and perlite, not to use fly ash. When the temperature is above 300 °C, for high alumina cement, it's more suitable to use fly ash or crushed aluminosilicate fabric. However, for geothermal wells, avoid the use of fly ash since the agent could degrade the compressive strength at curing temperatures over 230 °C and under a long term period of time.

From data gathered, the formation which has a poor fracture zone commonly used less than 12.5 lbm/gal of low density cement. For a density below 12.5 lbm/gal, microsphere-extended, multimodal particle size or foamed cement is required. Glass and ceramic microspheres can be used in high temperature wells. Although ceramic microspheres only can persist at lower bottom hole pressure (max 4500 psi), this system gives better performance at temperatures as high as 315 °C when compared to glass microspheres (Nelson *et al*., 2006).

1.3 Thick Filter Cake

Fluid loss cannot be avoided, but we can reduce the amount by adding fluid loss agents. If the amount of fluid loss is too large, it can cause a reduction in the strength of the cements. Other things to be aware of is a buildup of filter cake that can later lead to differential sticking problems. Fluid loss limit depends on each location, but generally around 50 ml to 100 ml per 30 minutes is the recommended rate. Normally, filter cake also can be reduced with mechanical or chemical practice. In terms of a cementing operation, chemical practice means by pumping the spacer or chemical wash into the wellbore prior to the cement job. Different ways to clean up filter cake includes pumping acid, enzymes, formate brines, or a combination of these. Ethyl-lactate ester gives a very good performance rather than organic acids (Alotaibi *et al*., 2010).Mechanical practice to reduce the filter cake is by reciprocates, rotation, or adding a scratcher into the casing.

1.4 CO_2 Attack

One of the problems found in high temperature geothermal well is cement carbonation. Shen and Pye (1989) mention casing were found ruptures and failures in Broadlands field, New Zealand geothermic well. These were caused by CO_2in the fluid that corrodes cement and casing. Analysis from geothermal wells in Brawley and Geysers fields found that the amount of cement carbonation relies on the ratio of CO_2on fluid, cement agents and temperature. Cement that has been exposed to CO_2has an acceptable compressive strength, but the permeability will be above the limit.

To avoid a strength reduction, the cement system must be designed with low bulk lime to silica (C/S) ratio, less or equal to 1.0 (Nelson and Gouedard 2006) and low permeability as well, but it does not apply in environments with high levels of CO_2 (Hedenquest and Stewart 1985). Tubermorite and Xonotlite are the cement phase which can stand least to carbonation; their deterioration is accelerated when bentonite is present in the cement (Eilers, Nelson and Moran 1980). By reducing the silica flour concentration from 35% to 20% BWOC improves the cement resistant to CO_2 (Milestone et al. 1986).In high levels of CO_2, it is necessary to use calcium aluminosilicate or calcium phosphate to prevent a weight loss. To increase the strength of Portland cement against corrosion, adding fly ash or latex could help (Berard *et al*., 2009).

2. GEOTHERMAL CEMENT DESIGN CONSIDERATION

Cementing in geothermal wells is more complex than ordinary oil and gas wells. Bottom hole temperature could reach 400 °C sometimes creating some failure in the cementing process. Cement systems for geothermic environments are normally designed to have a compressive strength of at least1000 psi and possess no more than 0.1 mD water permeability (API Task Group on Cements for Geothermal Wells, 1985). The formation waters are often highly saline, corrosive and contain toxic heavy metals; as a result, the set cement must be designed to be resistant to degradation of saline brines and any other destructive chemicals.

2.1 Portland Cement

Silica stabilized Portland cement is a typical cement system used in geothermal well, yet there isa cement system that is more resistant to destructive chemical environments. At the time of Portland cement designed for use in corrosive environments and high levels of salt brines, the addition of silica is very important. In cementing there are three types of silica; *silica sand* (175-200 µm particle size), *silica flour* (±15 µm particle size) and *silica fume* (0.1 µm particle size). Silica sand is easier to mix since it has lower surface area; however, in geothermal applications, silica sand cannot provide stability, the preference is to use silica flour.

Grabowski and Gillott (1989) and Dillenbeck *et al*. (1990) created a graph (Figure 6) that showed the compressive strength and permeability behavior of a silica-stabilized Portland cement system containing various amounts of silica fume, which developed less compressive strength but lower permeability compare to cement system containing silica flour. The studies were carried out using approximately 0.1 µm particle sizes and a curing temperature at 230 °C at 400 psi.

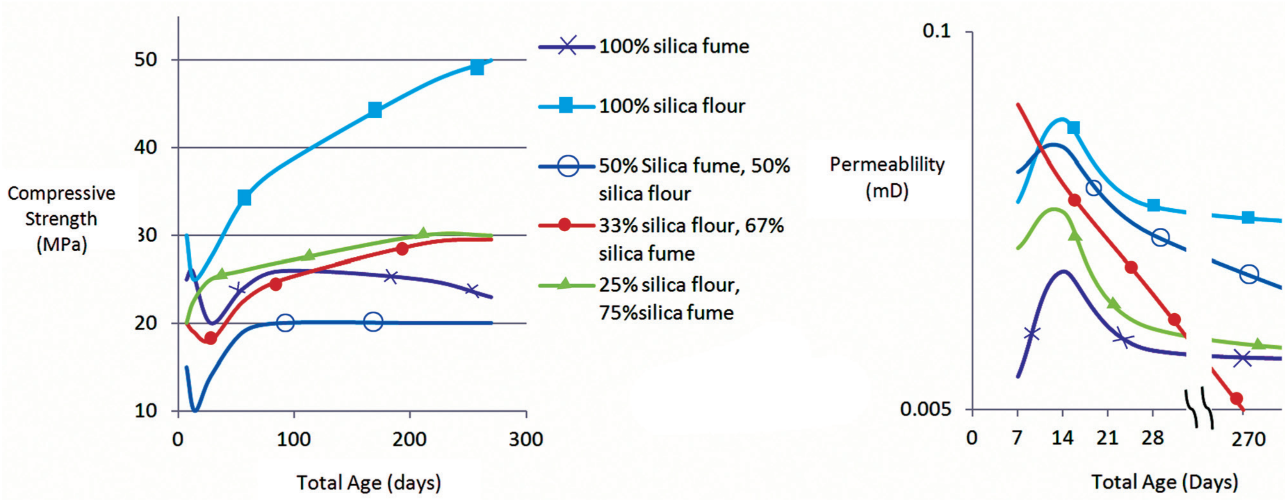


Figure 6
Effect of Compressive Strength and Permeability Behavior of Silica-Stabilized Portland Cement System, Containing Various Amounts of Silica Fume (After Grabowski and Gillot, 1989)

Nelson and Eilers (1979) investigated a 15.8 lbm/gal slurry density that performed a reduction in compressive strength and increase in water permeability at the time of the addition of silica above 15 µm particle size. With lower density, 13.5 lbm/gal class G perlite-bentonite cement systems, which cured in geothermal brine showed that different silica particle sizes give significant effects to the cement performance, compressive strength, and water permeability as seen in Figure 7.

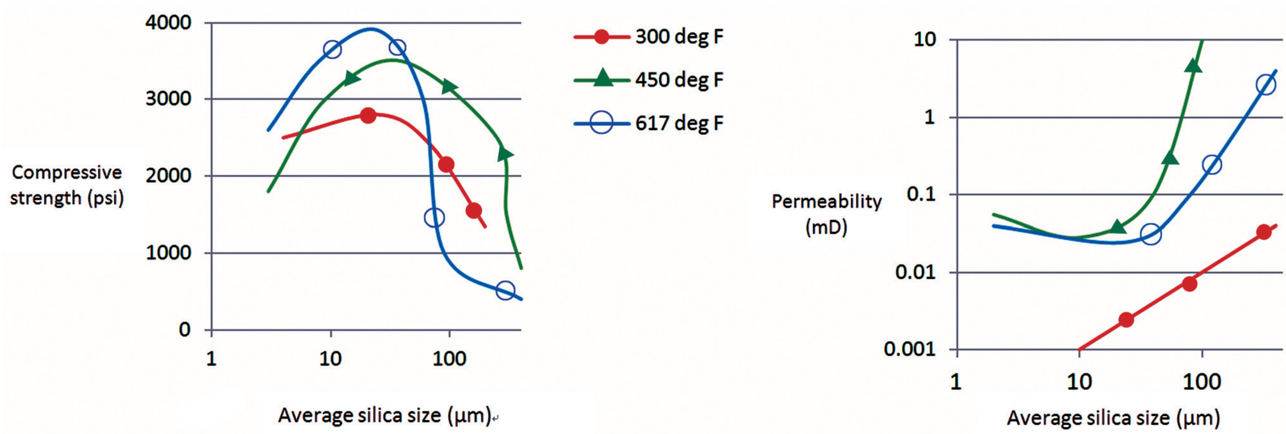


Figure 7
Effect of Silica Particle Size on 13.5 lbm/gal Vlass G Perlite-Bentonite, Cement System in Geothermal Brine (Eilers and Nelson, 1979)

The high concentration of sodium chloride will reduce the ability of silica to dissolve in a mixture. By reducing the size of silica particles the surface area will expand, allow the formation of the desire calcium silicate hydrates. The presence of carbonate in certain geothermal brines presents a serious difficulty for Portland cement systems (Milestone *et al*., 1986). Calcium silicate hydrates are not stable in such a chemical environment, even at an ordinary temperature (Taylor, 1964). High alumina cement is also known to degrade in the presence of carbonate (Crammond and Currie, 1993).Geothermal wells typically have a low fracture gradient; therefore, low density cement is one of the ways to solve the problem. Gallus *et al*. (1979) mentioned that silica flour usually is added for stability to low density cement, up to 100% BWOC (By Weight of Cement). Ultra-low density foamed cement and microsphere-extended systems also have been used to cement geothermal wells as well. They are used in formations that have an aggressive fluid such as corrosive brines.

2.2 Alternate Cement

An alternate cement composition for geothermal wells is calcium phosphate or calcium aluminosilicate, both are resistant to CO_2. The life of calcium phosphate is up to 20 years (Weber *et al*. 1998; Brookhaven National Laboratory, 2000), and it has been used in Japan and Indonesia from 1997. Cement system compositions that have been used include: fly ash, calcium aluminate cement, sodium polyphosphate, and water. The composition varies with the depth at which the cement will be used (Nelson and Gouedard, 2006).

The calcium aluminosilicate system is a newly developed cement system (Barlet-Gouedard and Vidick, 2001; Barlet-Gouedard and Goffe, 2002). Synthetic Cements are used in CO_2 flooding projects or chemical waste disposal, but they are weak polymers against corrosive brines. Epoxy based polymer systems often are used near the surface, not deeper than that since the temperature cycle in a geothermal well will create thermal degradation. Organosiloxane polymer cement has proven stability at the high temperature and was used as geothermic cement in an API Study (Zeldin and Kukacka, 1980). Degouy and Martin (1993) demonstrated phenolic resins with fillers such as calcium carbonate and sand provided acceptable performance at curing temperatures up to 150 °C.

3. TECHNOLOGY AND SOLUTION

3.1 Light Weight Cementing

A lost circulation could lead a stuck pipe event and the more dangerous, it can lead to blow out and certainly a non-productive time will be generated. Proper well trajectory, hole angle, insitu-stresses and pore pressure prediction should be planned ahead. Implementing light-weight cement could be a way to prevent these problems.

3.1.1 Foam Cementing

Geothermal wells were usually not drilled too deep and often intersected with the weak formation. Therefore, the most common problem related with them is lost circulation. A lighter density foam cement could prevent lost circulation while pumping the cement. Another reason for choosing foam cement is, when under high temperature, conventional Portland cement has poor tensile strength and is brittle. It could crack or buckle and is not resistant to CO_2. In foam cement, nitrogen is injected into the ready-mix cement slurry in order to produce low-density cement. Rozleres and Ferriere (1991) mentioned that, with laboratory equipment, foam cement can be mixed and characterized at representative filed conditions with a density as low as 4 lb/gal. Brookhaven National Laboratory asserted that milled carbon microfibers give more strength and are more resistant to ductility. Increasing or decreasing the amount of nitrogen is the way to control foam cement density.

3.1.2 Glass Bubbles

If the lost circulation is above the production zone, it will make the cement job more complex, as we have to isolate the production zone from upper intervals. Often the casing was set above the target zone or sometimes losses occurred before we reached the setting point. Therefore, some of the geothermal wells have no option, other than using glass bubbles as the light-weight cement system. The density with glass bubbles can be lower than water, and a particle size of glass bubble is around 75 microns. Type and density of glass bubbles are very diverse and depend on the hydrostatic pressure rating requirement. Smith, Powers and Dobkins (1980) shown to make 13 lbm/sack, 9.5 lbm/gal slurry should be mixed with 14 % low strength bubbles. Generally, glass bubbles which make highest density are the weakest. Increased pressure will decrease the slurry yield and break some of the bubbles, which will cause an increase in density.

Cement slurry using glass bubbles could reach 7.5 lbm/gal, but field tests conducted by Smith, Powers and Dobkins showed that to achieve the desired water permeability at least 9.5 lbm/gal was needed. Glass bubbles are available commercially in two different grades, grade 1 and grade 2. They are stronger, have a higher collapse pressure and are more expensive. Depending on the grade, lightweight slurries can preserve their desire properties only when the head hydrostatic does not exceed 2000 psi. To avoid strength retrogression in geothermal temperatures, at least 26% silica must be added into the system. If not, the glass bubbles will react with the cement creating disintegration of the bubbles and raising the permeability (Erik *et al*., 1981).

Since the glass bubbles are made of silica, under high temperatures of around 300 °F, the slurry gives constant compressive strength (Suman and Ellis 1977; Eliers and Root 1974). The thickening time also can be adjusted by the amount of water or calcium chloride. To reduce the density, the amount of water to be added to the glass bubble slurry is less than in a normal slurry. The strength will be higher and generate faster, compare to another light-weight cement, which means a decrease WOC.

3.2 Latex

In high thermal wells, expanding and shrinking of cement sometimes can occur, which may cause a gas migration problem. Latex slurry could be a cement additive to avoid a gas migration. Besidesthat, it has low fluid loss and could improve bonding. Latex slurry has anti gas invasion properties, if the gas invasion occurs, latex will form an impervious film with some strength to prevent gas migration into the slurry as well as up through the annulus(Fuquan *et al*., 2006). In an acidic environment, Latex would give the resistance.

3.3 Cementing Lost Circulation Fibers

As discussed above, geothermal wells often face fracture zone. Normally, in fracture zone, losses are encountered, and it will be more severe during cementing work. During cementing, cementing lost circulation fibers (CLCF) material could help form a bridging network in the loss zone and subsequently restore the circulation. CLCF can be designed to be placed only at the loss zone and can be added directly to the cement mix tank or *on the fly*, without disturbing the desired cement properties. By adding these fibers into a cement system, there will be no extra cement to be prepared for anticipated losses. This will reduce cement waste and eliminate cement disposal cost. Figure 8 shows how CLCF form a bridging network to help resume a circulation (Schlumberger and CemNet, 2002).

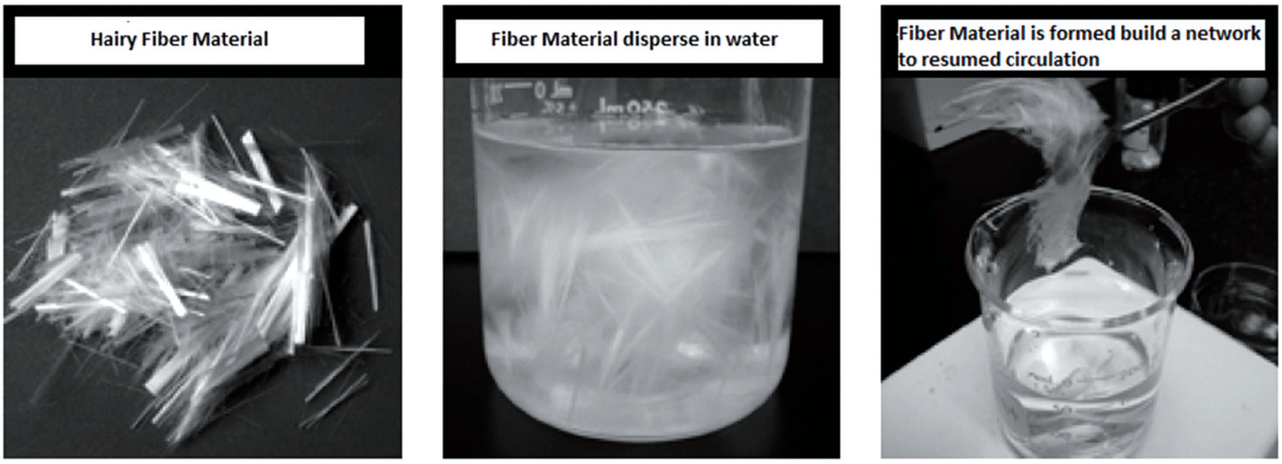


Figure 8
Cementing Loss Circulation Fiber Material's Ways of Working

3.4 Reverse Cementing

For a normal cement job, cement was pumped from the surface through the drillpipe, goes down and once passes the casing shoes the direction of flow changed to rise. Fill the formation and casing annulus until the desired zone cemented. A normal cement job needs horsepower to pump the cement slurry. When facing a massive lost circulation, wherever possible, reduces the circulation pressure to prevent more losses. Reverse cementing as used in central Wyoming and central California is another method to do a cement job. The slurry is pumped down through an annulus and return, trough inside casing. With the help of gravity, this could minimize pressure against the formation, as can be seen in Figure 10 (Moore *et al*., 2005).

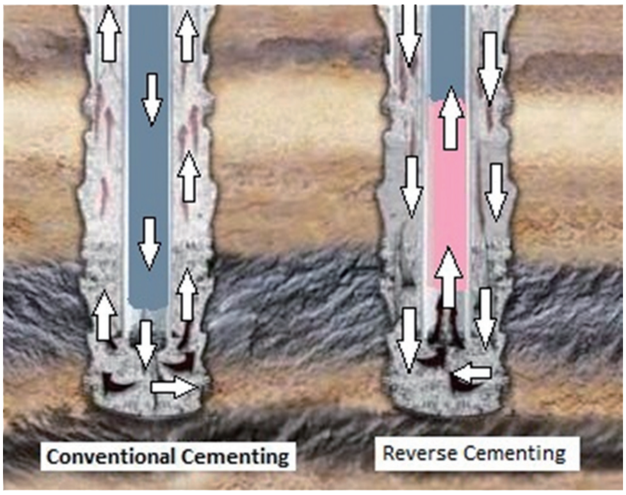


Figure 10
Reverse Cementing

Reverse cementing could be done with two techniques: the cement slurry pumped through the annulus then returned to the surface through the *casing* or through the *string / inner string method* (stabbed to the float collar/shoe, placed inside casing). Sticking the string to the casing shoe or collar with a flapper valve is very effective. After the cement job, flapper valve can omit cement inside the casing and can release pressure inside the casing while waiting for the cement to set. But additional time is needed to run the stabbing string and friction pressure will increase because of smaller strings. On reverse cementing, once the cement reaches the bottom of the wanted zone, trace will be found on the surface, the mixing and pumping of cement can be stopped, which could minimize the excess of cement. However, there is not much choice of tracer material that is environment friendly. Regarding no displacement in reverse cementing as in normal cementing, cement placement time will be diminished. A retarder should not be added to the cement slurry as it will reduce waiting on cement and save a rig time.

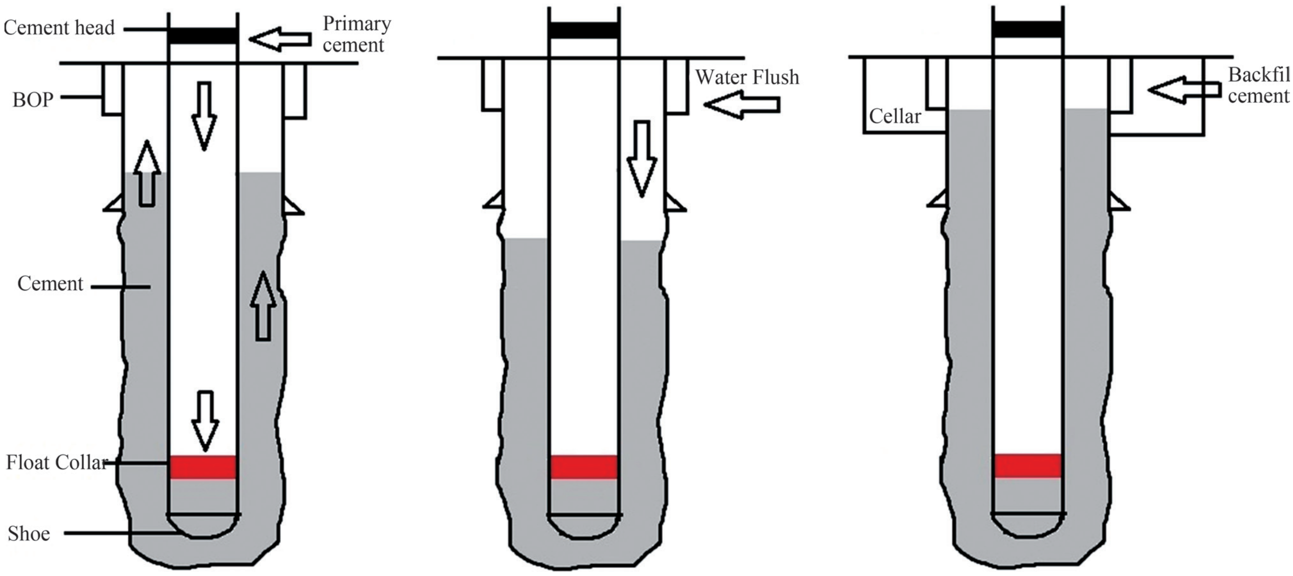
When the cement is pumped through the annulus, problem such as a part of the annulus is not cemented, can arise. To avoid these risks, trough the casing, we need to wait for the cement to return to the surface. This will take time and increase cost. If the return rises through the casing, pressure inside casing cannot be taken until the cement sets, as float equipment to perform this case is not available. At the time of running casing, circulation or fluid control is required by using a dual direction float-valve system. When the cement is cured, leaving the pressure inside the casing will trigger the microannulus; using foam cement will give flexibility in such circumstances.

3.5 Mechanical Barriers

A polymer sleeve or external casing packer could be used to reduce the hydrostatic pressure at the shoe. By setting the sleeve or packer outside the casing, it will split the annulus column into two. Apart from, that swellable rubber sleeves which expand by absorbing the water could be an alternate option. The concern will be the setting hydraulic system. With the losses, normally the borehole shape is irregular and most of the time LCM materials stick to the borehole. Packer or sleeve size should be considered to prevent sticking on the liner.

3.6 Plugback Cementing

During or after the primary cement operation, if there is no cement returning to the surface, sometimes water is suspended between casings. This requires to straight up cleaning the annulus as much as two times of the volume of annular. After the previous cement set, then continued with a several times cement backfilling until we get cement return on the surface. This technique showed 100% success in fifty seven Kenya geothermal wells. The cementation process can be seen in Figure 11.



1. Conventional Primary Cement **2. Water Flush Trough Annulus** **3. Backfill Cement Trough Annulus**

Figure 11
Flushing and Backfill Cement

Macaroni string is often used in plugback cementing (Figure 12). Macaroni string could be a small inside diameter (ID) drillpipe or tubing. It commonly is used at the time of loss circulation, in the well with large casing size. As in conventional primary, spacer or chemical wash was pumped before and after the cement slurry, to avoid cement contamination from mud. To be on the safe side, the operator usually designs the cement to be under displaced. If the plug shows balance, the pipe can be pulledout to circulateout of the excess cement. Special caution should be given to a plugback technique, especially in the top job operation, since the use of the macaroni string will produce a high friction pressure.

For a workover rig, a dump bailer could be used as one of the cement plug techniques. This tool can easily control the depth where we want to set a cement plug. But dump bailer can take only a little amount of cement, so that multiple runs should be made. It is run with wireline and it is opened once it touches the bridge plug, then cement will start to fill along with the toll drown out as can be seen in Figure 13.

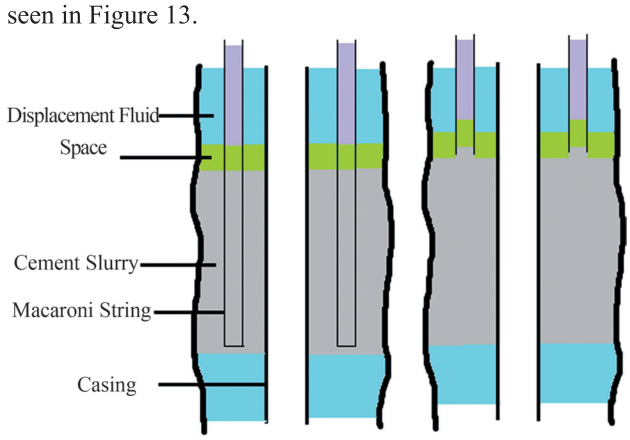


Figure 12
Plugback with Macaroni String

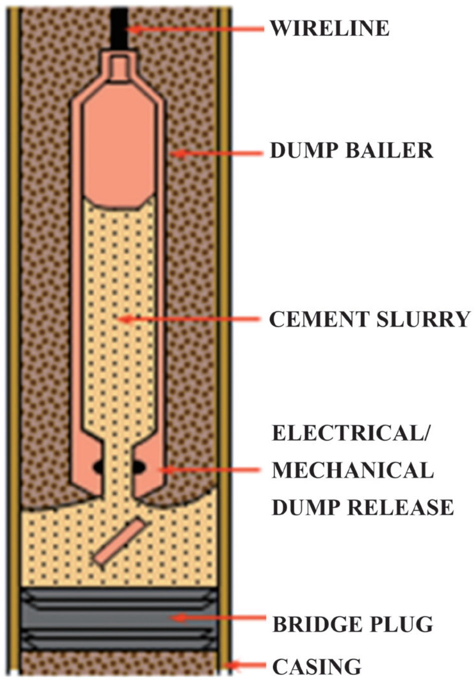


Figure 13
Dump Bailer

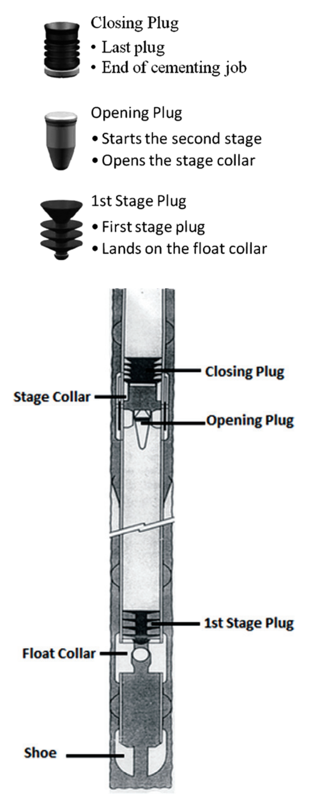
3.7 Two-Stage Cementing

When unconsolidated or loss areas need to case off and avoid long exposed cement, one of the ways to do is to use a multi-stage method. This procedure can reduce costs by having different densities of cement or leave some part un-cemented. In two-stage cementing, there are two techniques that could be used: each stage is performed in a separate operation or when both stages are performed continuously. A summary of the procedure of two-stage cementing can be seen in Table 3.

Stage collar as seen in Figure 9, is the tool that will divert the cement flow after the first stage. Opening the port of the stage collar could be done mechanically (drop the opening plug which falls by gravity) or hydraulically (apply pressure to displacement fluid). A proper calculation of the slurry volume is required; therefore, a caliper log is necessary. Special attention for using a stage collar is at the time it fails to open or pin to open the port did not shear. There are several reasons why it's happened, one of which is the opening plug might not seat; therefore, we have to wait until it arrives or increases the pressure. If still not been open, then we should use the drill pipe to help open the port. If this step fails to open the port, consequently, above the collar should be perforated.

Table 3
Two Stage Cementing

Separate Operation	
1st Stage	2nd Stage
● Mud circulation ● Pressure test ● Pump wash and/or spacer ● Pump 1st slurry ● Drop 1st plug ● Displace until 1st plug seated in float collar ● Bleed off and check returns	● Drop opening plug until it seated in stage collar (fall by gravitythe opening plug seated, pressure is applied to shear the pin which opening the ports, indicated by the pressure drop suddenly) ● Mud circulation ● Pump wash and/or spacer ● Pump 2nd slurry ● Drop closing plug and displace until it seated and close the stage collar ● Bleed off and check returns
Continuous Operation	
● Mud circulation ● Pressure test ● Pump wash and/or spacer ● Pump 1st slurry ● Drop wiper plug ● Displacement ● Drop opening plug ● Pump 2nd slurry ● Drop closing plug ● Displace until opening plug seated in stage collar and displace slurry through the port, then land ● closing plug to close the plug ● Bleed off and check returns	



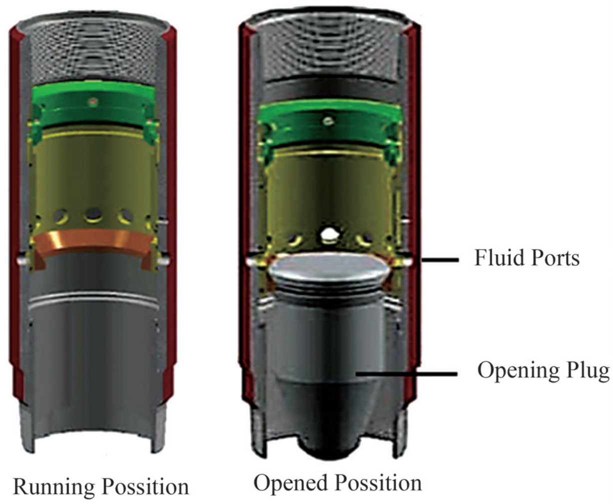


Figure 9
Stage Collar

Related to casing integrity, Mukhalalaty, Al-Suwaidi and Shaheen (1999) mentioned that the point where the stage collar is seated is the weakest point in the string and could cause a casing leak. Bending stress, repetition on opening and closing, and chemical / other hazardous material exposure, can lead to leaks in the seal's port. Some other critical considerations are to control circulation pressure, allow enough thickening time, and slow pumping while 1st stage plugs pass the stage collar.

3.8 Proper Cementing Preparation

Preparation stages such as cleaning the hole, mud conditioning, and mud displacements are some of the factors determining the success of the cement job. Failure to have good mud removal could cause an inter-zonal communication, gas migration, casing corrosion, and short term zonal isolation. Jones and Berdine (1940) proposed to centralize the casing to minimize cement channeling and fluid jets, scrapers or scratcher, casing reciprocation or pumping acid ahead of the cement slurry to remove mud cake.

3.8.1 Borehole

When the well was drilled poorly or has irregularities, most likely a washout zone has formed, which is difficult to clean. A crooked well makes casing centralizer hard to get in the wellbore, as well as removing mud in the narrow side of the annulus. An irregularity's borehole will give a space to unwanted dirt to sit. Swell and Billingsley (2002) find an effective method to bring cuttings out of wellbore is by pumping a viscos fluid with rotating pipe between 150-200 rpm.

3.8.2 Mud Conditioning

Mud is used to support wellbore hydrostatic pressure and to provide a good transport cutting. Reducing mud density in a minimum wellbore pressure limit, and/or reducing mud gel strength, yield stress and plastic viscosity will help displacement mobility. Caution is needed to keep the weighting agent from settling; otherwise, the control of density will be lost. To avoid mud to gel and filter cake, before removing the drill pipe, logging or running casing is recommended to have circulation for one borehole volume. After the casing is set, it is required to have at least one "bottoms up" and as much as one annular volume (Daccord *et al*., 2006). Mud conditioning will help clean the hole and remove influx if there is any gas flow. Turbulent flow generally gives higher circulation efficiencies than those for laminar flow. To achieve mud moving completely around the annulus; improving pipe standoff, reducing gel strength, increasing μ_p / τ_y ratio and increasing flow rate should be done.

3.8.3 Eccentricity

When the pipe inside the borehole is not centered, velocity across the pipe will distort and tends to flow into the larger side. This phenomenon will create a laminar flow on the narrow side and turbulent flow in the wider side. When the flow through the annulus is laminar, the effect of eccentricity will divert from calculated velocity. An acceptable standoff in oil industry is at least around 75%. From the experiment done by Daccord, Guillot and Nilsson (2006), fluid models will give different effects to circulation efficiency, as shown in **Table 4.** For Bingham Plastic fluid, after one hole volume, circulation efficiency is more sensitive to standoff than dimensionless shear rate (ξ) as can be seen in Figure 14.

Table 4
Things That Affecting Circulation Efficiency for Different Fluid Models

Fluid Models	Affecting Circulation Efficiency
Newtonian	- Pipe standoff - Volume pumped
Power Law	- Pipe standoff and - Power law index
Bingham Plastic	- Pipe standoff - Dimensionless shear rate

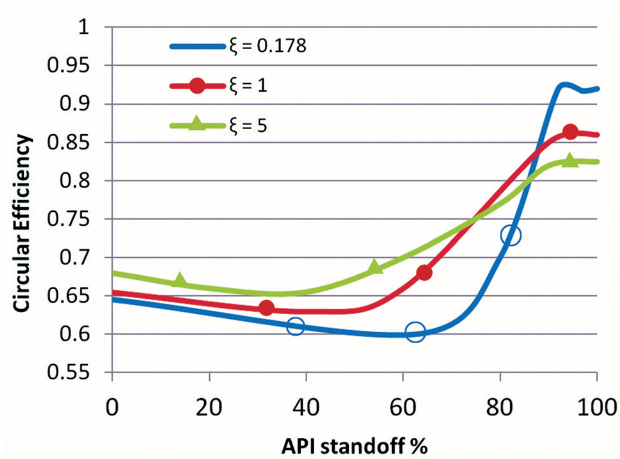


Figure 14
Circulation Efficiency with Sensitivity to ξ and Standoff

3.8.5 Gelled Mud

Drilling mud is designed to have good thixotropic gel strength properties to suspend cuttings and weighting agent once the pump is stopped. However, once the mud is allowed to gel, the force required to be overcome is no longer the yield stress, but will be the gel strength. Poor wellbore (washout) and casing eccentricity in circulation time, can create zones in which the velocity is zero, this phenomenon is known as *immobile mud.* If this mud is left in the hole after cement placement, the mud may dehydrate and shrink while the cement is set, leaving an empty space letting any gas or fluid to flow into. Normal gel strength test will consider one time reading for a maximum of 10 minutes rest, which was briefer than those which occurred within the field and could be several hours or days.

3.8.6 Mud Cake

When mud is passing through the permeable zone, once the pump is stopped, it tends to change over from dynamic filtration to static filtration which grows a mud cake. During circulation, mud cake thickness is likely to be larger at the narrow side of the annulus. If we left the mud cake after cement placement, it would dehydrate which is the same behavior as with immobile mud. The major difference is mud cake will not form on impermeable caprock layers. It makes mud cake less critical when associated with zonal isolation problems, however, is more critical to differential sticking problems.

3.8.7 Solid Beds

Solid beds usually are found in horizontal or highly deviated wells. They normally occur over long intervals, making it more harmful than mud cake. Bern et al (1998) found barite beds can be readily dispersed with a combination of high-flow rates and drill pipe rotation. Johnson et al. (1992) and Becker and Gardiner (2000) observed that the particles could break some part of the solid layer, as in flow loop tests of gravel placement or sand blast. Abrasion also can be achieved by scratchers fastened to the casing or by fluid jets directed perpendicular to the layer.

Solid beds are permeable as some flow can take place through them; however, this may weaken the bed with fluidization mechanism and increase the lift force on individual particles (Cho *et al*., 2001). Chemical or physico-chemical methods; which include acids, chelating agents, surfactants, dispersants, and oxidizers can be used for solids removal. This will occur when spacers and washes are pumped into the annulus. Various filter cake, and solid removal mechanism are summarized in Table 5 (Daccord *et al*., 2006).

Table 5
Summary of Cleaning Mechanism for Mud Cakes and Solid Beds

Domain Application	Mechanism	Flow
Mud circulation and displacement	Erosion by shear instability of interface	Wall shear stress
Mud circulation and displacement	Erosion by pressure fluctuations, rupture in tension	Reynolds number
Backflow during completion operations	Pinholing or peeling	Differential pressure
Completion operations, mud displacement	Weakening of layer mechanical properties, dissolution	Chemical composition, duration of treatment
Hole cleaning	Fluidization, increase in lift force	Pressure gradient
Gravel pack placement Cutting transport and corresponding hole cleaning	Abrasion by suspended particles	Inertia of particles

3.8.8 Casing Movement

On deviated and vertical hole, rotating or moving the drill string by reciprocating may help clean the cuttings out of the borehole. Sanchez *et al*. (1999) mention that it is the orbital motion and not the rotation that improves hole cleaning. Together with scratchers, scrapers and cable wipers, casing movement mechanically erodes the filter cake and improves the displacement process. Other techniques to remove a mud deposit include jetting using a specific pipe shoe (Way *et al*., 2000), vibrating the casing during circulation by rotating the casing at high speed (Sutton and Ravi, 1991), reverse circulating and special hardware placed around the casing to generate turbulence (Kinzel and Martens, 1998). Best practice is to start the movement during mud conditioning.

3.8.9 Mud Circulation Efficiency

By using carbide pills, Smith (1990) recommends, the flow rate and the circulation time were designed under the assumption that 95 % of the calipered hole volume was circulating. His measurement (Figure 15) led him to recommended circulated velocity in excess of 76.2 m/min. This circulation should be maintained until the caliper shows 90 % of the borehole volume is in circulation.

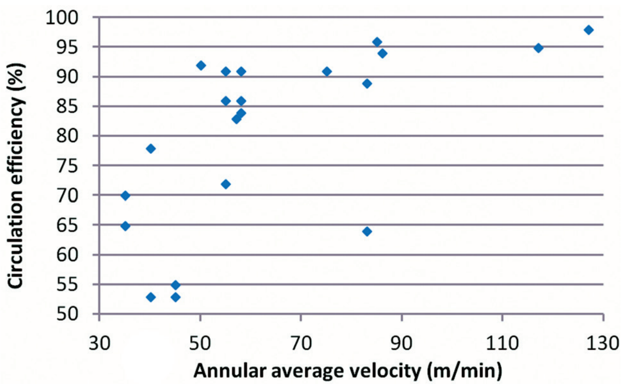


Figure 15
Effect of Annular Velocity on Circulation Efficiency

In some circumstance circulation bottoms up is insufficient for a mud removal. A better approach is to measure the mud circulation efficiently (Smith, 1984). Figure 16 shows a fluid caliper and tracer concept used to determine mud-circulation efficiency; a small volume of mud marked with tracer is pumped through the wellhead. The time for the tracer to return to the surface indicates the volume of mud that has been circulated and then this volume compared with the result of caliper measurement. Tracer could be inert particles (rice, oats), dyes, radioactive material, chemical tracers, or reactive materials. The detection can be visual by monitor particles in the shale shaker or chemical. These techniques only can give the qualitative result; the quantitative result needs a continuous monitoring of the tracer and proper interpretation to conclude average circulation velocity.

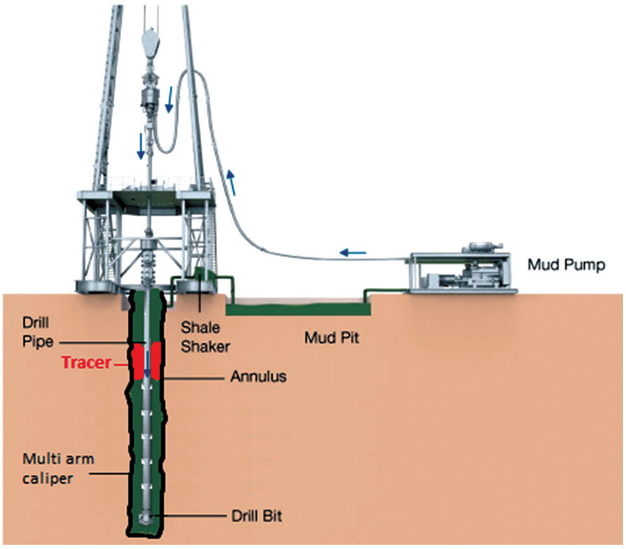


Figure16
Fluid Caliper Concept Used to Determine Mud-Circulation Efficiency

Surface and downhole pressure measurement could indicate the hole cleaning condition. Ravi et al (1993) and Griffith (1995) performed measurement of surface pressure, together with continuous measurement of fluid rheology, density, and flow rate could determine the efficiency. Hutchinson and Rezmer-Cooper (1998) showed that annular pressure while drilling could determine the hole cleaning condition and mud solid carrying capacity.

SUMMARY AND CONCLUSION

With the increasing energy needs among the world's population, geothermal energy could be one of the resources to fulfill this demand. However, high-temperature environments cause challenges for the cementing operation. A few things to note on cementing geothermal wells:

(1) Problems which usually arise in geothermal wells include; high temperature, lost circulation, thick filter cake, and CO_2 attack.

(2) Cement design must be considered carefully;
  a) If there are brines, Portland cement should be stabilized by adding fine silica flour.
  b) If there are high levels of CO_2, it is necessary to use an alternatecement system by using calcium phosphate or calcium aluminosilicate.If using Portland cement to inhibit the degradation, it is required to reduce the silica concentration to 20% BWOC.

(3) Technology has evolved to avoid the above problems, lost circulation problems prevented by using light weight cement such as; foam cement or glass bubbles. Use of Latex is good for expanding and shrinking cement. If lost circulation has occurred, cementing-lost-circulation-fibers can provide sealing by forming a network across this loss zone.

(4) Some of the techniques to case off loss area or avoid long exposed cement include: reverse cementing, mechanical barriers, plugback cementing or multi-stages cement job.

(5) To prevent a differential sticking due to thick filter cake or to get a decent bond between cement-casing and cement-formation, it is required to have a proper cementing preparation such as good borehole, mud conditioning, eccentricity, gelled mud, mud cake, solid beds, casing movement and mud circulation efficiency.

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REFERENCES

[1] Abdul-Rahman, R., & Chong, A. (1997). Cementing Multilateral Well With Latex Cement. Presentation at the *1997 SPE/IADC Drilling Conference*, 4-6 March, 1997, Amsterdam, The Netherlands.

[2] Al-Yami, A. S., Nasr-El-Din, H. A., Al-Humaidi, A. S., Al-Saleh, S. H., & Al-Arfaj, M. K. (2010). Evaluation and Optimization of Low-Density Cement: Laboratory Studies and Field Application. *SPE Drilling and Completion*, *25*(1), 70-89.

[3] Alotaibi, M. B., Nasr-El-Din, H. A., Hill, A. D., & Moajil, A. M. (2010). An Optimized Method To Remove Filter Cake Formed by Formate-Based Drill-In Fluid in Extended-Reach Wells. *SPE Drilling and Completion*, *25*(2), 253-262.

[4] Anderson, J. W., Buchanan, A. I., & Susanto, A. (1996). New Technology Improves Cement Slurry Design. Presentation at the *1996 SPE Asia Pacific Oil and Gas Conference*, 28-31 October 1996, Adelaide, Australia.

[5] API Work Group Reports Field Tests of Geothermal Cements. (1985). API Task Group on Cements for Geothermal Wells. *Oil and Gas Journal*, Feb. 11, 93-97.

[6] BBC. (2013). *Geothermal Energy*. Retrieved from http://www.bbc.co.uk/schools/gcsebitesize/science/aqa_pre_2011/energy/mainselectricityrev5.shtml. Downloaded January 2013

[7] Barlet-Gouedard, V., & Goffe, B. (2002). *Cementing Compositions and Application of These Compositions to Cementing Oil Wells and the Like*. Patent PCT WO 01/70646, 2002.

[8] Barlet-Gouedard, V., & Vidick, B. (2001). A Non-Conventional Way of Developing Cement Slurries for Geothermal Wells. *Transactions of the Geothermal Resources Council Annual Meeting*, Davis, California, USA, 2001.

[9] Becker, T. E., & Gardiner, N. H. (2000). Laboratory Modeling of Mudcake Application and Erosion for Gravel-Pack Design in Horizontal Wells. *SPE Drilling Completion*, September, 2000.

[10] Bern, P. A. *et al*. (1998). Barite Sag: Measurement, Modeling and Management. IADC/SPE 47784 was Presented at the *1998 IADC/SPE Asia Pacific Drilling Conference*, 7-9 September 1998, Jakarta, Indonesia.

[11] Bernard, B., Hernandez, R., & Nguyen, H. (2009). Foamed Calcium Aluminate Phosphate Cement Enables Drilling and Cementation of California Geothermal Wells. SPE 120845 was Prepared for Presentation at the *2009 SPE Western Regional Meeting*, 24-26 March 2009, San Jose. California, USA.

[12] Brookehaven National Laboratory. (2000). Brookhaven Lab, Halliburton Company and Unocal Corporation Win R&D 100 Award for High Pergormance Cement. Retrieved March 9, 2007, from http://www.bnl.gov/bnlweb/pubaf/pr/2000/bnlpr080200.html

[13] Cho, H., Shah, S. N., & Osisanya, S. O. (2001). Effects of Fluid Flow in a Porous Cuttings-Bed on Cuttings Transport Efficiency and Hydraulics. SPE 71374 Presented at the *SPE Annual Technical Conference and Exhibition New Orleans*, Louisiana, USA, September 30 – October 3, 2001.

[14] Crammond, N. J., & Currie, R. J. (1993). Survey Condition of Precast High-Alumina Cement Components in Internal Locations in 14 Existing Buildings. *Magazine of Concrete Research*, *43*(165), 275-279.

[15] Daccord, G., Guillot, D., & Nilsson, F. (2006). *Mud Removal* (Well Cementing 2nd edition).

[16] Degouy, D., & Martin, M. (1993). Characterization of the Evolution of Cementing Materials After Aging Under Severe Bottomhole Conditions. *SPE Drilling & Completion*, *8*(1), 57-63.

[17] Denny, D. (2005). *Technology Application*.

[18] Dickson, M. H., & Fanelli, M. (2012). What is Geothermal Energy? Retrieved from www.geothermal-energy.org/314.what_is_geothermal_energy .html

[19] Eilers, L. H., Nelson, E. B., & Moran, L. K. (1983). High Temperature Cement Composition–Pectolite, Scawtite, Truscottite or Xonotlite: Which Do You Want? First Presented at the *1980 SPE Annual Technical Conference and Exhibition*. Dallas, Sept, 21-24.

[20] Eilers, L. H., & Root, R. L. (1974). Long Term Effects of High Temperature on Strength Retrogression of Cements. SPE 5028 was Prepared for the *49th Annual Fall Meeting of the Society of Petroleum Engineers of AIME*. Huston Texas, October 6–9, 1974.

[21] Feng, Z. Z., Njee, J. M., Min, H., Ming, S. A., Min, Z., & Sheng, S. F. (2012). Successful Implementation of HT Geothermal Drilling Technology in Kenya. IADC/SPE 155831 was Prepared for Presentation at the *IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition*. Tianjin, China, 9-11July, 2012.

[22] Finger, J., & Blankenship, D. (2010). Handbook of Best Practices for Geothermal Drilling. Sandia Report SAND2010-6048, *Sandia National Laboratories*. December, 2010, California.

[23] Fuquan, S., Guangming, L. V., & Jianzhou, J. (2006). Application and Research of Latex Tenacity Cement Slurry System. SPE 104434 was Prepared for Presentation at the *2006 SPE International Oil & Gas Conference and Exhibition*. Beijing, China, 5-7 December, 2006.

[24] Gallus, J. P., Pyle, D. E., & Moran, L. K. (1979). Physical and Chemical Properties of Cement Exposed to Geothermal Dry Steam. SPE 7876 was Presented at the *1979 SPE of AIME International Symposium on Oilfield and Geothermal Chemistry*. Huston, Texas, 22-24 January, 1979.

[25] Gallus, J. P., Watters, L. T., & Pyle, D. E. (1978). Performance of Oilwell Cementing Compositions in Geothermal Well. SPE 7591 was Presented at the *SPE AIME 53rd Annual Fall Technical Conference and Exhibition*. Huston, 1-3 October, 1978.

[26] Gaurina, N., Medimurec, D., Matanovic, D., & Krklec, G. (1994). *Cement Slurries for Geothermal Wells Cementing*. Croatia: Faculty of Mining, Geology and Petroleum Engineering.

[27] Geohil, A. G. (2013). *Geothermal Energy*. Retrieved from http://www.mpoweruk.com/geothermal_energy.htm

[28] Ghori, KAR. (2006). *The Search for Western Australia'S Geothermal Resources*. Technical papers, Annual Review 2006-07.

[29] Griffith, J. E., & Ravi, K. M. (1995). Monitoring Circulatable Hole with Real-Time Correction: Case Histories. SPE 29470 Presented at the *Production Operations Symposium*. Oklahoma, Oklahoma, USA, April 2-4, 1995.

[30] Hedenquest, J. W., & Stewart, M. K. (1985). Natural Co2-Rich Steam Heated Waters in the Broadlands-Ohaaki Geothermal System, New Zealand: Their Chemistry Distribution and Corrosive Nature. *Geothermal Resources Council, International Symposium Energy*. Hawaii, August 26, 1985.

[31] Hutchinson, M., & Razmer-Cooper, L. (1998). Using Downhole Annular Pressure Measurements to Anticipate

Drilling Problems. SPE 49114 was Presented at the *SPE Annual Technical Conference and Exhibition*. New Orleans, Louisiana, USA, September 27-30, 1998.

[32] International Geothermal Association. Installed Generating Capacity–Electric Generation. Retrieved from http://www.geothermal-energy.org/226,installed_generating_capacity.html

[33] Johnson, M. H., Ashton, J. P., & Nguyen, H. (1992). The Effects of Erosion Velocity on Filter Cake Stability During Gravel Placement of Openhole Horizontal Gravel-Pack Completion. SPE 23773 was Presented at the *SPE International Symposium on Formation Damage Control*. Lafayette, Louisiana, USA, February 26-27, 1992.

[34] Jones, P. H., & Berdine, D. (1940). Oil Well Cementing: Factors Influencing Bond Between Cement and Formation. *API Drilling and Production Practices*. Washington, D.C., USA, American Petroleum Institute, March 1940.

[35] Jones, R. R., & Carpenter, R. B. (1991). New Latex, Expanding Thixotropic Cement Systems Improve Job Performance and Reduce Cost. SPE 21010 was Prepared for Presentation at the *SPE International Symposium on Oilfield Chemistry*. Anaheim, California, February 20-22, 1991.

[36] Kalousek, G. L., & Chaw, S. Y. (1976). Research on Cements for Geothermal and Deep Oil Wells. SPE 5940 was Presented at the *SPE-AIME 51st Annual Fall Technical Conference and Exhibition*. New Orleans, 3-6 October, 1976.

[37] Laws, M., Riaymi, A., & Soek, H. *et al*. (2006). Special Cement System and Cementing Techniques Improve Zonal Isolation in South Oman Fields. SPE 102414 was Prepared for Presentation at the *2006 SPE Annual Technical Conference and Exibition*. San Antonio, Texas, USA, 24-17 September, 2006.

[38] Milestone, N. B., Sugama, T., Kukacka, L. E., & Caricello, N. (1986). Carbonation of Geothermal Grouts-Part 1. *Cement and Concrete Research*, *16*, 941-950.

[39] Moore, R., Bour, D. L., Reed, S., & Hernandez, R. (2003). High-Temperature Wells with Lost-Circulation Demands and Reverse Circulation Placement Technique Using Foamed Cement System: Two Case Histories. SPE 84563 was Prepared for Presentation at the *SPE Annual Technical Conference and Exhibition*. Denver, Colorado, USA, 5-8 October, 2003.

[40] Moore, R., Bour, D. L., Reed, S., & Hernandez, R. (2005). High-Temperature Wells with Lost-Circulation Demands and Reverse Circulation Placement Technique Using Foamed Cement System: Two Case Histories. *SPE Annual Technical Conference and Exhibition*. 5-8 October 2003, Denver, Colorado.

[41] Mukhalalaty, T., Al-Suwaidi, A., & Shaheen, M. (1999). Increasing Well Life Cycle by Elimination the Multistage Cementer and Utilizing a Light Weight High Performance Slurry. SPE 53283 was Prepared for Presentation at the *1999 SPE Middle East Oild Show*. Bahrain, 20-23 February, 1999.

[42] Nabi, A. G., Qureshi, S. A., & Arif, M. U. (2010). Designing of Ultralight Slurry for Liner Cementation: Case Study. SPE 13269 was Prepared for Presentation at the *Trinidad and Tobago Energy Resources Conference*. Port of Spain, Trinidad, 27-30 June, 2010.

[43] Nelson, E. B., & Eilers, L. H. (1979). Effect of Silica Particle Size on Degradation of Silica Stabilized Portland Cement. SPE 7875 was Presented in the *1979 SPE of AIME International Symposium on Oilfield and Geothermal Chemistry*. Huston, Texas, January 22-24, 1979.

[44] Nelson, E. B., & Eilers, L. H. (2006). *Well Cementing* (2nd edition). France: Schlumberger.

[45] Nelson, E. B., Eilers, L. H., & Spangle, L. B. (1981). Evaluation and Development of Cement System for Geothermal Wells. SPE 10217 was Presented at the *56th Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME*. San Antonio, Texas, 5-7 October, 1981.

[46] Nelson, E. B., & Gouedard, V. B. (2006). Thermal Cementing. *Well Cementing* (2nd edition).

[47] Nelson, E. B., Michaux, M., & Drochon, B. (2006). Cement Additives and Mechanism of Action. *Well Cementing* (2nd edition).

[48] North, J., Brangetto, M. O., & Gray, E. (2000). Central Graben Extreme Offshore High Pressure/High Temperature Cementing Case Study. IADC/SPE 59169 was Prepared for Presentation at the *2000 IADC/SPE Drilling Conference*. New Orleans, Louisiana, 23-25 February 2000.

[49] Ostroot, G. W., & Shryock, S. (1964). Cementing Geothermal Steam Wells. SPE 904 was Presented at *89th SPE Annual Fall Meeting*. Huston Texas, 11-14 October, 1964.

[50] Ravi, K. M., Beirute, R. M., & Covington, R. L. (1993). Improve Primary Cementing by Continuous Monitoring of Circulation Hole. SPE 26574 was Presented at the *SPE Annual Technical Conference and Exhibition*. Huston, Texas, USA, October 3-6, 1993.

[51] Ravi, K., Fukuzawa, M., Hunter, W. J., & Noerdin, A. I. (2008). Advance Cement System Used to Improve Geothermal Well Reability in Java. SPE 11538 was Prepared for Presentation at the *2008 SPE Annual Technical Conference and Exhibition*. Denver, Colorado, USA, 21-24 September, 2008.

[52] Ripley, H. E., Harms, W. W., Sutoon, D. I., & Watters, L. T. (1981). Ultra-Low Density Cementing Compositions. *Journal of Canadian Petroleum Technology*, *20*(1).

[53] Roy, D. M., White, E. I., Lengton, C. A., & Grutzeck, M. W. (1979). Potential New High Temperature Cements for Geothermal Wells. SPE 7877 was Presented at the *1979 SPE of AIME International Symposium on Oilfield and Geothermal Chemistry*. Huston, Texas, 22-24 January, 1979.

[54] Roy, D. M., Langton, C. A., Grutzek, M. W., & White, E. L. (1980). Hydrothermal High Temperature Cements for Potential Geothermal Application. SPE 8994 was Presented at the *SPE Fifth International Symposium on Oilfield and Geothermal Chemistry*. Stanford, California, 28-30 May, 1980.

[55] Rozieres, J., & Ferriere, R. (1991). Foamed-Cement Characterization Under Downhole Conditions and Its Impact on Job Design. *SPE Production Engineering*, *6*(3), 297-304.

[56] Sanchez, R. A., Azar, J. J., Bassal, A. A., & Martins, A. L. (1999). Effect of Drillpipe Rotation on Hole Cleaning During Directional-Well Drilling. *SPE Journal*, *4*(2), 101-108.

[57] Sabins, F. (2000). Ultra Light Cement. 1 October 1 – 31 December, 2000.

[58] Sewell, M., & Billingsley, J. (2002). An Effective Approach to Keeping the Hole Clean in High-Angle Wells. *World Oil*, *10*.

[59] Shadravan, A., & Amani, M. (2012). HPHT 101–What Every Engineer or Geoscientist Should Know About High Pressure High Temperature Wells. SPE 163376 was Prepared for Presentation at the *SPE Kuwait International Petroleum Conference and Exhibition*. Kuwait City, Kuwait, 10-12 December 2012.

[60] Shen, J. C., & Pye, D. S. (1989). Effects of CO_2 Attack on Cement in High-Temperature Application. SPE/IADC 18618 was Prepared for Presentation at the *1989 SPE/IADC Drilling Conference*. New Orleans, Louisiana, 28 February – 3 March, 1989.

[61] Shryock, S. H. (1984). Geothermal Well Cementing Technology. *Session 14*, *Drilling/Geothermal, 5th Offshore South East Asia*.

[62] Smith, R. C. (1984). Successful Primary Cementing Can Be a Reality. *Journal of Petroleum Technology*, *36*(11), 1851-1858.

[63] Smith, R., Powers, C. A., & Dobkins, T. A. (1980). A New Ultra Lightweight Cement With Super Strength. *Journal of Petroleum Technology*, *32*(8),1438-1444.

[64] Smith, T. R. (1990). Cementing Displacement Practice: Field Applications. *Journal of Petroleum Technology*, *5*, 564.

[65] Suman, G. O., & Ellis, R. C. (1977). *World Oil's Cementing Oil and Gas Well, Including Casing Handling Procedures*. Huston, Texas, USA: Gulf Publishing Company.

[66] Schlumberger, CemNet. (2002). *Controls Lost Circulation to Improve Cement Returns*. France: Schlumberger.

[67] Tanner, C. H., & Harms, W. M. (1983). Unique Ultra Light-Weight Cement Slurry Compositions for Use in Unique Well Conditions, Laboratory Evaluation and Field Performance. SPE 11486 was Presented at the *Middle East Oil Technical Conference of the Society of Petroleum Engineers*. Manama, Bahrain, 14-17 March, 1983.

[68] Taylor, H. F. W. (1964). *The Chemistry of Cements*. London: Academic Press Inc.

[69] Teodoriu, C., Yuan, Z., Schubert, J., & Amani, M. (2012). Experimental Measurements of Mechanical Parameters of Class G Cement. SPE 153007 was Presented at the *SPE/EAGE European Unconventional Resources Conference and Exhibition*. Vienna, Austria, 20-22 March 2012.

[70] Turki, W. H., & Mackay, A. S. (1983). Primary Cementing Across Massive Lost Circulation Zones. SPE 11490 was Presented at the *Middle East Oil Technical Conference of the Society of Petroleum Engineers*. Manama, Bahrain, March 14-17, 1983.

[71] Way, P. H., Howard, P., & Johnson, A. (1998). Jetting Clean-up Of Formation Damage Caused by the Drilling Process. SPE 62799 Presented at the *Asia Pacific Drilling Technology Conference*. Kuala Lumpur, Malaysia, September 11-13, 2000.

[72] Weber, L. *et al*. (1998). The Application of a New Corrosion Resistant Cement in Geothermal Wells. *Transaction of the Geothermal Resources Council*. Davis, California, USA, 1998.

[73] Wikipedia. (2013). *Population Growth Rate*. Retrieved form http://en.wikipedia.org/wiki/Population_growth_rate#Population_growth_rate

[74] Wikipedia. (2013). *World Population*. Retrieved form http://en.wikipedia.org/wiki/World_population

[75] Wikipedia. (2013). *World Population History*. Retrieved form http://id.wikipedia.org/wiki/Berkas:World_population_history.svg

[76] Yuan, Z., Al-Yami, A., Scubert, J., & Teodoriu, C. (2012). Cement Failure Probability Under HPHT Conditions Supported by Long Term Lab Studies and Field Cases. SPE 154746 was Prepared for Presentation at the *SPE Annual Technical Conference and Technical Conference and Exhibition*. San Antonio, Texas, USA, 8-10 October, 2012.

[77] Zeldinm, A. N., & Kukacka, L. E. (1980). Polymer Cement Geothermal Well Completion Materials. *Brookhaven National Laboratory Report BNL 51287*. New York City, New York, USA.

[78] Zeng, J., Sun, F., Li, P., Liu, A., & Gao, Y. (2012). Study of Salt-Tolerable Latex Cement Slurries". *Isope 1-12-075 Proceeding of the Twenty-second (2012) International Offshore and Polar Engineering Conference*. Rhodes, Greece, 17-22 June, 2012.

