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CEMENTING OF GEOTHERMAL WELLS

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ABSTRACT

The objective of casing cementing is to provide a complete fill up of cement in the cased hole annulus to resist specific environmental conditions and anchor the casing. In geothermal wells, the cement sheath must also protect the casing against possible corrosion by thermal brines and help prevent the uncontrolled flow of thermal water and steam outside the casing.

It is well recognized that good casing cementing is one of the most important factors for long life of geothermal production wells. It has, however, proven difficult to get the cement slurry to return to the surface, especially in deep wells with many lost circulation zones. Various methods and materials, mainly from the oil industry, have been applied to geothermal drilling and are described in this report. Case histories of casing cementing from Iceland and El Salvador are presented.

1. INTRODUCTION

Casing cementing is an essential stage in the drilling of a well. It takes place when each stage of the well has been drilled and a heavy steel pipe (casing) is lowered into it. Dry bulk cement and additives are mixed with water to form a cement slurry in a continuous process. The slurry is pumped to the bottom of the well and rises to fill the annular space between the casing and drilled rock. The cement sets, fixing the casing and isolating productive zones from water and other contaminants.

The cement slurry is made from cement, water and additives. There are different types of cement additives such as silica flour, perlite or microspheres, accelerators, retarders, dispersants, fluid loss and bridging agents. Deciding which of these additives to add to the basic composition is based on well conditions and what is thought necessary to accomplish the job successfully. The success of such an operation depends on the knowledge of many physical parameters. Temperature is the most critical factor since it strongly affects the setting time of the cement slurry, and will in time cause the cement to lose strength if not properly formulated.

Various materials and methods have been developed and adopted to fill the cement slurry from the bottom to the top of casing. One of them is lowering the cement slurry density from 1.83 kg/l with perlites or ceramic microspheres to 1.30-1.50 kg/l. Recently foam cementing has been applied to geothermal wells to lower the density and improve returns. But these methods sacrifice the cement strength. The most common placement method is the inner-string technique. Another solution is the multiple stage cementing method. This method is applicable for as many stage cementings as are desired, but because of more complicated operations with an increase in the number of stages, two stages have been used for geothermal well cementing so far. With this method, cement returns have improved, but even this approach gives no guarantee of success prior to the operation.

2. WELL CEMENTING PROGRAMME

2.1 Cementing conditions specific to geothermal wells

It is necessary for geothermal well casings to be cemented the full length to minimize casing expansion when producing steam and to prevent buckling. It is especially important to have good cementing for the production casing on which master valves and production pipes are attached. If the primary cementing job is not done properly, the valves and pipes expand upwards and vibrate. It may become very dangerous because the production casing may part and a steam blowout occur (Saito, 1994).

FIGURE 1: Photograph of a casing collapse in well SG-5, Svartsengi SW-Iceland

When the cased-hole annulus is not totally filled with a cement of good quality, tightly-sealed pockets of water from the drilling fluid, preflush fluid, or mud spacer may exist. This water is heated as the well temperature reverts back to static conditions. Upon initiation of production, higher temperatures from the produced fluid or steam increase the temperature of this trapped water. The expansion of trapped water caused by increasing temperatures generates forces on the order of 5.6-6.2 bar/°C (45-50 psi/°F), which can cause collapse failures due to too high external casing pressure (Edwards et al., 1982). In several instances of casing collapse in geothermal wells, the only reason for the collapse is thought to have been the expansion of water trapped in these pockets. This can, for example, be seen in a photograph taken in well SG-5 in Svartsengi, Iceland (Figure 1) where the warm pocket was trapped between the production and surface casing.

Figure 2 shows the formation temperatures of the Berlín geothermal field in El Salvador and the Svartsengi geothermal field in Iceland. Case histories of cementing jobs from these fields are presented in Chapter 6. The shallow aquifer at Berlín caused a lot of problems during well construction, due to the frequent loss of circulation treatment.

2.2 Well information from logs and drilling operations

At every casing depth and maximum depth, a temperature log is run inside the drillpipe while mud or cold water is pumped continuously onto the annulus, before the drillstring is pulled out. This is done for

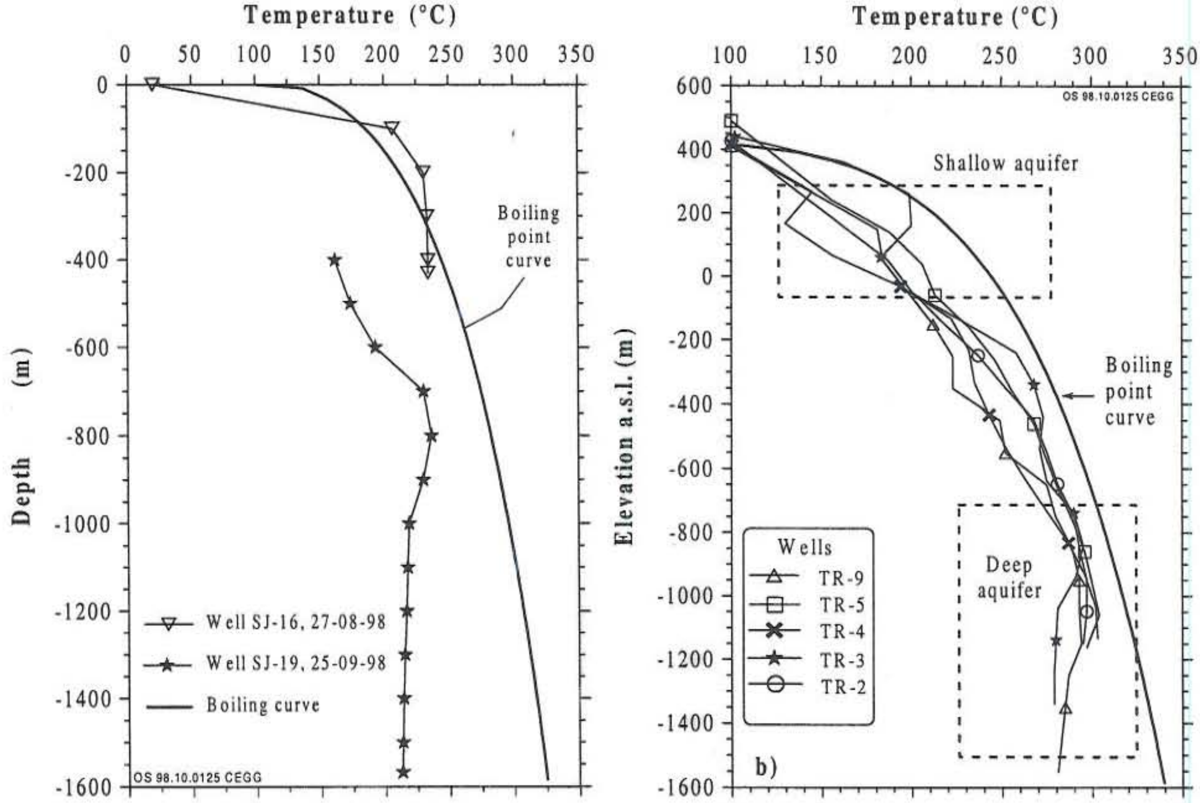

FIGURE 2: Formation temperature of, a) Svartsengi geothermal field in Iceland, and b) Berlín geothermal field in El Salvador (Monterrosa, 1993)

safety reasons to check the warm-up rate in the well and to evaluate the risk of a blow-out. The log also gives information on the location of aquifers (loss zones).

When the drillstring has been pulled out (mud or cold water is still pumped on the wellhead), the following logging is done in the open hole: a) temperature log, b) caliper log, and c) lithology logs such as resistivity, gamma ray and neutron-neutron logs. The temperature and caliper logs are especially useful in planning a cementing operation.

2.2.1 Temperature measurements

Temperature logs provide valuable information for the cementing job, such as, a) determination of hole temperature, b) location of aquifers and loss zones, c) cross-flow between aquifers (inter-zonal flow), and d) locating the top of cement.

The determination of bottomhole circulating temperatures (BHCT) has received considerable attention in oil well drilling due to ever greater depths being drilled. The BHCT is conventionally obtained through five basic methods: a) maximum reading thermometers, b) API temperature charts, c) temperature gradients and field experience, d) temperature balls, and e) temperature subs (Kabinoff et al., 1992).

With the first three methods, a good temperature value is achieved when there is an agreement between the temperature model and well conditions. These methods frequently use a bottom hole static temperature (BHST) value or an estimate of that value for a starting point to determine the bottomhole circulating temperatures. The last two methods are used to obtain temperature data during circulation of the wellbore. These methods measure the temperature of the well under conditions which are usually similar to conditions at the time of cementing.

2.2.2 Caliper log

Caliper logs are made by a multi finger tool, that measures well diameter (typically with four arms) in order to investigate, a) cavities in the well (location of cavities, see if cementing of cavities has succeeded, estimate the amount of cement for casing cementing jobs and determine location for packers), b) casing damages, and c) scale depositions in wells.

2.2.3 Cement bond logging (CBL)

A cement bond log is made after cementing the casing in order to determine, a) the top of cement in the annulus, b) cement quality, c) bonding of cement to the casing and hole wall, and d) if the cement is everywhere around the casing.

According to Nicholson (1984), bonding of cement to the casing and hole wall are improved when: a) mill varnish is removed from the pipe, b) cement is not contaminated by drilling mud, c) mud does not wet the pipe, d) water content of the slurry is low; and e) mud cake is removed from the formation.

2.3 Planning of cementing operations

When planning a casing cementing operation in a geothermal well, an important requirement is a reasonable estimate of the downhole temperature at the time of cementing. As this temperature increases, more accurate estimates are needed. One of the most accurate methods is to take a direct circulating temperature measurement (Nicholson,1984). However, the design of the retarded cement slurry must frequently be made prior to obtaining this direct data. After logging, a clean-out trip with the drill string is usually made to the bottom of the hole and the fluid is circulated to clean the hole prior to running the casing.

In a cementing job, plans are also required in the event that circulation is interrupted during cementing. If pumping is interrupted prior to displacement operations, it may require circulating out the slurry and re-starting the job instead of risking a poor cement job (Nicholson, 1984). It could also mean drilling out a long column of cement from inside the pipe.

Slurry volume estimates are often difficult. Sufficient cementing material should be available to adjust the volume after information from a caliper log is available. If caliper logs are not available, it is conventional practice to double the theoretical volume of the annulus (100% excess) to get an estimate for the required cement slurry volume. If the inner string method is used, precision slurry volume is not as critical. However, for liner jobs and the two-plug method, slurry volume can be critical. Uncontaminated mixing water is crucial to the highly retarded geothermal cement mixture. Minor contaminants can either cause the cement to set too quickly, or not set at all. All pumping and curing tests made prior to the job should preferably be done with the same water that will be used during the actual job.

2.3.1 Quality control

A successful cement job requires, a) the pumped slurry be that which was designed and tested in the laboratory, b) control of the mixing water quality, c) control of the dry material, and d) the cement and additives tested in the laboratory should be from the same batch to be used in actual operations (Nicholson, 1984). Small changes in material properties can greatly affect the behavior of high temperature cement slurries. Thus, all site storage facilities and transportation equipment must be clean of previously stored and transported material.

A series of dry cement and cement slurry samples should be taken during the mixing operations of the dry cement mix. Tests such as curing time vs. strength or thickening time can be done to determine that the desired slurry properties are being met (Nicholson, 1984).

2.3.2 Downhole hardware

Proper centralization of the pipe is required to obtain a uniform cement sheath around the pipe. This requires that good heavy-duty centralizers be used. A general rule is to place one centralizer immediately above the shoe and one on top of each of the bottom six joints. Centralizer spacing above the joints should be based on the hole curvature. Usually, one centralizer every three to four joints is sufficient if the dogleg angle and hole angle are low (Nicholson, 1984).

2.3.3 Drilling fluid displacement

Prior to the cementing operation, drilling and pumping procedures should be reviewed. To achieve the major objectives in geothermal cementing, i.e. complete annular fill and 100 percent displacement efficiency, several proven placement methods can be implemented. Drilling fluid systems should exhibit low fluid loss, low viscosity (unless the wellbore is deviated), and should not gain static gel strength. If the drilling fluid is properly designed, it can be removed from the wellbore more easily during cementing, thereby increasing displacement efficiency (Evanoff and Harris, 1992). Spacers or flushes ahead of the cement slurry will also aid in removing drilling fluid from the wellbore. Spacers are designed to flow in turbulence and are typically used on each casing job.

Drilling fluid remaining in the casing-hole annulus usually contaminates the cement slurry resulting in an increase of slurry viscosity, which may require significantly higher pump pressures to maintain its movement in the annulus. Higher pump pressures result in increased pressure imposed on the exposed formation, and often cause fracturing and subsequent lost circulation. Sufficient quantities of mud-contaminated cement are also thought to be responsible for channeling of the cement slurry in some parts of the annulus, leaving portions of the casing only partially cemented (Edwards et al., 1982).

2.3.4 Slurry mixing and pumping

When cement slurry mixing is initiated, dry cement is pneumatically delivered to the cement pumping unit which consists of a slurry mixing system, displacement measuring tanks, and high pressure pumps. Examples of this equipment are described in the two case histories in Chapter 6. The purpose of the slurry mixing system is to apply high energy to the cement composition to achieve a downhole design with consistent properties. Proper slurry density and correct mixing rate are two critical parameters that a mixing unit must deliver (Evanoff and Harris, 1992). Important cementing features such as compressive strength, free water, and wellbore displacement efficiency are very dependent upon slurry density and mixing rate.

2.3.5 Primary casing cementing steps

The main steps for primary casing cementing are the following:

1. The hole should be in the best possible condition prior to running casing as far as mud, cleaning cutties and losses are concerned;
2. The casing must be run slow enough to help prevent fracturing the exposed formations due to pressure surges;

3. It is necessary to stage, circulate and reciprocate the casing while it is running every hour to clean the debris and mud cake away from the centralizers, collars and scratchers;
4. Once the casing is in position to cement, circulate at least two (2) hole volumes while reciprocating the casing to clean the hole;
5. Circulate until the well has been cooled sufficiently as indicated by the return temperature;
6. Check to be sure you have the correct amount of materials, equipment, and manpower to perform the job;
7. Be sure there is an adequate volume of suitable cement mixing water accessible to the cement mixing pumping units;
8. Establish a maximum pump pressure not to be exceeded, based on the collapse resistance of the casing;
9. Mix and pump the flush, spacer, Flo-Chek chemical, cement slurry, plugs, and displacement fluids in their correct sequence at the maximum rate possible without exceeding the predetermined maximum pump pressure;
10. Wait at least 12 hours for the cement to harden prior to disturbing it.

3. CEMENTING EQUIPMENT

3.1 Special casing tool

Casing equipment is designed and manufactured to meet the requirements for guiding, floating, and cementing casing, regardless of size, type or depth of well drilled. A brief description of the most commonly used tools for geothermal wells is found below, and some figures are shown in Chapter 5.

3.1.1 Centralizers

Centralizers are an integral part of the cementing process. They provide the mechanism that centers the casing in the hole and allows uniform cement flow around the casing to help protect it at all points. Several styles of centralizers are available for matching different well specifications and hole sizes, including turbulence generating designs that help clean the annulus and distribute the cement more evenly and uniformly.

All models offer ample clearance for fluid passage and are effective in centering the casing. Based on the manufacturers recommendations, more centralizers are required in highly deviated holes. The centralizers are run free on the joint or can be secured to the casing with stop rings.

3.1.2 Floating equipment for inner string cementing

Floating equipment is used for holding the slurry in place after pumping and has the following features: a) provides casing buoyancy, b) prevents reentry of cement, and c) guides casing into hole. Figure 3 shows examples of these casing cementing tools.

A float shoe is installed on the casing bottom. This tool guide directs the casing away from ledges to minimize sidewall caving and aids in safely passing hard shoulders and through crooked holes. The float shoe has a float valve assembly (check valve). The area through the valves and concrete guide nose allows maximum pumpability for jobs even where cement or mud additives of abnormally high mixtures are required. Guide shoes without a float are sometimes used for the surface casing where it is not necessary to have a check valve.

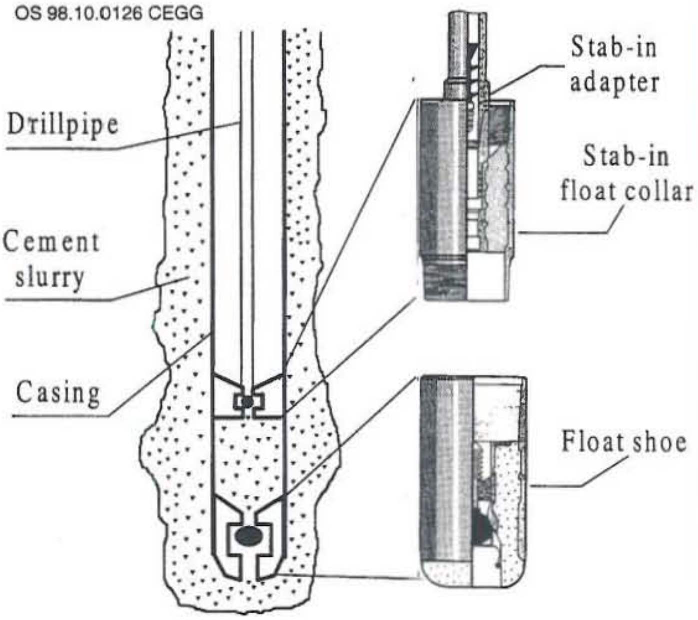

FIGURE 3: Float equipment for inner string cementing

Float collar comes equipped with a float valve (check valve), and is placed in the casing string one or two joints from the bottom. In geothermal wells a float collar named "Stab-in float collar" incorporates a receiver built into the float equipment that receives the stab-in adaptor on the bottom of the inner-string (usually drill pipe).

Cementing plugs are rubber wipers launched from plug containers. They are pumped ahead of the cement slurry to minimize contamination of the cement as it is pumped down the casing. Cementing plugs are also pumped following the cement slurry to wipe away accumulated cement film from the casing and separate cement slurry from the displacement fluid. Its use gives the following advantages: a) removes mud sheath to help prevent contamination or wet shoe joints, b) separates cement from mud, c) prevents over-displacement of cement, d) allows pressure testing of casing prior to drillout for rig-time savings, and e) provides surface indication that displacement is complete.

The multiple stage cementer makes it possible to effectively place more than one stage of cement on the outside of the same string of casing at different selected points. Some of the many applications for this tool are: a) cementing full depth, b) cementing off formations at any point, c) reducing channelling, d) reducing pump pressures, e) completing dual zone wells and f) minimizing loss of cementing slurry to thieving formations.

Currently, two types of stage cementers are available. One type can be hydraulically operated or with an opening plug. The second type can only be opened with a free fall plug. The free fall opening plug, used with the ordinary multiple stage cementer, may not reach the tool in wells deviated 30° or more. In this case, the hydraulically operated stage cementer produces the best results.

3.2 Mixing and pumping system

The purpose of a mixing system on any cementing operation is to proportion and blend the dry cementing compositions with the water. When this is properly accomplished, the end result is a cementing slurry with predictable properties (on site, measured as slurry density), which is supplied at the desired rate. Figure 4 shows the slurry mixing system used a) in Iceland and b) in El Salvador.

3.2.1 Recirculating mixer system (RCM) as used by Halliburton Company

This high-energy system provides mixed slurry at a wide range of densities and rates. The axial flow mixer is an integral part of the recirculating mixer system, uses water jets, a high slurry recirculation rate, and high horsepower agitators to improve the rheological properties of the slurries. Air entrainment is reduced for more accurate density measurement.

The main feature of the recirculating mixer system is the recirculating mixer used in conjunction with a two compartment 1.27 m^3 (8 bbl or barrels) mixing tub equipped with a turbine agitator in each compartment. The mixer combines fresh water and recirculated slurry with dry cement. These components are partially mixed and then discharged into the first compartment of the tub.

The rate at which dry cement enters the mixer is controlled by a bulk cement control valve located on top of the mixer. The fresh water rate is controlled by the mixing manifold atop the 1.27 m^3 (8 bbl) tub.

In the first compartment of the tub, the slurry is blended by an agitator, recirculated by a centrifugal pump, and measured by a densometer. Any density variations are corrected by the operator. When the first compartment is full, the slurry flows over a weir into the second compartment. Flowing over the weir helps remove entrained air.

The second compartment already contains some slurry at the desired density. The combined slurries are blended further by the agitator in the second compartment in order to help insure a uniform mixture. This slurry is then pumped downhole.

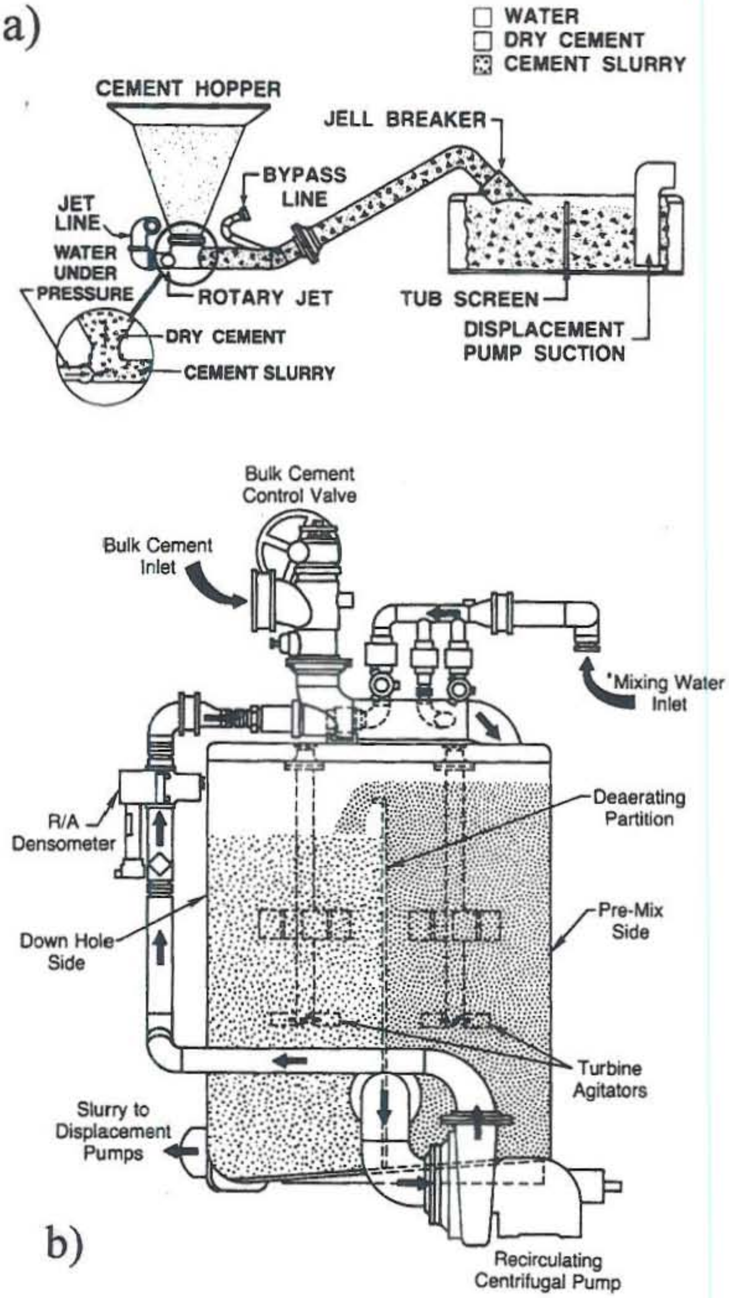

FIGURE 4: Slurry mixing systems, a) Jet mixer, and b) Recirculating mixer

3.2.2 Automatic density control

The automatic density control system is said to automatically control slurry density to within 0.02 kg/l of the targeted value throughout the cementing job. This equipment works with a digital radioactive densometer mounted in the loop of the recirculating mixer system, for all cement blends at normal rates for a wide variety of slurry densities. Information on the blend or blends to be mixed, including density and mixing rate, is keyed into the operator interface keypad. As mixing proceeds, the automatic density control processor detects even slight changes in specified slurry density. It quickly adjusts the throttling valve and the recirculating mixer system mix-water valves to maintain targeted densities.

3.2.3 Steady flow separator bulk material system

The steady flow separator bulk material system works in conjunction with the automatic density control and recirculating mixer units. It is designed to discharge bulk cement to the recirculating mixer in a very

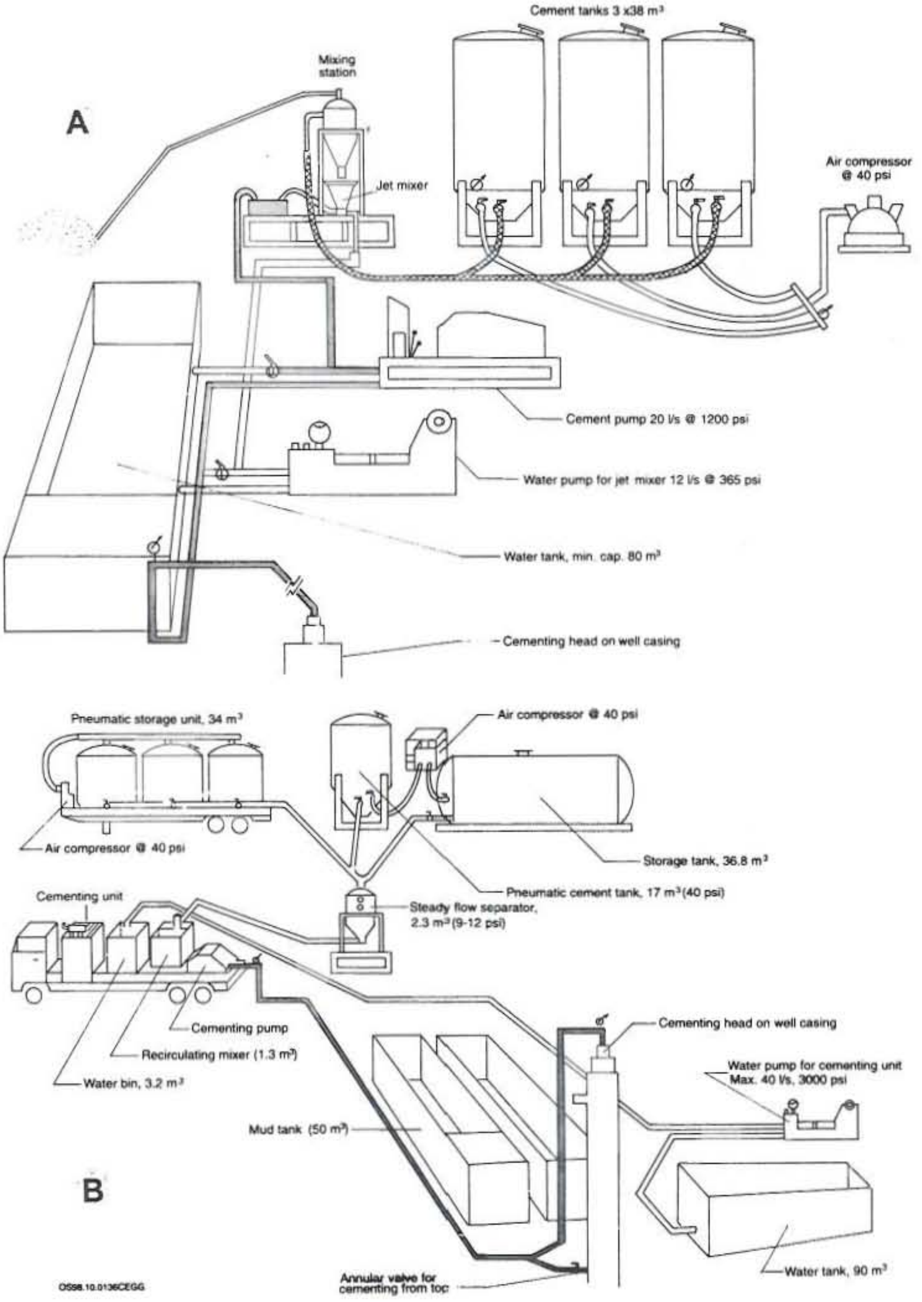

FIGURE 5: Comparison of general arrangement of cementing units used in a) Iceland, and b) El Salvador

consistent flow at a regulated, reduced pressure of 0.6-0.8 bar (9-12 psi). This is critical for accurate density control and it minimizes cement dust. Its 2.2 m^3 (80 ft^3) capacity allows for surges in the cement supply. Figure 5 shows the cementing units on drillsite used in Iceland and in El Salvador.

3.2.4 Cementing pump

The HT-400 pump (Halliburton) is a positive displacement pump and is used for pumping cement slurry, with 5 ½" pistons (plunger diameter), providing pumping rates to 43 l/s (680 gallons per minute) and pressures ranging up to 200 bar (3000 psi) under continuous operating conditions.

3.3 Testing equipment

3.3.1 Thickening time tester

A thickening time tester or consistometer is an instrument which is used to determine the pumpability of cement slurries under downhole conditions of high temperature and pressure. It is calibrated in such a manner that the units of consistency of the slurry in the cup can be recorded by a voltmeter. Thus, one can obtain a record of the slurry viscosity or consistency throughout the duration of each test. Once the value of the consistency units reaches a designated value, such as 100, the test is terminated and the time is referred to as the "thickening time" (API 1997, practice 10B). Normally, thickening times for casing cementing jobs are 2½ to 3½ hours. It is a common practice to compute the time to do the job and then add an additional hour for safety. Because the thickening time test schedule for a squeeze or plugback cementing job is different than that for a casing job, one should not use test results interchangeably (Edwards et al., 1982).

Thickening time tests are performed at temperatures referred to as bottomhole circulating temperatures (BHCT), which are always less than the bottomhole static temperatures (BHST).

3.3.2 Ultra-sonic cement analyzer

The ultrasonic cement analyzer is a system that continuously monitors the strength development trend of cement compositions while the cement is curing. A single sample of cement slurry is placed in the high pressure autoclave with pressure and heat applied to simulate downhole conditions. The processor unit monitors strength development by measuring the time required for an ultrasonic pulse to travel through the sample in the autoclave. Up to eight samples can be monitored simultaneously by the processor, allowing quick examination of several slurry design options. The result is a complete history of strength development for a cement slurry design which can be plotted versus time at any point in the test (Halliburton Services, 1990).

3.3.3 Pressurized fluid density balance

The pressurized fluid density balance is similar in operation to the conventional mud balance, the difference being that the slurry can be placed in a fixed volume sample cup under pressure. The purpose of placing the sample under pressure is to minimize the effect of entrained air upon slurry density measurements. This equipment is used in the field during cementing operations in order to know the true slurry density achieved in the mixer and compare that to the automatic density control readings.

4. CEMENTING MATERIALS

Slurries for casing cementing and cement plugs require bulk cement and cement additives. Cement additives are used to modify and improve the basic cement slurry for different well applications. The main cementing materials used in geothermal wells are listed below under the general purposes for which they are used in the cement slurry.

4.1 Cements

A basic cementing material is classified as one that, without special additives for density control or setting properties, when mixed with the proper amount of water, will have cementitious properties. This may be a single ingredient or a combination of two or more ingredients, but they are always used in this combination even when special additives are used with them.

API classification (API, 1997, Spec. 10A) for oil well cements are, a) common portland cement (class A and B), b) high early cement (class C), c) basic cement (class G and H), and d) retarded cement (class D, E, and F). Class G and H cement is commonly used for geothermal applications and sometimes Portland cement.

Geothermal wells present severe conditions to which cements are exposed. As a result, the performance requirements are stringent. At present, geothermal cements are usually designed to provide at least 69 bar (1000 psi) compressive strength, and no more than 1.0 mD water permeability (Anderson et al., 1996).

4.2 Cement additives

4.2.1 Accelerators

Accelerators are materials which, when added to portland cement or portland cement blends, shorten the thickening time, setting time and time to develop compressive strength. Accelerators are primarily used in wells having BHCT less than 49°C (120°F). Calcium chloride and sodium chloride are commonly used for the surface casings. The concentration of calcium chloride is commonly 2% by weight of cement.

4.2.2 Lightweight additives (extenders)

Extenders are used to increase the yield of a sack of cement, and at the same time, decrease slurry density to reduce hydrostatic pressure. Extenders can be selected to react or not-react with the cement to provide the desired properties. Lightweight additives are in this category.

Lightweight additives are used for the reduction of slurry densities and to increase the chances for a fill-up of cement between the casing and formation. These products include expanded perlite, spherelite, and bentonite which reduce the density because of their lower specific gravities and require larger volumes of mixing water. Figure 6 shows the effect on cement strength for different slurry densities.

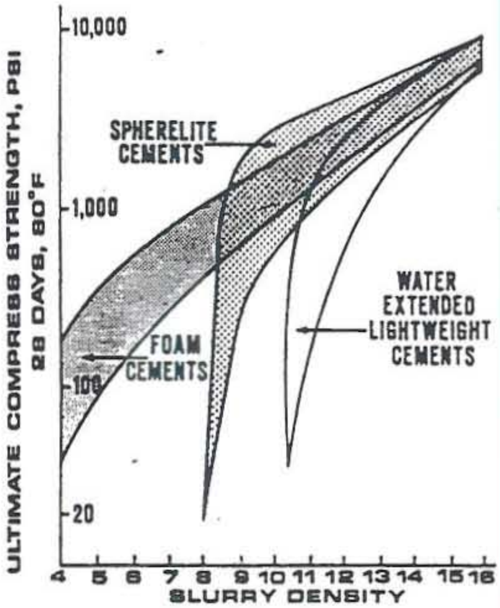

FIGURE 6: Strength vs. density (lb/gal) for lightweight cementing systems (API, 1991, Committee 10)

4.2.3 Fluid loss control additives

Fluid loss additives are used in cement slurries to keep the mix water from being forced out of the slurry into porous media (formation rock) or in narrow annulus when the slurry is subjected to downhole pressures and temperatures. Some of the benefits from using fluid loss additives in the cement system design are, a) to maintain slurry homogeneity and desired flow properties, b) to minimize formation damage caused by cement filtration, c) to ensure cement column uniformity and complete annular fill, and d) higher success rates for remedial jobs (squeeze cementing).

4.2.4 Friction reducers

Friction reducers (dispersants) are added to cement slurries to facilitate blending at densities greater than the API recommended densities for classes of cement without the need for excess water. Some of the features and benefits for using dispersants are, a) to reduce friction pressures, b) to reduce critical pump rates for turbulent flow placement, c) the application of reduced water slurries, d) to enhance fluid loss additives, e) to enhance retarder response, and f) to improve rheological properties.

4.2.5 Lost circulation materials and formation control

Lost circulation differs from fluid loss in that fluid loss is the measure of cement filtrate lost to the formation, whereas lost circulation is the loss of the entire fluid/solid mixture. Lost circulation materials are inert plugging which seal off high permeability thief zones or bridge off natural fractures. The four basic classes of lost circulation materials are: a) granular (perlite), b) laminar (mica flakes, cellulose film flakes, cellophane flakes), c) semisolid (permanent rigid-gel control of large thief zones and underground aquifers) and d) pliable.

4.2.6 Cement retardents

Retardents are classified as any reactive chemical which will extend the pumping time and/or thickening time for a cement slurry. Requirements for cement slurries to remain fluid and pumpable, while still allowing good strength development, become more complex at depths where higher temperatures are encountered. But it is important not to over-retard the slurry in the cooler temperatures found in the upper sections of the hole. It is necessary to take into account the chemical composition of each additive present in the slurry so that the retardent is compatible. In some conditions, a retardent may contribute to an increase in slurry viscosity, which translates into higher pumping pressures that could fracture a healthy zone. Often, the lignosulfonates used in many retardents display a wide variation in quality, which can certainly affect retardent consistency from batch to batch.

4.2.7 Strength retrogression materials (silica flour)

Silica flour is used in cement formulations at BHST above 110°C to combat strength retrogression. It is also used as a weighing agent in some cases. The silica flour is ground quartz sand of -325 mesh and its function is to react with the free lime and form calcium silicate. Figure 7 shows the compressive strengths of cements during 28 hours of curing time.

4.2.8 Antifoamers and foam cement additives

Cement slurries have tendencies to foam during mixing operations or to entrain air. This makes it very difficult to attain the desired slurry density unless anti-foamers or defoamers are used, as long as the foam does not build up in the mixer and cause pumping problems. Anti-foamers are often not required.

4.2.9 Cement preflushes and spacers

A cement preflush or spacer fluid is used to separate the drilling mud from the cement slurry, as the two are usually incompatible. Not only do preflushes and spacers provide this function, but they must also a) remove all circulatable drilling mud from the wellbores ahead of the cement, b) be formulated to be

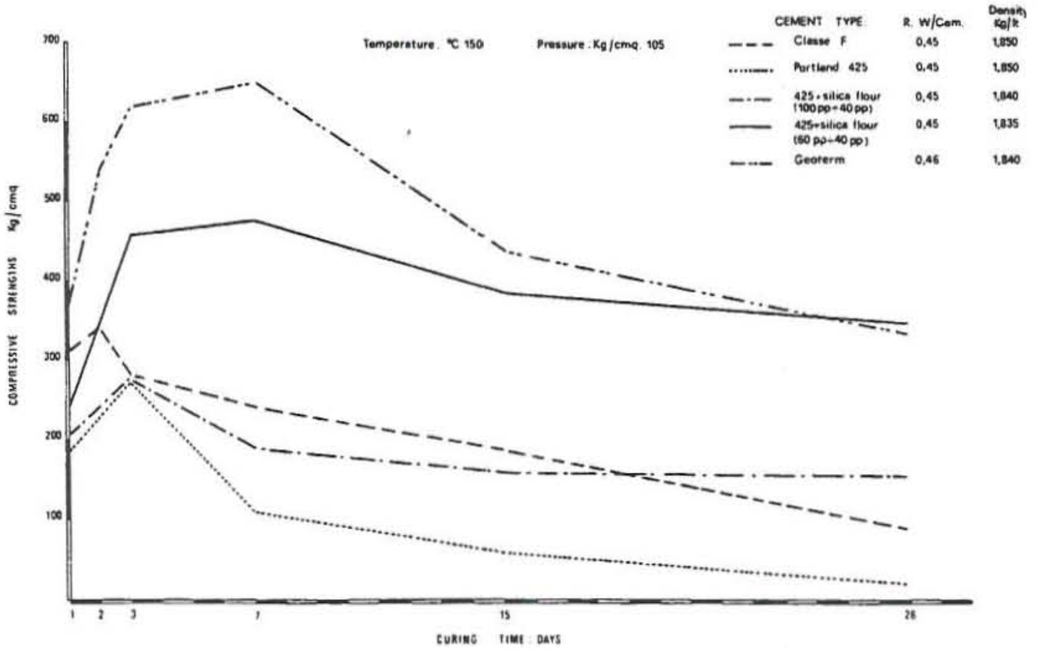

FIGURE 7: Compressive strengths of cements vs. time at well simulation temperatures and pressures (Cigni et al., 1975)

compatible with water-based/or oil based muds, c) provide fluid loss control where applicable, and d) leave the pipe and formation water-wet to enhance cement bonding. Chemical wash preflush is a thin fluid which removes drilling muds by a combination of surfactant and turbulent action.

4.3 Estimate of material requirements

Chapter 6 describes the calculation procedure for estimating material requirements. Figure 8 shows an example of cement slurries commonly used for primary casing cementing according to well diameter. Cement compositions should be designed to obtain the maximum compressive strength possible, but at the same time they must be of the correct density to prevent fracturing weak formations and losing cement to the formation. Inherently, higher strength cements have corresponding higher densities which usually makes it necessary to compromise compressive strength for the ability to circulate cement to the surface. All geothermal slurries are designed for zero free water to avoid formation of water pockets behind the pipe (Evanoff and Harris, 1992).

The cement additives for a particular cementing job are chosen based on well behaviour during drilling such as loss zones, temperature logs and depth of casing. The most accurate quantity of material requirement for casing cementing is usually based on caliper logs. From the caliper logs volume, a certain safety factor is applied for partial loss of cement slurry during the cementing operation.

When caliper logs are available, the theoretical volume is calculated for the annulus and other space that the cement has to cover. If caliper logs are not available, it is common practice to apply 100% to the theoretical volume (double the theoretical volume). Having estimated the total slurry volume, the yield of the selected cement mix has to be known in order to calculate the tonnes of dry cement required. Also, it is important to know the water requirement for that slurry design.

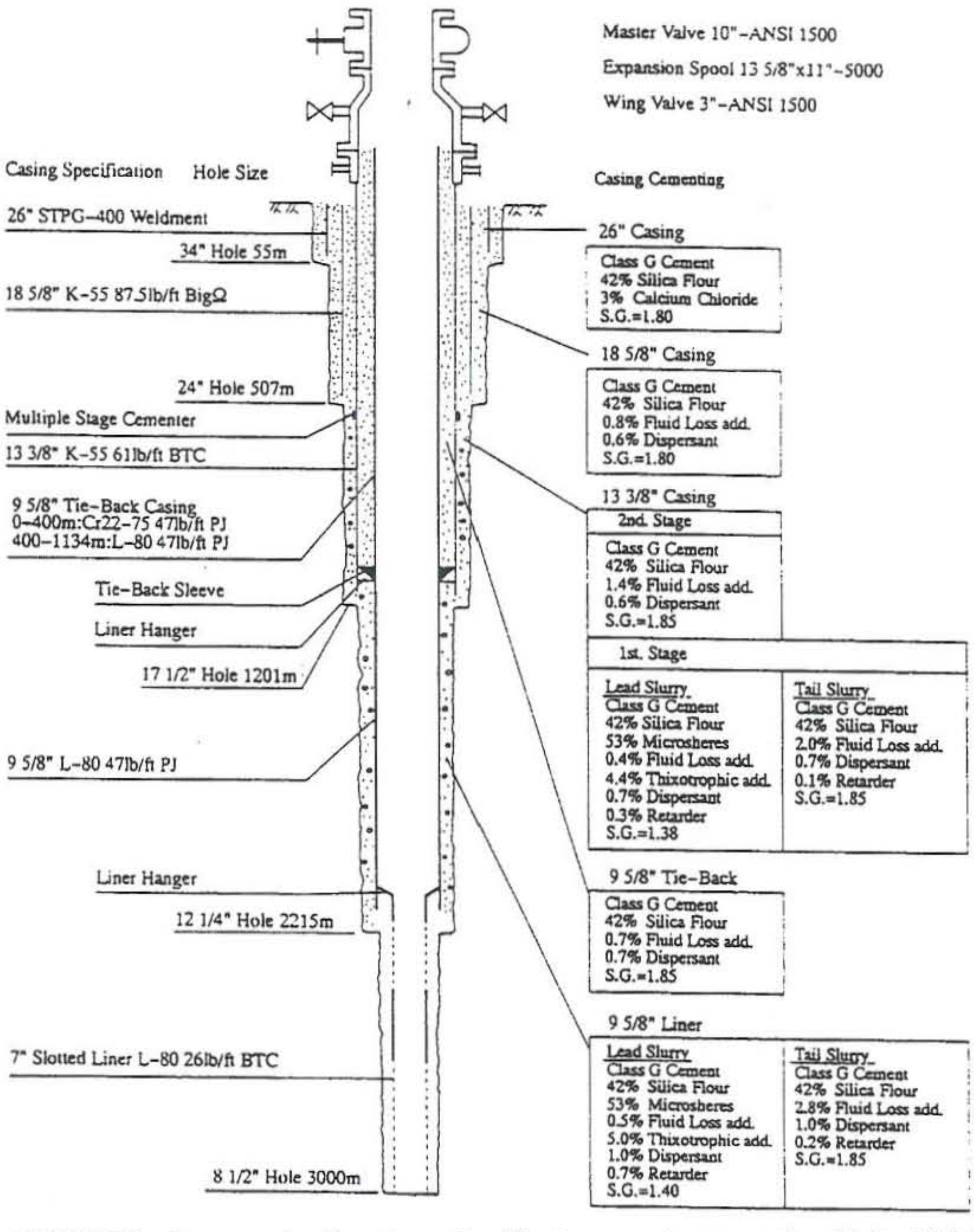

FIGURE 8: An example of geothermal well primary casing cementing (Saito, 1994)

5. GEOTHERMAL CEMENTING TECHNIQUES

5.1 Generalities

There are usually three primary casing cementing operations performed while drilling a geothermal well. They are for the, a) surface casing, b) intermediate casing, and c) production casing. Occasionally there is also the cementing of a production liner or tieback casing. This chapter will also describe the techniques used for placing cement plugs in open holes.

Cement plugs are used for several reasons, such as a)to solve a lost circulation problem during drilling operation, b) to sidetrack above a fish or to initiate directional drilling, c) to plug back a zone or a well,

d) to provide an anchor for an open-hole test, and e) for other remedial work.

5.1.1 Surface casings

The surface casing serves as a base upon which to secure well control equipment, protect fresh water zones, and isolate lost circulation intervals. Cementing objectives for these shallow casings include: a) complete circulation of cement slurry to the surface for full protection, b) early compressive strength development so drilling can continue, and c) long term stability against high temperatures (Evanoff and Harris, 1992).

Slurry designs for surface casing cements consist of API Class G or H cement with the addition of an accelerator ($CaCl_2$) to enhance early compressive strength, and silica flour to prevent compressive strength retrogression when the cement is later exposed to temperatures in excess of 110°C (Evanoff and Harris, 1992).

5.1.2 Intermediate casings

Intermediate casing is usually set at a depth based on local geology and survey considerations so that drilling may later continue down to the depth of the production casing. Objectives of the cementing process are consistent with shallow casings, a fully cemented casing string, early compressive strength development, and long-term stability. Along with the aforementioned cementing objectives, retardation of the cement slurry becomes an important parameter as casing depths increase to prevent premature setting of slurry before final placement.

5.1.3 Production casings

The cement slurry design for production casing is the basic geothermal cement mix (Figure 7) with a high-temperature retardent, based on the bottom hole circulating temperature. Due to the long columns of cement that must be lifted to the surface and the presence of low fracture gradient formations, the prevention of lost circulation is a critical aspect of this cementing operation.

Based on the bottom hole circulating temperature, retardents may need to be utilized. Perlite is used on many production casings to reduce density, and help prevent lost circulation. When lost circulation is severe, spherelite may be used to provide a lightweight composition. Besides providing for lost circulation control, spherelite in the cement slurry helps insulate the wellbore from heat losses, exhibiting thermal conductivity values in the range of 0.2 W/m°C (0.125 BTU/hr-ft-°F) (Evanoff and Harris, 1992). Lately, cement foamed with nitrogen or air has also been used for this purpose.

5.1.4 Production liners

Production liners are attached to drillpipes during the cementing operation and are afterwards detached and left in place (using a liner hanger assembly). The drill pipe is pulled and circulated free of excess cement, leaving the liner casing section completely cemented downhole. After the liner cement has hardened, the cement plug on the inside of the liner string is drilled out. In some cases, a tieback casing is set in the well and cemented (Evanoff and Harris, 1992). This casing programme has been used, for example, at the Geysers in California but is not in wide use for geothermal wells.

Production liner cement designs are identical to those for intermediate casing.

5.2 Casing cementing techniques

5.2.1 Two-plug cementing

The two-plug cementing technique is sometimes used in the cementing operation for surface and intermediate casing. For that, the follow equipment is needed, a) Plug container which allows the release of the cementing plug at the proper time, b) bottom and top plugs to minimize contamination of the cement with the mud within casing and the displacing fluid, and c) standard shoe and float collar.

Figure 9a shows casing tools and the method for two-plug cementing. The general procedure for this technique is the following:

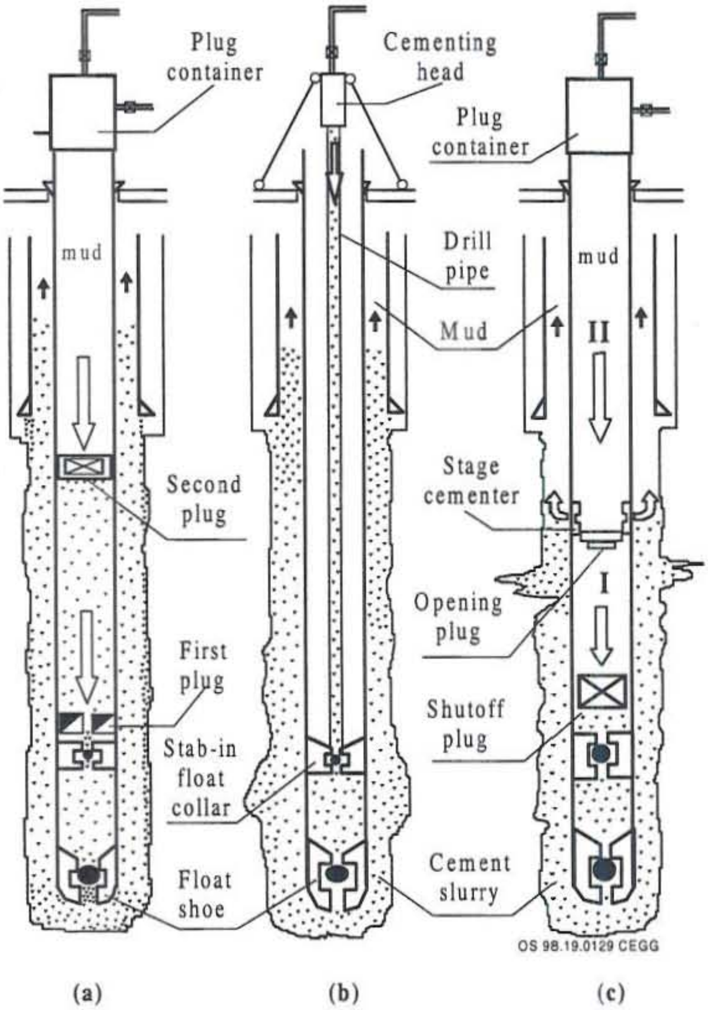

FIGURE 9: Casing cementing techniques, a) Two-plug cementing, b) Inner-string, and c) Two-stage cementing

1. Float collar is placed in casing string one or two joints from bottom;
2. Plug container is installed on the head of the casing string with two rubber plugs inside it;
3. Bottom plug is pumped ahead of the cement slurry;
4. When the bottom plug reaches the float collar, a small differential pressure ruptures the rubber diaphragm in the top of the plug and allows the cement slurry to proceed down the casing, through the plug and floating equipment, and up the annular space between casing and hole;
5. Pump the volume of cement slurry previously calculated;
6. Release the top rubber plug from the container and pump the displacing fluid until the top plug reaches the bottom plug; this causes a normal pressure rise at the surface and notifies the operator that the cementing job has been completed.

Disadvantages of this cementing method are, a) it does not allows flexibility in adjusting the volume of cement slurry while a job is in progress, b) sometimes the rubber plugs do not reach the float collar, allowing cement contamination which is difficult to drill out after the cementing operation, and c) cement pumping time is about twice as long as for inner-string cementing.

5.2.2 Inner string cementing

The inner-string method of casing cementing is the one most commonly used for geothermal wells. Inner string cementing equipment allows cementing the casing through a drillpipe that is inserted and sealed in the stab-in float collar. The advantages include:

1. Cement is discharged outside the casing much sooner after mixing, reducing the risk of the cement slurry setting within the casing;
2. Less circulating time is required with inner string cementing than for two plug cementing;
3. Reduces cement waste;
4. Reduces amount of cement that has to be drilled out of the casing;
5. By pumping through the inner string, reduced cement contamination results from channelling;
6. Reduces cement drill-out time.

Figure 9b shows casing tools and the method for inner-string cementing. The general procedure for this technique is the following:

1. A float shoe is installed on the bottom of the casing string;
2. Float collar with sealing sleeve is installed two joints from bottom during running casing;
3. As the casing is run in, the hole needs to be filled up with water;
4. Sealing adapter (stab-in) is connected to a drillpipe and lowered down as far as the float collar sleeve, where it is seated, the sealing must be complete;
5. Cementing head is installed on the drillpipe; the drillpipe needs to be tied down with chains to avoid parting of the drillpipe from the float collar when pressure builds up;
6. Mud or water is circulated through the drillpipe for cleaning and cooling the well;
7. Chemical spacer is pumped, followed by water volume (about 6.5 m^3);
8. Cement slurry is pumped through the drillpipe until its return at surface is observed (when loss circulation does not occur);
9. Displace the cement slurry contained within drillpipe, pumping an equivalent water volume;
10. Wait for cement to harden (8-18 hours).

When lost circulation occurs during primary cementing, the cement slurry displacement must be balanced in order to avoid washing the cement from the casing shoe zone. At the same time, it is necessary to pump water from the top into the casing annulus to remove mud or cement contained in that zone down to the loss zone and achieve good complementary cementation.

5.2.3 Two-stage cementing with a cementer tool

Multiple stage cementing can be used when, a) the hydrostatic pressure of the cement is too great for the formation or casing, b) it is necessary to separate different types or blends of cement, c) limited pump time is available, and d) it is necessary to cement only certain sections of the annulus.

Figure 9c shows casing tools and the method for two-stage cementing. The general procedure for this technique is as follows:

1. Casing shoe, float collar and multiple stage cementer are placed in the casing string; the float collar is installed two joints from bottom to help stop the top cementing plug; the stage cementer is placed above the main loss zone and casing centralizers should be put above and below this tool;
2. Cementing head is installed to the casing string to be cemented;
3. Mud or water is circulated through the casing for cleaning and cooling the well;
4. Pump chemical spacer followed by water volume (about 6.5 m^3);

5. Enough cement slurry to fill up the annulus between bottom hole and stage cementer is pumped through the casing (12-18 l/s);
6. Shut-off plug is landed on the float collar; pressure can be applied immediately to open the cementer (a rapid decrease in pressure and the start of fluid circulation indicates that the cementer has opened);
7. After the cementer has opened, a displacement type opening plug may be pumped ahead of the second stage of cement if desired, which will serve as a bottom plug for the second stage;
8. Wait 12 hours for cement to harden, meantime mud is pumped in order to clean and cool the well;
9. The second amount of cement slurry is pumped into the casing; the closing plug is released; a steady pumping rate should be maintained until the closing plug lands;
10. A sudden increase in pressure and lack of circulation indicate that the closing plug has landed on its seat in the tool, at this time a pressure of 100 bar (1500 psi) above the final circulating pressure should be applied smoothly and rapidly for three to five minutes.

5.2.4 Foam cement for geothermal wells

Foam cement consists of a conventional geothermal cement slurry that is extended by the incorporation of microscopically dispersed nitrogen gas. The gas is injected into the slurry with foamers and foam stabilizers. The job design for geothermal use commonly is the constant density method, where the volume of gas used per volume of cement slurry is varied. This method provides a cement column with a constant density from top to bottom. The compressive strength of the cement column will be relatively constant using this method. It is, however, reported to be is less than 35 bar (500 psi) after 48 hours cured at 100°C and 1.08 kg/l slurry density (Rickard, 1985).

Foam cement is placed into the well using the inner string method. A back pressure control is required where the slurry returns to the surface in order to decrease cement expansion due to gas bubbles. The foam cement programme is often designed to give higher density cement around the shoe and near the surface for greater strength.

5.2.5 Casing cementing remedial jobs

Various methods have been developed and adopted to fill the cement slurry from the bottom to the top in a casing cementing operation during the primary job. With these methods, cement returns have improved, but even with this approach, no guarantee of success can be given prior to the operation. If the cement slurry is poured into the annulus from the surface, water may be trapped between two cement plugs and when steam production starts, this water in the annulus heats up and pressure increases about 6 bar/°C (85 psi/°C) temperature rise (Saito, 1994). But if steam production is started without any remedial cementing operation, the casing will expand upwards and vibrate. It is not only difficult to maintain steam production but also sometimes dangerous to keep producing from such a well, especially if the well has high temperature and pressure. The conventional remedial top-job casing cementing methods, are the following:

Squeeze cement slurry into the annulus. Another alternative is to perforate the casing from inside the well and squeeze cement slurry into the annulus. However, this method has the following major disadvantages, a) It is not certain whether the cement slurry will replace the existing fluids in the annulus, b) some section of the annulus is not cemented but just filled with gravel and sand, c) it is almost impossible to find the exact depth and shape of the cement top where perforations are to be placed, d) it is necessary to perforate the casing (Saito,1994).

Cement on top of gravel and sand. When the cement top is deep, small diameter pipe strings with ports in the lower section are run. Then the annulus is filled with gravel and sand to some depth, then the upper section of the annulus is cemented through another small diameter short pipe string (Saito, 1994).

Tieback casing job. On many wells the tieback casing job is performed as a remedial procedure to repair intermediate casing, damaged by subsequent drilling operations or a poor primary cement job. Tieback casings connect the top of a liner to the surface and provide insurance for zonal isolation and casing protection. Cementing objectives remain consistent with previous casing operations. However, since cement is not exposed to formation during pumping, obtaining a full column of cement to the surface is a relatively easy task and lost circulation practices are not required (Evanoff and Harris, 1992).

Since lost circulation is not a problem during tieback cementing. Perlite or spherelite are not required unless greater thermal insulation is desired. Bentonite is usually added to tieback casing slurries to make absolutely sure there is no free water separation between casings (Evanoff and Harris, 1992).

Cementing through small diameter pipe. When the cement top is shallow, small diameter pipe string (spaghetti string) is run into the annulus to the cement top. Cement is pumped through the strings to the surface. The "spaghetti" method was improved for remedial cement jobs between two casing strings. Then the annulus is heated and dried up before the remedial cementing operation. Since there is no possibility of water pockets, casing does not collapse (Saito, 1994). The following procedure is used in this case:

1. Find the top of the cement in the annulus using a small diameter pipe (about 34 mm of diameter);
2. Air lift the annulus fluid with compressed air; this is done for safety reasons to minimize the amount of boiling water and steam coming out of the annulus when heating up the well;
3. Run 5" drill pipe string into the well as far as the cement top and air lift until the water level is lifted;
4. Circulate steam through the 5" drill pipe until the annulus water is dried up;
5. Circulate water in the well to cool the annulus to prevent flash setting of the slurry while pumping;
6. Pump the cement slurry through small diameter pipe into the annulus;
7. When the operation is finished, pull the pipe out of the annulus.

5.3 Cementing plug

5.3.1 Lost circulation treatment

The most costly problem routinely encountered in geothermal well drilling is lost circulation. Lost circulation costs represent an average of more than 10% of total well costs in mature geothermal areas. Reducing the cost of lost circulation would thus significantly reduce overall geothermal costs and help expand the role of geothermal energy. One significant way lost circulation costs can be reduced is by making the right decisions sooner. That requires the driller to be better informed in real time (Harmse et al., 1997).

Conventional lost circulation treatment practice in geothermal drilling is to place a cement plug by the loss zone through the lower end of an open-end drill pipe positioned near the suspected loss zone. A quantity of cement is pumped downhole, depending on the length of well section that has to be healed. The objective is to emplace enough cement into the loss zone to seal it; however, this does not always occur. One or more plugs may have to be placed on top of each other to heal the loss completely. Because of its higher density relative to the wellbore fluid, the cement can channel through the wellbore fluid and settle to the bottom of the wellbore. If the loss zone is not at the bottom, the entire wellbore below the loss zone must sometimes be filled with cement before a significant volume of cement flows into the loss zone. Consequently, a large volume of hardened cement must often be drilled to re-open the hole, which wastes time and contaminates the drilling mud with cement fines. Furthermore, because of the relatively small aperture of many loss zone fractures, the loss zone may preferentially pull wellbore fluids, instead of the more viscous cement, into the fractures. This causes dilution of the cement in the loss zone and loss of integrity of the cement plug. As a result, multiple cement plugs are often required to plug a single loss zone, with each plug incurring significant time and material costs.

5.3.2 Balanced cement plug

In the balance method, a viscous mud pill or mechanical plug is set just below the selected depth interval. The desired quantity of cement is pumped down the drillpipe and displaced until the level of cement is the same both inside and outside the string. The pipe is then pulled slowly from the slurry, leaving the plug in place.

Such work often demands a cement plug be set at a specific place in the well, and rarely at the bottom of the wellbore. As the well fluid commonly has a lower density than the cement slurry, it has been found that the cement slurry tends to fall or flow down through the well-fluid column, leaving the top of the cement deeper in the well than anticipated (Harestad et al., 1997).

There are several reasons for plug failures, including such primary causes as poor drilling-fluid removal, insufficient slurry volume, poor job execution, poor slurry design, incorrect well parameters, and downward movement of the cement slurry (Harestad et al., 1997).

5.3.3 Two-plug placement technique (Flo-Chek)

The volume of cement slurry used should be sufficient to offset the inevitable commingling of well fluids during slurry placement to minimize contamination effects. It is believed that some of these failures are due to downward migration of cement slurry after placement. The driving force for this occurrence would be the density difference between the cement slurry and well fluid. In cases where there is a large difference between mud and slurry density, dense cement slurry can still migrate downward into lower density drilling fluid causing contamination and a poor plug (Bour et al., 1986).

This method uses a reactive fluid system which contains a chemical component (sodium silicate) which reacts with the calcium chloride brine to create a rapid forming gel. Halliburton Company has used this system under the trade-name "Flo-Chek". This gel acts as a bridge upon which the cement slurry can reside until it builds enough strength to support itself. In addition to calcium chloride brine, the reactive fluid system also forms a gel when contacted by cement slurry. Flo-Chek will react with cement slurry to increase the stability of the bridge (Bour et al., 1986).

According to laboratory investigations and field experiences, Bour et al. (1986) found that using a cement plug placement method with Flo-Chek provides the following advantages:

a) Can be used with open ended drill pipe or a diverter tool to successfully place a competent cement plug;
b) Provides a means of placing competent cement plugs, without downward migration of cement slurry, under severe well conditions in which other techniques failed, with slurry - well fluid density differences as high as 0.85 kg/l;
c) Large volumes of spacer can be used to clean out annular space and minimize mud contamination;
d) Gelation of Flo-Chek does not occur until after it is circulated in place.

6. CASE HISTORIES OF GEOTHERMAL WELL CEMENTING

The objective of this chapter is to present and compare the methods and techniques utilized for geothermal casing cementing in Iceland and El Salvador.

6.1 Svartsengi geothermal field, SW-Iceland and production casing cementing of SJ-19

The Svartsengi area is located on the Reykjanes Peninsula, approximately 50 km southwest of the capital Reykjavík. The power plant is of co-generation type with 125 MW_t and 17 MW_e produced. Presently wells are being drilled for a 75 MW_t and 30 MW_e expansion to be commissioned for 1999/2000. A total of 15 high-temperature wells have been drilled with, the deepest one being 2,000 metres (Figure 10).

The well SJ-19 is located about 250 m southeast from the power plant. First stage was drilled with a 24" air hammer to 76 m depth using a small drillrig and the well was cased with a 22 ½" surface casing. Then a larger drillrig (Jötunn) continued the drilling in order to reach the final depth required (1593 m), in three further stages. Figure 11 shows the final casing profile for the well and Figure 12 shows the working days vs depth curve.

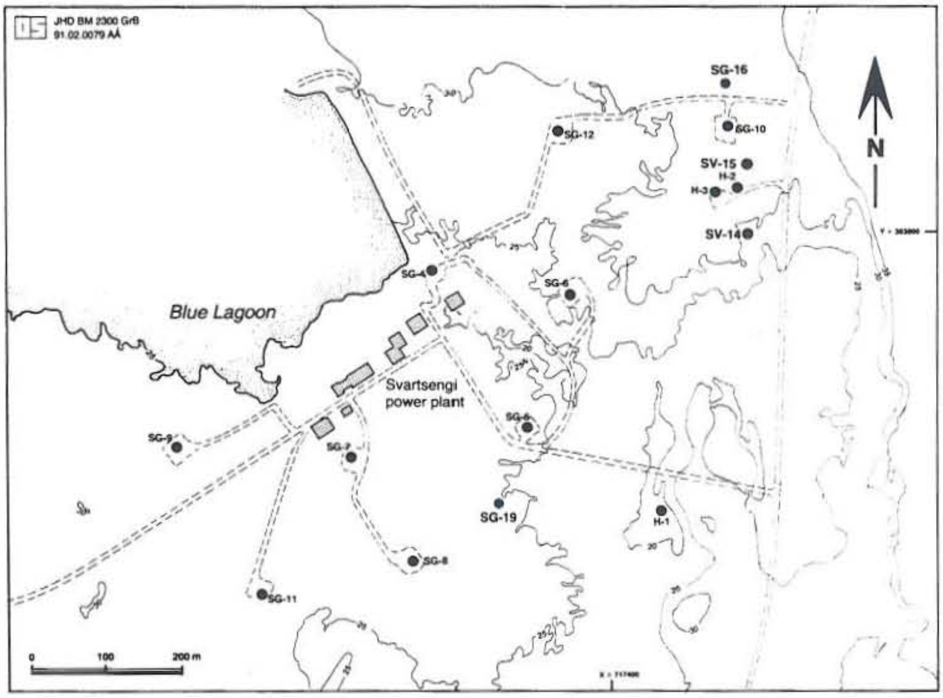

FIGURE 10: Location of the Svartsengi geothermal field and wells, SW-Iceland (Björnsson and Steingrímsson, 1991)

The second drilling stage in well SJ-19 was made using a 22" bit from 72 to 247 m depth. Based on temperature logs made before running the casing (Figure 13), the BHCT was estimated about 40°C and no retardent was required in the cement slurry (Table 1).

TABLE 1: Cement slurry design used in Iceland for production casing cementing

Cement and additives	Concentration (% bwoc)
Portland cement (local)	100
Silica flour (325 mesh)	40
Expanded perlite	2
Bentonite	2
Retardent	0.5
Slurry density	1.65

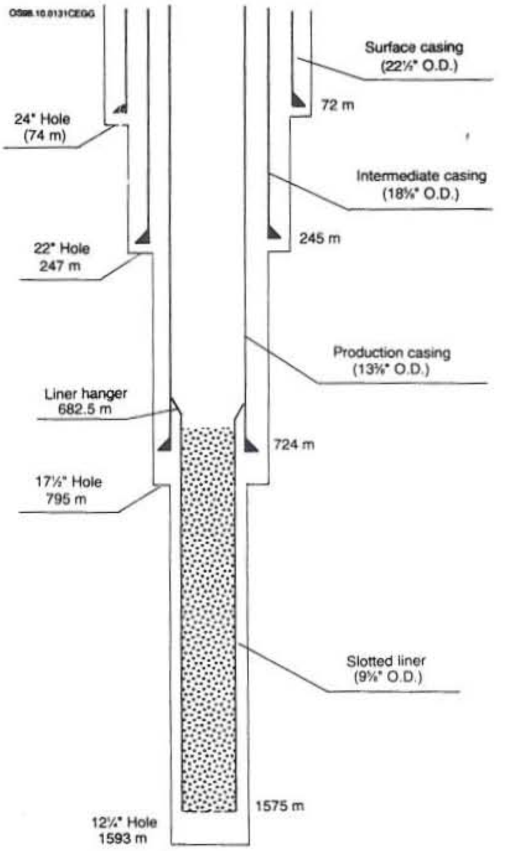

FIGURE 11: Casing profile of well SJ-19, Svartsengi

After a caliper log (Figure 14a) showed a reduced diameter between 100 and 150 m, it was decided to ream and clean the hole. The cement slurry volume for 18 ⅝" intermediate casing cementing (21 m^3) was calculated based on the caliper log (Figure 14b). The intermediate casing was anchored at 245 m and the inner-string method was used for casing cementing. Cement returns were obtained during the primary operation.

Figure 15 shows the cement bond log made after 12 hours from cementation. An acceptable cement bond was found for the full length of casing.

Several treatments due to loss of circulation were made at 450-550 m depth during drilling with a 17½" bit, reaching 755 m depth with partially lost circulation. However, prior to running 13 ⅜" casing, circulation was totally lost. Temperature logs (Figure 16) showed the total loss to be at 500 m, and led to the decision to do casing cementing in two phases.

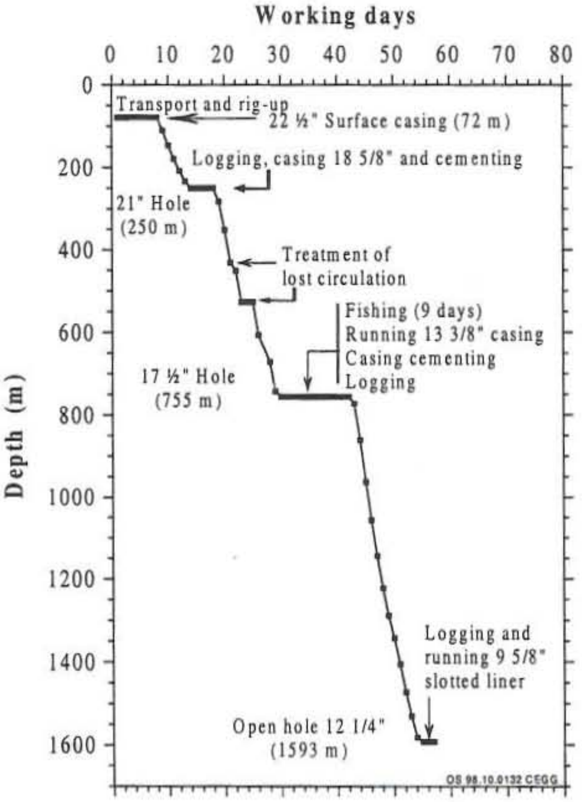

FIGURE 12: Drilling process diagram, well SJ-19, Svartsengi

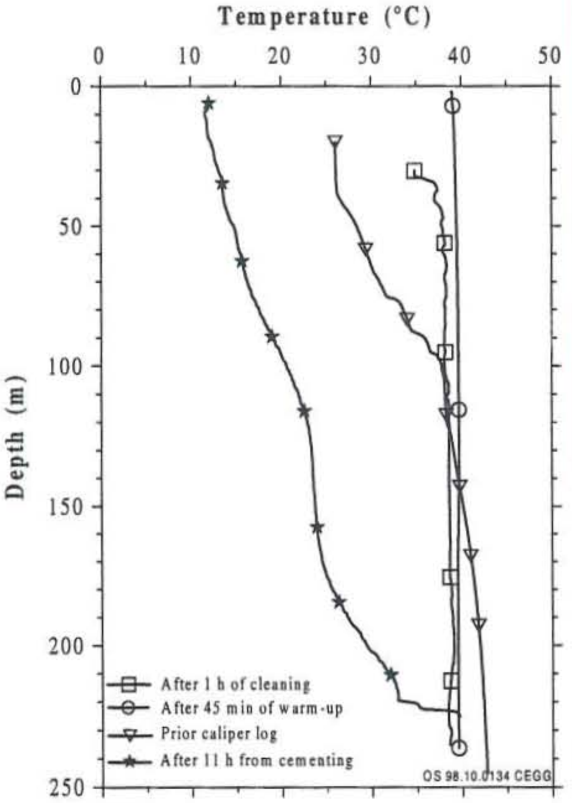

FIGURE 13: Temperature log before and after 18 ⅝" casing cementing, well SJ-19, Svartsengi

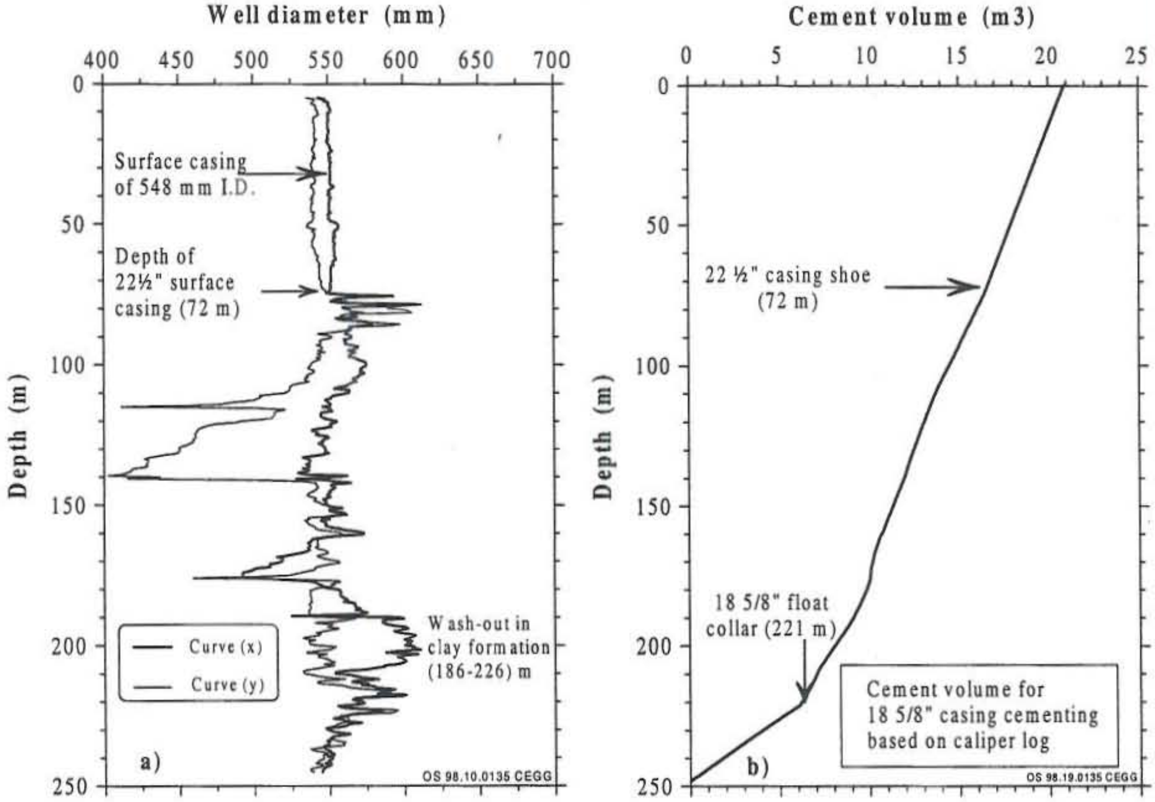

FIGURE 14: Well SJ-19 in Svartsengi, a) Caliper log in 22" open hole, and b) Cement slurry volume for 18 ⅝" casing cementing

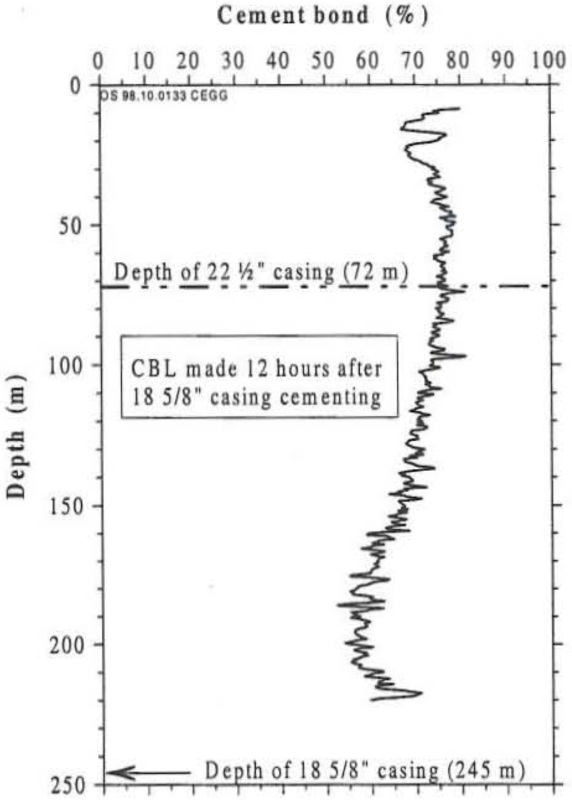

FIGURE 15: Cement bond log in well SJ-19 after intermediate casing cementing

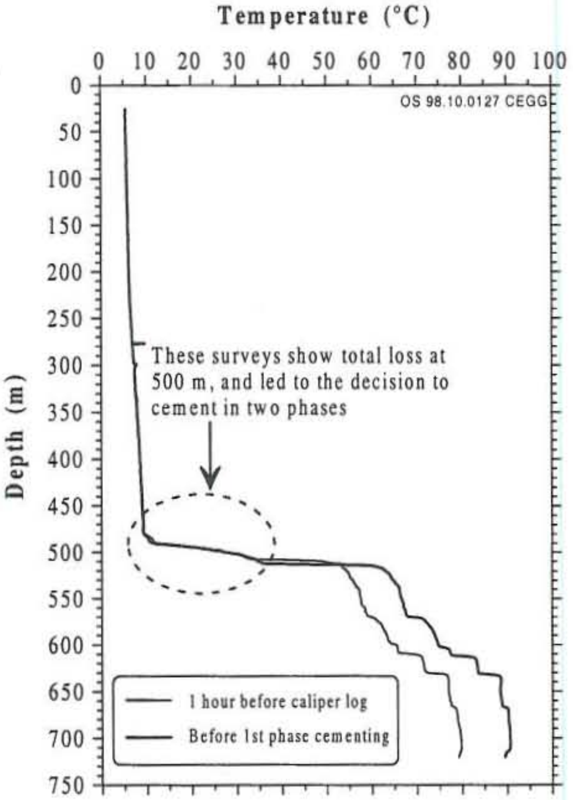

FIGURE 16: Temperature log prior 13 ⅜ casing cementing, well SJ-19

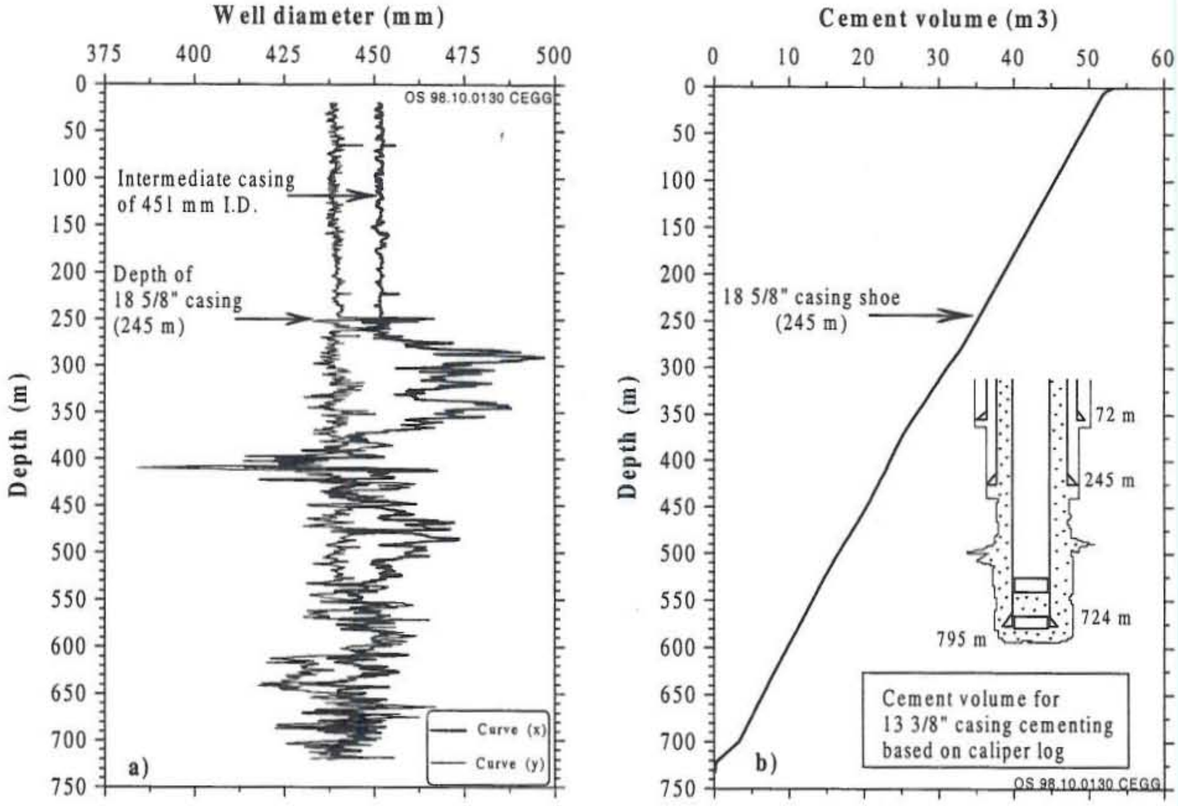

FIGURE 17: Well SJ-19 in Svartsengi, a) Caliper log in 17 ½" open hole, and b) Cement slurry volume for 13 ⅜" casing cementing

First-phase cementing was made using the plug cementing method. Inner-string cementing was not possible because the threaded joint between the stab-in sealing adapter and float collar did not engage. According to caliper logs done in the 17 ½" hole, the total cement slurry needed for 13 ⅜" casing cementing was about 52 m^3 (Figure 17). The procedure for the first phase cementing was as follows:

1. Mud inside the casing was displaced with fresh water and the well cooled down;
2. The first phase consisted of 47 m^3 of cement slurry (36 tonnes of cement) with an average density of 1.68 kg/l. At the same time, water was pumped from the top into the annular space between casing in order to clean the annulus as far as the main loss zone (500 m) and prepare that area for the second phase of cementing;
3. The cement was displaced with 43 m^3 of fresh water without the use of rubber plugs (78% of the total displacement);
4. The cement was allowed 18 hours to harden. During this period, three temperature logs were made (Figure 18a) which show an aquifer zone around 460 m. Also, the cement bond log (Figure 18b) shows the top of the cement in the annulus to be at around 460 m, with unsupported casing above this depth. The top of the cement within the casing was found at 531 m;
5. The second phase of cementing was made pumping 44 m^3 of cement slurry (35 tonnes of cement) down the annulus with average density of 1.68 kg/l, but it did not fill up the annulus;
6. After 5 hours of cement hardening, 13 m^3 of cement slurry (10 tonnes of cement) were pumped through the annulus from the top with no return to surface. Three hours later, 0.7 m^3 of cement slurry were pumped and cement was returned to the surface.

Figure 18b also shows the cement bond log made 15 hours after the last cementation. An acceptable cement bond was found for the full length of the production casing with an average quality of 80%.

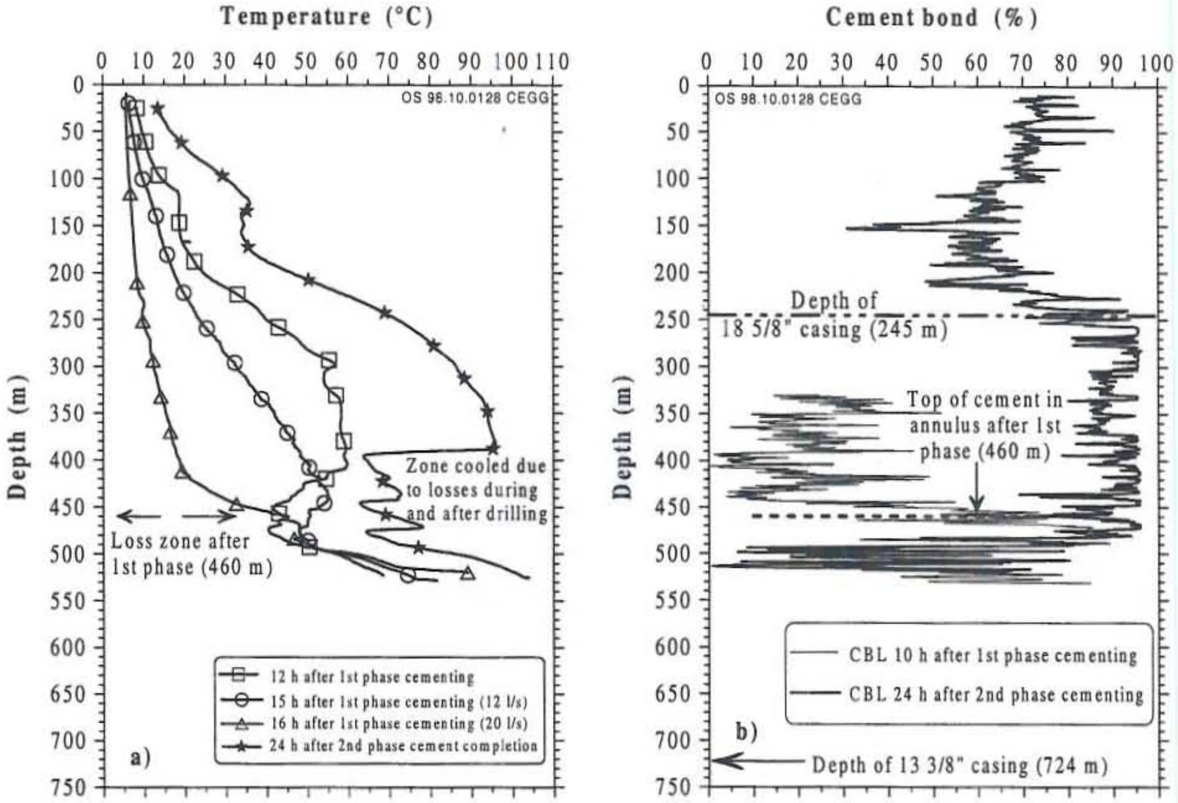

FIGURE 18: Well SJ-19 in Svartsengi, a) Temperature log after 13 ⅜" casing cementing, and b) Cement bond log after 1st and 2nd phases of 13 ⅜" casing cementing

6.2 Berlín geothermal field, El Salvador and production casing cementing of TR-4A

The Berlín geothermal field is located in the eastern part of El Salvador, about 100 km from San Salvador. The first deep well (TR-1) was drilled in 1968, and in the time interval from 1978-1995 nine deep wells were drilled (Figure 19). Three of them are used for injection of waste water from a 8 MWe power plant. Now the project "Primer desarrollo a condensación campo geotérmico de Berlín", is under construction which plans to drill sixteen new deep wells to serve a new power plant for 56 MWe of installed capacity.

Well TR-4A was the first directional and production well drilled in this project, with a 2157 m developed depth (Figure 20). This well is located in the southern part of the geothermal field and its construction took 200 working days. The long drilling time was due to several losses of circulation treatments, fishing operations and a stuck pipe. Figure 21 shows the main activities during drilling of well TR-4A, as a time vs. depth curve.

The third drilling stage in well TR-4A was made using a 12 ¼" bit from 562 to 1575 m depth. Serious partial and total mud losses were encountered in the depth interval 583-1450 m. They were healed with loss of circulation materials (LCM) based on coffee skins, high viscosity mud and 51 m^3 of cement slurry in fourteen cement plugs (Table 2). Temperature logs taken during drilling show a main loss zone at 700-750 m (Figure 22). A total of 33.4 m^3 of cement slurry needed to be placed in that zone in seven cement plugs.

The cement slurry volume for 9 5/8" production casing cementing (60 m^3) was calculated based on the caliper log (Figure 23). The production casing was anchored at 1571 m and the inner-string method was used for casing cementing. The bottom hole temperature, measured at 1574 m after four hours of warm-up, was 183°C. However, based on temperature logs made before running casing, the BHCT was estimated at about 120-130°C and the cement slurry design was as shown in Table 3.

TABLE 2: Cement plugs placed during drilling of well TR-4A, El Salvador

Plug no.	**Well depth (m)**	**D. pipe depth (m)**	**Mud loss (m^3/h)**	**Cement volume (m^3)**	**Top of cement (m)**	**Lost cement (m^3)**	**Comments**
1	4	3	Total	3.0	1.7	2.2	
2	12	11	Total	5.0	6.7	3.1	
3	17	16	Total	6.0	12.7	4.5	
4	17		Total	5.0	12.0	4.7	Cement-sand (hand mix)
5	17		Total	5.0	10.5	4.5	Cement-gravel (mix truck)
6	17		Total	5.5	0.0	1.9	Cement-gravel (mix truck)
7	26	25	Total	3.0			Stuck cement in RCM
8	26		Total	3.0	16.0	2.5	
9	26		Total	5.5	6.0	2.0	Cement-gravel (mix truck)
10	38	37	Total	4.8	31.5	2.6	
11	47	46	40	7.7	31.8	2.6	It was not healed
12	47	31	40	4.6	18.0	0.2	
	94			**18.0**			20" casing cementing
1	166	165	24	4.2	141.0	0.3	
2	205	204	Total	6.0	187.0	3.2	
3	205	187	Total	7.4	186.0	7.2	Partial loss, 3 m^3/h
4	556	555	Total	10.0	492.0	0.0	Partial loss, 3 m^3/h
5	556	543	Total	6.5	539.0	5.8	
6	583	537	Total	7.6	495.0	1.1	
7	583	325		16.2	238.0	2.7	
8	583	237		27.0	190.0	19.7	
9	583	188		18.0	120.0	7.4	
10	562	559	Total	9.0	501.0	0.0	
11	562	545		5.0	519.7	1.1	
	547			**41.0**			13 3/8" casing cementing
				17.0			From top into annulus 20"-13 3/8" casing
				4.8			From top by tubing
1	750	744	Total	5.6	694.0	1.8	
2	750	693		6.3	694.0	6.3	
3	750	693		8.3	583.9	0.0	
4	750	566		5.7	530.0	2.9	
5	750	583		3.5	545.0	0.6	
6	750	722		2.0			
7	750	566		2.0	566.0	2.0	
8	846	750	Total	1.5			
9	846	567		1.5			
10	1229	1134		8.5	1046.0	1.8	To seal wrong hole
11	1418	1418	20	2.0			
12	1418	746		2.0	736.0	1.2	
13	1455	755	10	2.0	738.0	0.7	
14	1455	681		1.2			
15	1455	743		7.4	699.0	4.0	
	1574			**89.0**			9 5/8" casing cementing
				34.0			From top into annulus 13 3/8"-9 5/8" casing
				20.0			From top into annulus

% bwoc: Percent by weight of cement

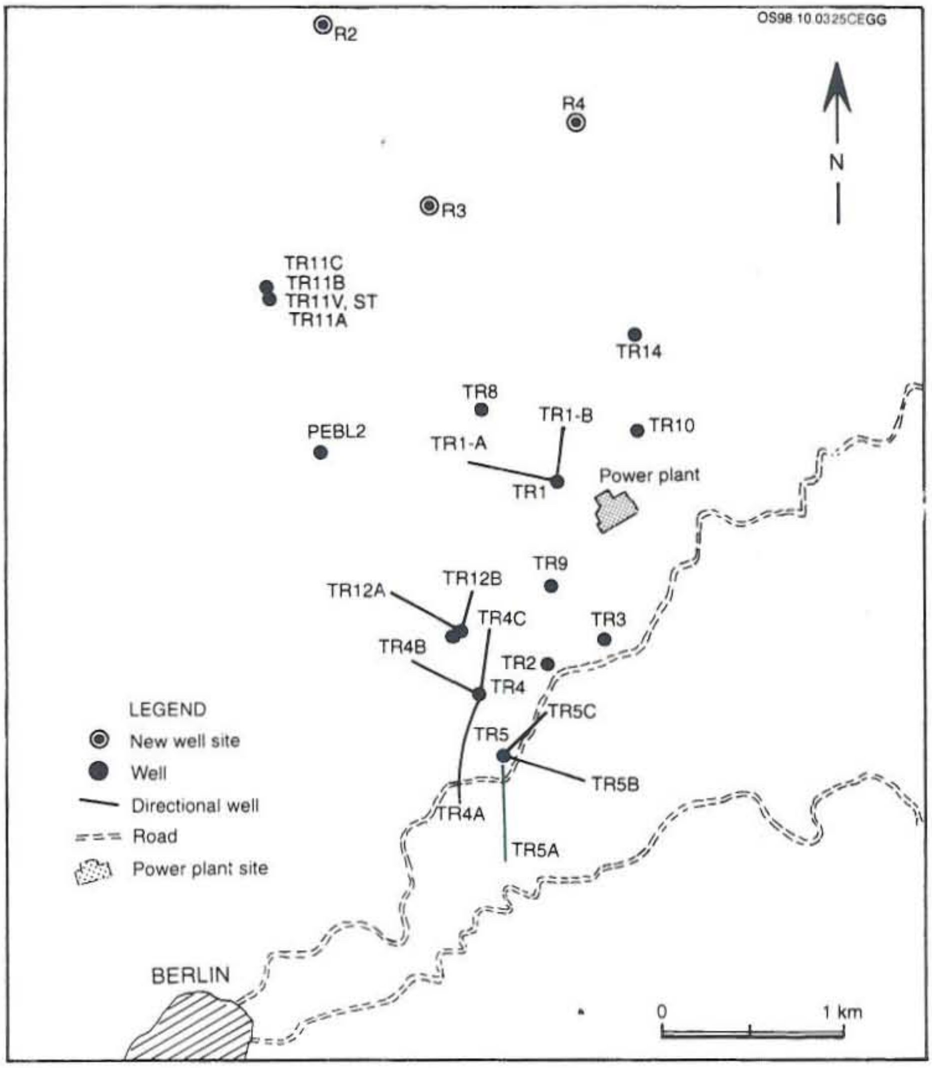

FIGURE 19: The Berlín geothermal field and wells, El Salvador

TABLE 3: Well TR-4A Berlín field, cement slurry design for production casing cementing,

Cement and additives	**Inner string cementing**	**Cementing from top**
Class H cement	100	100
Silica flour (% bwoc)	35	35
Dispersant (% bwoc)	0.6	
Fluid loss additive (% bwoc)	1.5	1.5
High-temp. retardent (% bwoc)	2	
Antifoamer (% bwoc)	0.2	

% bwoc: percent by weight of cement

In order **to calculate the cement slurry density** with zero free water it is necessary to know the following information: a) Slurry design (percent by weight of cement), b) additive density, and c) additive water requirement. The data of items two and three are found in the "Halliburton Services (1995) Cementing Tables Handbook" and is shown in Table 4.

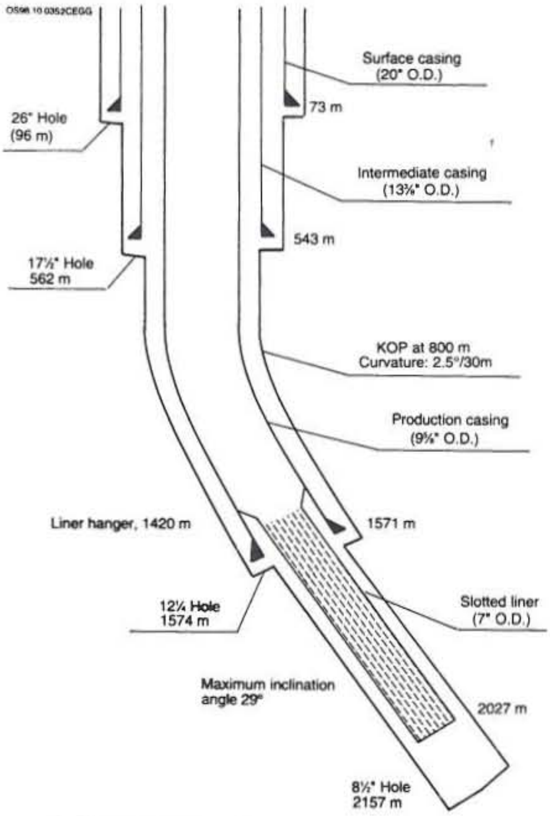

FIGURE 20: Casing profile of well TR-4A, Berlín

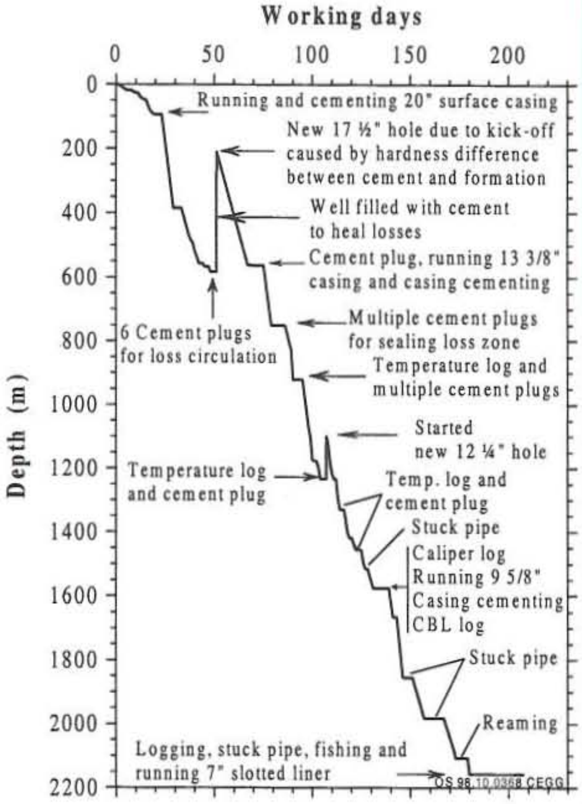

FIGURE 21: Drilling progress diagram of well TR-4A, Berlín

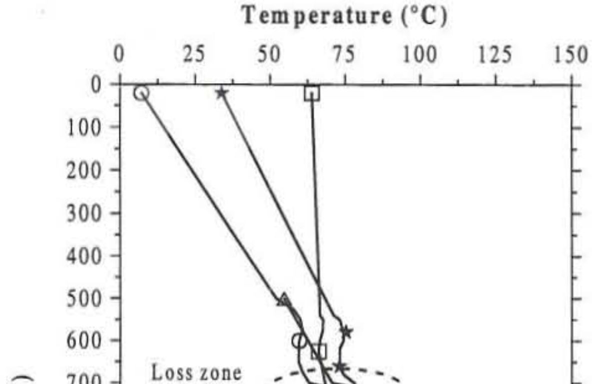

FIGURE 22: Temperature logs taken during drilling of TR-4A, Berlín

The weight of each additive is given by the equation

$$m_a = \frac{42.6(\%bwoc)}{100} \tag{1}$$

where

m_a = Cement additive weight (kg/sack);

$\%bwoc$ = Additive percent by weight of cement.

The contribution of each material to slurry yield, is obtained by

$$S_a = \frac{m_a}{\rho_a} \tag{2}$$

where

S_a = Slurry yield from each additive (l/sack);

ρ_a = Additive density (kg/l).

Based on density definition, the cement slurry density will be

$$\rho_s = \frac{m_T}{S_T} = \frac{85.06\ kg/sack}{46.42\ l/sack} = 1.83\quad kg/l$$

where ρ_s = Cement slurry density (kg/l);
m_T = Total mass (kg/sack);
S_T = Total volume (slurry yield) (l/sack).

According to Table 4, the total slurry yield is 46.42 l/sack and the water requirement is 25.80 l/sack for the cement slurry design.

TABLE 4: Water requirement and slurry yield calculation

Cementing materials	Concent. (% bwoc)	Weight (kg/sack)	Density (kg/l)	Slurry yield (l/sack)	Water requirm. (l/sack)	Dry material (tonnes)
Class H Cement	100.0	42.60	3.14	13.57	19.70	91.12
Silica flour	35.0	14.91	2.63	5.67	6.10	31.89
Dispersant (CFR-2)	0.6	0.26	1.30	0.20	0.00	0.55
Fluid loss additive	1.5	0.64	1.32	0.48	0.00	1.37
Retarder (HR-12)	2.0	0.85	1.22	0.70	0.00	1.82
Water		*25.80*	1.00	*25.80*		
Total sum		**85.06**		**46.42**	*25.80*	126.75

% bwoc: Percent by weight of cement

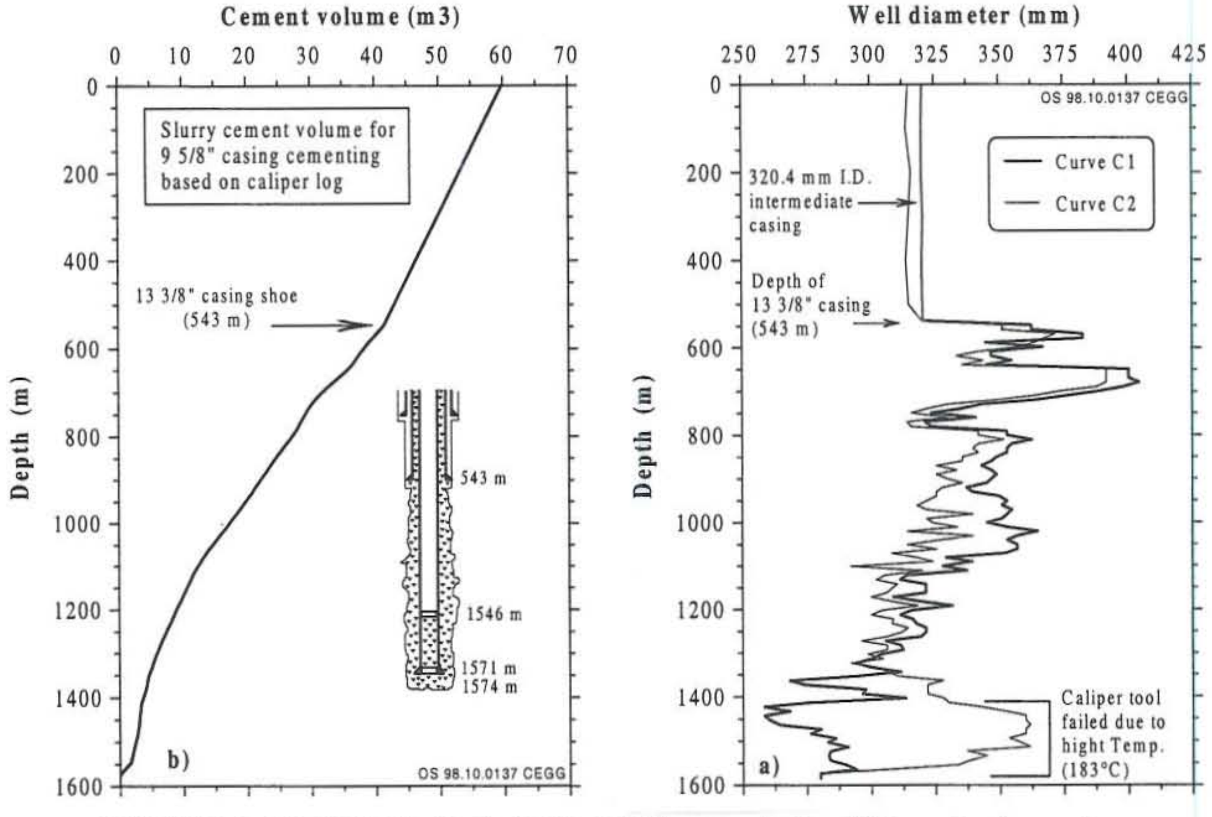

FIGURE 23: Well TR-4A, Berlín field, a) Caliper logs before 9⅝" production casing, and b) Cement slurry volume for casing cementing

Total quantity of bulk cement required. Based on caliper logs from well TR-4A (Figure 23), the cement slurry volume needed for 9 ⅝" casing cementing is 60 m^3. But, depending on the well condition and experience from this field, a 50% excess volume was added to the calculated volume from the caliper log. Therefore, the total slurry volume was 90 m^3.

The slurry yield for this cement slurry design is 46.42 l/sack. Then the weight of cement class H will be

$$WOC = 0.047\left(\frac{V_s}{S_T}\right) = 0.047\left(\frac{90{,}000}{46.42}\right) = 91.12 \ tonnes \tag{3}$$

where WOC = Weight of cement (tonnes);
V_s = Cement slurry volume (l);
S_T = Slurry yield (l/sack).

Finally, according to the water requirement (25.80 l/sack) and the total sacks of cement class H (91.12 tonnes = 1940 sacks), the total water for mixture required will be

$$W_T = \frac{25.80 \ (l/sack) \times 1940 \ sacks}{1000} = 50 \ m^3$$

Procedure used in primary cementing of well TR-4A. Production casing cementing was made using the inner string method according to the following procedure:

1. Float collar with sealing sleeve was installed 25 m above float shoe;
2. A sealing adapter (tag-in) was connected to the drillpipe string and lowered down as far as the float collar sleeve, where it was seated;
3. Cementing head was installed on the drillpipe;
4. Mud was circulated through drillpipe for three hours for cleaning and cooling well;
5. 6.5 m^3 of sodium bicarbonate in water solution (10 % P/V) was pumped as a chemical spacer;
6. Cement slurry 89 m^3 in total was pumped through the inner-string (drillpipe), the first 58 m^3 were pumped with partial return of mud and the last 31 m^3 with no returns;
7. Cement slurry contained within the drillpipe was displaced pumping 12.8 m^3 of mud;
8. Immediately 17.5 m^3 of water volume was pumped into the annulus from the top followed by 34 m^3 of cement slurry, but without fluid return;
9. After 12 hours of cement hardening, 20 m^3 of cement slurry were pumped to fill-up the annulus, ending the operation.

Four days after the casing cementing was finished, CBL log found good cement bonding (40-90%) in all of the annulus space (Figure 24).

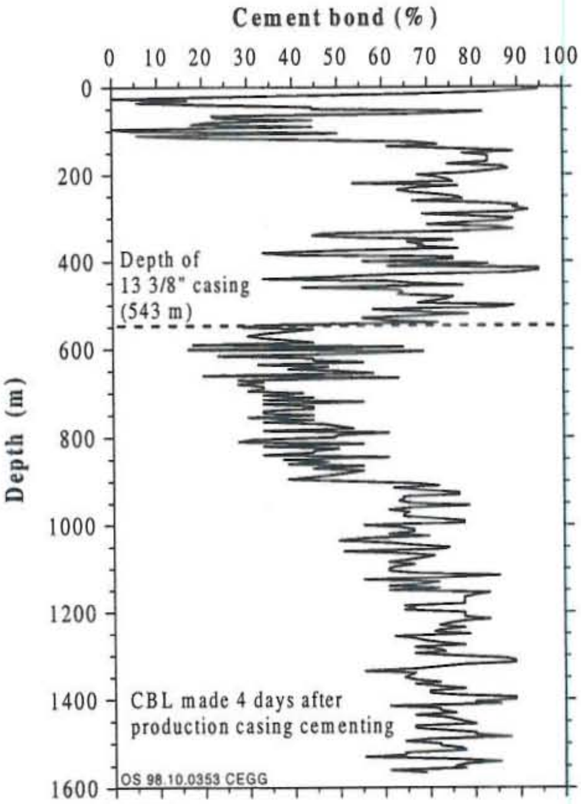

FIGURE 24: Well TR-4A, Berlín, cement bond log made after production casing cementing (C.E.L, 1997)

7. CONCLUSIONS

a) Before initiating a conventional primary cementing operation, the lost circulation problems should be eliminated or significantly reduced. Further field evaluation is required to determine the best time to attempt to heal the lost circulation zone, either during the drilling phase or prior to cementing the casing. Nevertheless, sometimes lost circulation occurs after running casing.

b) The success of a cementing operation in a geothermal well depends on completely filling the annular space between the casing and the well with cement slurry of most suitable properties. This can be achieved even though it is necessary to do the operation in two or more phases, when loss of circulation occurs and cement returns to surface are not obtained.

c) The main feature of the cementing program being utilized in the Svartsengi field, SW-Iceland, is its simplicity. Its merits follow from an understanding of the conditions in the field based on experience with what does and does not work with lost circulation control, and using only the basic cement additives for cement slurry designs, achieving success in deep wells. An important part of that is the use of expanded perlite as a good bridging material for controlling losses.

d) Field experiences show that in most cases, the best technique for deep casing cementing in geothermal wells is the inner string method, due to its flexibility in adjusting the volume of cement used to actual well conditions while a job is in progress. Also, it accepts any cement slurry design. Commonly, a second operation from the top is necessary when lost circulation occurs during primary cementing, in order to fill the annular space between casings. This practice does not decrease the cement quality in that important zone when the operation is correctly done.

e) The success of cementing operations in geothermal wells, depends greatly on the information obtained from well surveys as well as temperature logs, caliper logs and cement bond logs. Also, the quality of the cement materials (cement and additives) plays a very important role in achieving the desired results.

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