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GEOTHERMAL DRILLING AND WELL PUMPS

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ABSTRACT

Geothermal drilling in Iceland started in 1930 to enhance the natural discharge of geothermal springs that were exploited for house heating. Initially the wells were self flowing (artesian) but in 1964 the fist deep well pumps were installed which allowed much higher production rates and new areas to be tapped. The geology of Iceland is characterised by sequences of basaltic lava flows and an active volcanic zone passing through the centre of the island from SV to NE. Outside the volcanic zones there are the so called low-temperature areas where the temperature gradient is 70–100°C/km but associated with the volcanic centres are the high-temperature fields with temperatures exceeding 300°C at 2 km depth. The paper describes the drilling technology applied in tapping these geothermal resources and the main challenges. Now most wells are drilled of bigger diameters than in the past to take advantage of larger flows and directional drilling is becoming widespread to minimize the environmental impact and to better target the near-vertical structures that conduct the fluid. The well designs have been standardized and together with uninterrupted drilling year after year the drilling technology has advanced. Exploration wells and shallow production wells are drilled with air hammers. Deeper wells are drilled with tri-cone bits with water as the drilling fluid. Drilling mud is only used to improve the cutting removal when drilling with large bits. Highly automated rigs with top-drives together with down-hole mud motors have allowed much faster drilling. It typically takes 35-45 days to complete wells to 2000 m. Although new technology is important the knowledge and experience of the drilling crew is essential in achieving success.

Pumping is required in most low-temperature wells but the high-temperature ones are self-flowing. In many cases the maximum flow is limited by the pump diameter that can be installed inside the well. In Iceland the average pumping rate per well is 40 l/s and the maximum 90 l/s. There are some 200 well pumps installed in the city owned district heating systems and an equal number in rural areas. The large pumps are shaft driven but submersible pumps are used in the smaller wells serving rural areas. The “Icelandic geothermal pump” evolved after 1964 where the challenge was to obtain long life of the shaft bearings. Now these pumps work for 5–10 years without requiring maintenance. Submersible pumps are gaining popularity as higher temperature motors and of larger size become available.

1. GEOTHERMAL DRILLING

Drilling into geothermal reservoirs started about a century ago and came of age in the second part of the last century. Early drilling was by cable tool drilling rigs where a heavy chisel suspended on a wire rope pounds the earth to make the hole. Rotary drilling with hollow steel pipes came into use early, at first by drilling with drag bits and with steel balls, until the advent of the tri-cone bit in 1933. There have been great advances in the depth capability and the technology applied but the basic elements are still the same: to make a hole by applying rotary motion and weight to the bit to transmit energy to make the hole. Then fluid is circulated to bring out the cuttings. While there are thousands of rigs active, drilling for oil and gas around the world, there are only a handful of rigs drilling geothermal wells. The equipment and technology for geothermal drilling is practically all derived from the oil and gas drilling industry, but some of the technology is adopted from deep freshwater drilling and core drilling.

In this paper low temperature drilling refers to drilling into reservoirs below 200°C and high temperature drilling is defined as above 200°C at 2000 m, according to the custom in Iceland. The geologic environment is very different where geothermal drilling is carried out, in: sedimentary basins, crystalline rock, and volcanic rocks of either basaltic or andesitic composition. The low-temperature reservoirs are found in all these environments. The high-temperature reservoirs are on the other hand in one way or other associated with volcanic activity where the heat source is hot intrusions or magma bodies. They are most often situated inside, or close to, volcanic complexes such as calderas and/or spreading centres. Permeable fractures and fault zones mostly control the flow of water in volcanic systems.

The majority of low temperature wells are drilled to 600–2500 m in Iceland. Where the gradient is not as high much deeper wells are required, some going as deep as 6000 m. The high-temperature geothermal wells are drilled to 1500–3000 m and some as deep as 4500 m. Many of these are drilled as directional wells, for example more than half of the high temperature geothermal wells currently being drilled in Iceland. The trajectory chosen is rather similar, a kick-off point (KOP) at 300–600 m after landing the anchor casing and then a build-up to 30–45° after which the inclination is maintained to the final depth. The resulting horizontal displacement for directional wells is 700–800 m for a 2000 m deep well. The casing programme is virtually the same for directional wells as for vertical ones. Directional wells have proven to be relatively problem free to drill but their cost is about 30% higher. The higher cost is partly offset by shorter surface pipelines and less civil works. Directional wells are preferred for environmental reasons, and the targeting of near-vertical structures is easier.

2. GEOTHERMAL DRILLING EQUIPMENT

The rigs used for geothermal drilling are oil well rigs with 200–450 t hook load capacity and were equipped with rotary table drives, but now many have a top-drive. Top drive rigs have a hydraulic or electrical motor riding high in the mast connected directly to drill string. This provides several advantages over the conventional rotary table rigs as the drill string can be rotated while it is being tripped out of the hole, lessening the chances of becoming stuck. Water or mud can also be pumped through the drill string while the sting is being lowered into a hot hole, thus avoiding heat damage to the bit, mud motor and down-hole tools such as Measurement While Drilling (MWD) tools. Such top-drives are found on most new rigs and can be retrofitted to older ones. Old unmodified rotary rigs with rotary table drives are nevertheless still being used for geothermal drilling as they are less expensive, are robust, and have performed well. In the past hoisting of the drill string was done by a wire winch but now hydraulic pistons or motors do the job. This allows more precise weight on bit to be maintained, keeping the rate of penetration high. Most of the modern rigs handle only “singles” 13 m long drill pipe ("super-singles") or "doubles" and not the "triples" 3 x 9 m long pipe stands. The tripping speed of the new rigs is around 250 m/hr, slightly below what is achieved on a rig pulling "triples". Automation has entered the rig floor where the drill pipe is brought into position by a robotic arm and the "iron roughneck" tightens the threads to the prescribed torque. Now the only manual work for the "roughnecks" in handling the drill pipes is to apply the grease to the connections. This technology originated in offshore drilling but is now being introduced on land drilling rigs. Modern rig digital instrumentation displays the important parameters to aid the driller in his work. The same information can also be transmitted on-line over the Internet to allow remote observation. The work on the new technology rigs is easier and safer for their crews and that helps attract qualified personnel.

Of the total time it takes to drill a geothermal well, only 30–40% is actually spent to make hole by rotating the drill bit on bottom. The rest of the time is spent on: rig transport and rigging up, installing and cementing casings, installing safety valves, logging operations, to solve drilling problems related to loss of circulation or instable formation, for "fishing" when the drill string becomes stuck or breaks. A good way to assess whether there are drilling problems is to look at the drilling progress curve by potting depth vs. number of days. Any "flat spots" where there is no advance in depth for several days shows clearly up and their cause can be analysed further.

The technology is now such that a production well can usually be drilled to 2000 m in 35–45 days. In the past, drilling 40–100 m/day was considered quite acceptable, but now drilling of 200–300 m/day is not uncommon. The main reason for such fast drilling is the use of down-hole mud motors. The mud motor sits just above the drill bit, and is driven by the hydraulic power of the circulated drilling mud. That results in some 200 rounds per minute (rpm), and when the drill pipe rotation is added the final bit speed may be around 250 rpm, quite a bit faster than the 50-70 rpm for conventional rotary drilling. The mud motors are required to build-up angle during directional drilling, but after they were found to improve dramatically the rate of penetration, they have also been deployed in drilling vertical holes. The mud motors have parts made of elastomer (rubber) that cannot take high temperatures, but this is not as serious a problem as one would think, because the drilling fluid cools the well so efficiently that temperatures under 100°C can be maintained inside a 2000 m deep well even though the reservoir temperature exceeds 300°C. Effective cooling of the well also allows Measurement While Drilling (MWD) tools to be run deep in the hole. The MWD tool transmits information to a surface read-out unit the azimuth, inclination and tool-face orientation of the bit, information that is used to steer the drill bit. The MWD is often removed from the string after the final inclination of 35–45° has been reached because a danger of losing the tool if the drill string should get stuck or temperature damage. The Bottom Hole Assembly (BHA), the lowest 100 m of the drill-string or so, has also seen changes. In the past there was a drill bit and on top of it the drill collars to exert pressure to the bit and then stabilizers to keep the string in the middle of the hole. Now the BHA usually also contains a mud motor, the MWD tool, a shock absorber, and then the drill collars with a hydraulic jar near the top to free the string should it get stuck. On top of the drill collars there is a key-seat reamer and a few "heavy-wate" drill pipes to smooth the transition over to the normal drill pipes.

The lifetime of tri-cone drill bits has steadily improved especially those with journal bearings and with hard metal tungsten carbide inserts "teeth" and "gauge protection". These are considerably more expensive but can be rotated over one million rounds and drill up to 1000 m without being replaced. This results in time savings as fewer round trips for replacing the bit are required. Polycrystalline Diamond bits (PCD) are now widely used in oil drilling and have found some use in geothermal drilling, especially in sedimentary formations. They can drill very fast and are used with mud motors. Drilling with PCD bits without a mud motor is possible, but the rotary torque is commonly twice as high and life shorter than for a tri-cone bit. These bits are now used together with a special reamer to drill oversize holes relative to the last casing diameter, as the combination functions as a bi-centric bit. For drilling of the surface hole to a depth of 100 m or so, air-hammer drilling with foam has been applied up to a hole diameters of 26". Air hammers are also used for drilling to 200–400 m, especially small production wells and temperature gradient holes. The surface hole is sometimes drilled with another smaller rig, prior to bringing in the large rig. For drilling the large diameter surface holes sometimes a reverse-circulation system is used as it aids in cleaning the cuttings from the hole. That requires a double-walled drill pipe where the cuttings come up through the centre pipe.

3. WELL DESIGN

Geothermal wells are designed to enable safe drilling into geothermal reservoirs and then to allow production of the geothermal fluid, be it steam or water or both. As most geothermal fluids are compatible as far as the scaling chemistry is concerned the produced fluid can come from any depth, as long as the minimum temperature requirements are met. For geothermal wells it means that the open hole part is usually over 1000 m long but supported by a slotted liner or screen. This allows any fluid to enter the well. Most geothermal wells have 2–5 cemented casing strings, the deepest one reaching to 700–1200 m in the case of Iceland (production casing). The purpose of these casings is to:

- To seal out unwanted aquifers and to prevent fluid migration between formations.
- To support the hole.
- To allow control of blow-outs and to anchor the wellhead.
- To provide a conduit for the well production.

The basic steps in the well design are to:

- Determine the number of casing strings required (2–5 strings) and the diameters and lengths of each of the following casing strings:
    - Conductor casing
    - Surface casing
    - Intermediate casing (sometimes omitted)
    - Anchor casing
    - Production casing
    - Slotted liner or well screen
- Calculate the collapse and burst and determine the required casing thickness.
- Specify the casing to meet the requirements.

The expected productivity of the reservoir and target output of the well primarily influence the diameter selection. For low temperature wells the output of the well is commonly restricted by the outside diameter of the down-hole pump that can be installed inside the well. For the pumps in Iceland the maximum flow is 15 l/s for 6", 45 l/s for 8" and 90 l/s for 12". For this reason low-temperature wells are sometimes designed with a larger casing in the upper most 400 m, so-called pump-chamber, to accommodate a larger pump.

The casing type used for low-temperature wells in Iceland is line pipe, conventional steel pipes as used on surface, and the connections are welded. This allows larger casing sizes to be installed in a hole and the casing is slightly less expensive. It does, however, take longer to install due to the time it takes to weld the connections. The depth of the production casing is usually determined by the minimum required temperature, as its main function is to exclude unwanted fluid from entering the well. Sometimes the formation in the open hole can be unsupported, so called "bare-foot", and that is the case for all low-temperature wells in Iceland. In sedimentary formations most wells, however, require a slotted liner or screen in the productive part of the well. Occasionally a liner is cemented in place, as in an oil well, and then the casing is perforated with explosive charges to make holes that allow fluid to enter.

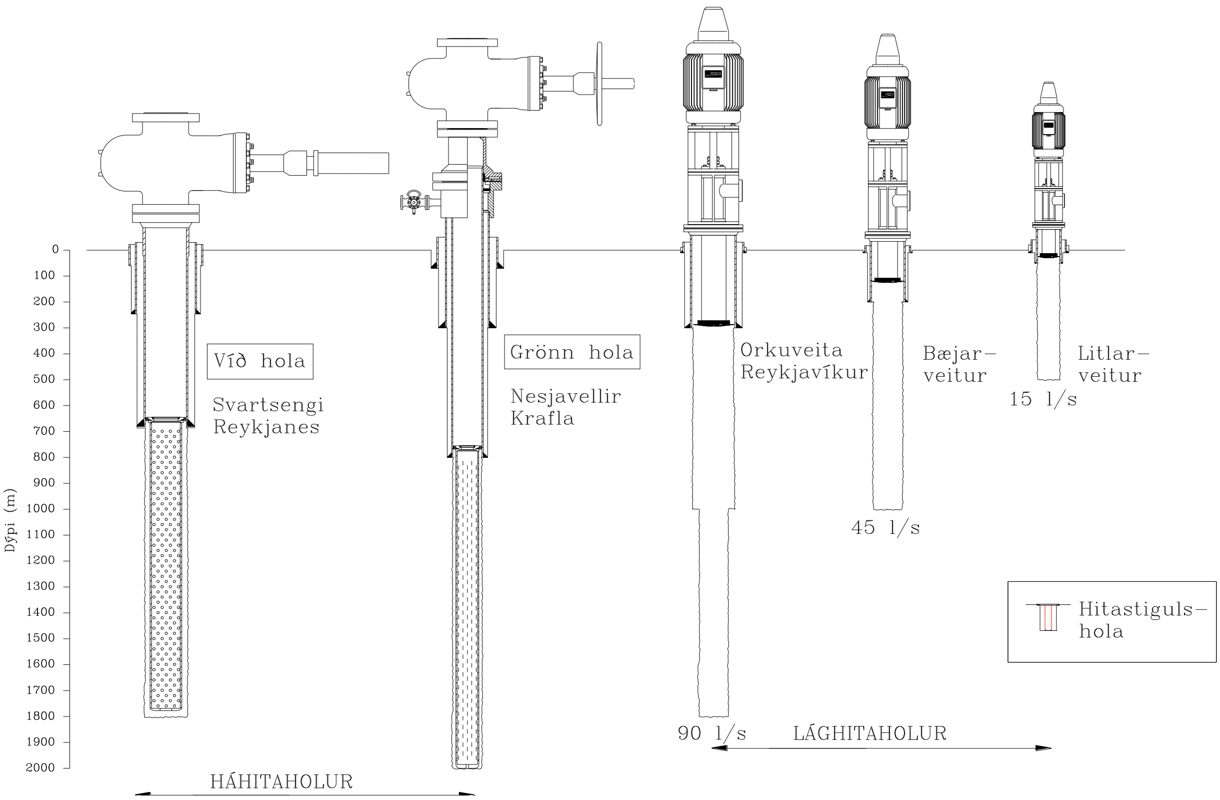

FIGURE 1: The most common casing programmes for low- and high-temperature wells in Iceland

For most high-temperature geothermal wells the diameter selection for production casings stands between a 9–5/8" a 13–3/8" casing. A few extra large wells with a 16" production casing have been drilled. If the permeability of the reservoir is excellent then the diameter of the wells becomes the limiting factor as far as its output is concerned, the output being roughly proportional to the cross-sectional are of the production casing. This has been proven several times in Iceland where a 9–5/8" well delivered up to 80 kg/s and a 13–3/8" well up to 180 kg/s. This knowledge also allows the output of small diameter exploration wells to be scaled up to larger diameter production wells (Finger, 1999). The other casing strings are of conventional American Petroleum Institute (API) oilfield tubular diameters, the most common ones being: 7" or 9–5/8" (for slotted liner), 9–5/8" or 13–3/8" for production casing and then 18–5/8", 22–1/2" or 24–1/2" etc.

The reason for the many casing strings for high temperature wells is to support the hole and especially to provide safety in controlling blow-outs. The last cemented casing string, the production casing, also has to consider the minimum target temperature by reaching at least that deep into the reservoir. There are cases where the casing is not deep enough to screen out temperatures below say 200°C and this can lead to cycling of output as the two systems, say 190° and 290°C, fight for control. The geology also comes into consideration when deciding on the casing depths, but usually it is the minimum casing depth for safety or the minimum temperature requirement that is the deciding factor.

To determine the minimum casing depth for each casing string in a high-temperature well the temperature and pressure vs. depth should be known for the well to be drilled. The "worst possible case" for casing design, e.g. in a new area where actual information is not available, is the Boiling Point Depth curve (BPD). There are primarily two methods used for casing depth determinations when the reservoir conditions are not known: One is from the New Zealand Standard NZS 2403:1991 that assumes the bottom hole pressure to be transmitted up the hole through a steam column (steam filled hole). This pressure should not exceed the overburden pressure at the respective casing shoe depth, as depicted in the following diagram from the NZ standard.

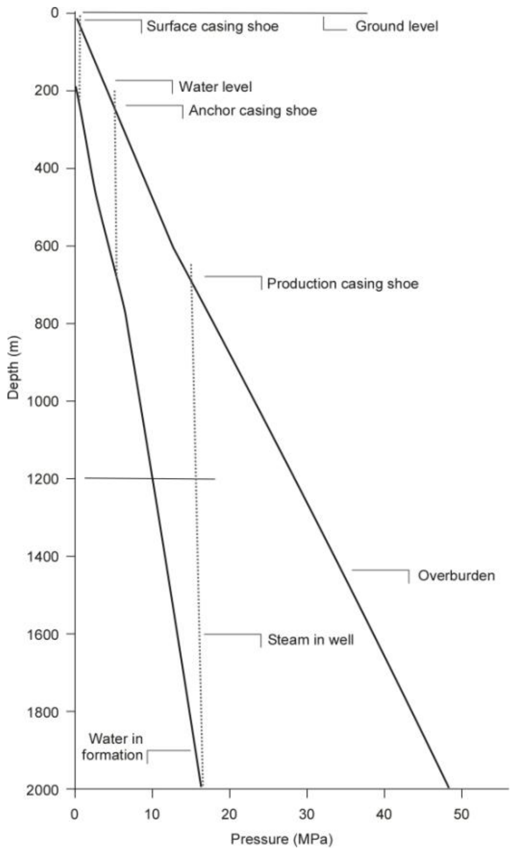

FIGURE 2: Determination of the minimum *casing* depths of high-temperature wells where formation characteristics are not known (NZ standard 2403:1991)

Another method used in Iceland is to assume the same bottom-hole pressure (from BPD curve) but the pressure profile is that of an adiabatically boiling column of water. The criterion is to be able to kill the well with mud of SG 1.4 density in the worst possible case. If there are reasons to believe that there is some deviation from the BPD curve, a colder well, then the most desirable case is to be able to kill a well during an underground blow-out with water alone (SG 1.0). This method gives slightly longer casing strings than the NZ standard. As a very rough "rule of thumb" for each section of the well being drilled, the casing needs to cover 1/3 of the target depth for that section. For example in a 2400 m hole with three casing strings the production casing should reach 800 m, the anchor casing to 267 m and the surface casing to 89 m. Note that by targeting a well to go deeper all casing strings need to be longer to fulfil the criteria. Once the exact temperature and pressure is known for a particular site a more precise determination of the casing depths can be made. The previous descriptions were for the determination of minimum casing depths. The actual determination also considers at what depth the target temperature will be reached and geological conditions.

A special case to consider is drilling into "steam cap", that are commonly found to have a temperature of 240°C and a pressure of 32 bar. The pressure gradient in the steam zone is almost constant. This pressure can reach near surface to give rise to special blow-out control problems. Actually "kicks" (sudden eruptions) are most common while drilling the 100–300 m interval where there is boiling ground. For such wells it also means difficulty in landing the slotted liner, which may in cases not be possible at all due to "kicks". In spite of not having a slotted liner, these wells have been used "barefoot" and are very good steam producers. These shallow "steam cap" conditions may not be present during the exploration phase but can develop as the result of a draw-down in the reservoir form prolonged production.

The casing steel grade takes notice of the H_2S found in the geothermal fluid and usually grade API K55 or N80 is used. Connections were mainly screwed API Buttress but WAM and Antares or ER are now also found. In Iceland the 18–5/8" casing and 22–1/2" are butt-welded to allow small clearances in the 21" and 24" drilled holes. All casings in low-temperature wells have welded connections.

If wells intersect good permeability the mass flow may become limited by the diameter of the production casing. There are, however, cases, especially if there is boiling in the formation, where the formation and not the well itself restricts the flow. In the past most high-temperature wells had a 9–5/8" production casing but now many have a 13–3/8" casing. The corresponding open hole part is drilled with a 8–1/2" bit and 12–1/4" bit. In exceptional cases a 16" production casing has been run. As the rigs are generally big, the larger hole and casing diameters are not a problem. The larger diameter casing also has the advantage that it does not clog as quickly by scaling and in case the well requires repairs later on there is room for a liner inside. By standardizing on two to three casing program sizes the inventory of drilling tools becomes simpler and the drilling becomes routine.

4. DRILLING FLUIDS

The main function of the drilling fluid is to bring out the cuttings from the bit, support the hole, cool the well, lubricate the drill string and supply power to the mud motor and MWD. The formation to be drilled dictates the type of drilling fluid to be used and the properties to be maintained. The selection of the fluid programme is a special subject, especially in sedimentary basins where unstable clays or salt formations are encountered. In the volcanic environment simpler mud programmes can be used, as described below, and quite often it is possible to drill by water alone.

Water-only with no additives is the preferred drilling fluid in the productive part of geothermal wells, perhaps occasionally using polymer or mud-pills to clean fill-ins. It is felt that less formation damage is caused by the use of water and also less expensive than mud and allows uninterrupted drilling after loss zones are encountered. The drilling fluid heats up as it goes down the drill pipe to the bit and is cooled by it as it returns to surface in the annulus. In Iceland it is quite common for freshwater being pumped into the well at 5°C to return to the surface at 25°C, after having reached perhaps 80°C in the deepest part of the hole. When mud is re-used the heat has to be removed to avoid build-up of temperature.

In Iceland water based bentonite mud is used while drilling with large diameter bits >17–1/2" to obtain adequate hole cleaning. The low-solids water based mud (SG 1.02) is a "simple" one made with high yield bentonite clay (Wyoming bentonite), and the additives are only caustic soda to maintain high pH, and a dispersant. A high density mud of SG 1.4 is rarely required, then only to control artesian overpressure in wells. The mud is cooled by passing it through a tubular heat exchanger with mud runs on the inside and water on the outside. Air-cooled mud coolers are also used. The cooling is by about 20°C from 90°C to 70°C or say from 60°C to 40°C.

Usually the pressure within a geothermal reservoir is low, so a well full of drilling fluid will show a fluid loss, often causing a total loss of circulation, once a fracture is intersected. A large loss is a positive indicator for future production from the well but may cause problems with hole cleaning while the well is being drilled. The cuttings from the drill bit will thrust into the rock formation and may with time partially plug fractures. Lately, methods that attempt to overcome the formation damage have been applied by what is called "balanced drilling" (aerated drilling) or sometimes "underbalanced drilling" (Hole, 2006). It requires large air compressors, a rotating head, and a separator on the flow-line. Similar amounts of water are pumped into the hole as during normal drilling, together with the air. Compressed air and soap is mixed with the drilling fluid (usually water) thereby reducing the density enough so that the pressure inside the well will be no greater than the respective reservoir pressure. Thus no fluid or sand should be lost to the formation. For many wells, especially deviated ones, the air is lost together with the water after a large loss zone is intersected and neither water nor cuttings return to the surface. Remarkably the rate of penetration for normal rotary drilling (without mud motor) goes up during balanced drilling, offsetting in part the higher air cost. On average these wells are reported to have up to twice the output of conventionally drilled wells in the same field (Hole, 2006). When wells are drilled into steam dominated reservoirs compressed air alone is sometimes used. After intersecting steam it flows out of the well together with the air. This is another way to achieve under-balance, that has been is use for 25 years in Iceland for low-temperature wells. A 9-5/8" casing is temporarily suspended from the wellhead down to 220 m, inside the 10-3/4" production casing. Compressed air goes down the narrow annulus and produces air-lift pumping inside the main well, thereby reducing the pressure down in the well enough to achieve negative pressure relative to the reservoir (under-balance). This requires air compressors of only 24 bar capacity. The method has contributed to obtaining good production from wells in areas where the prospects were not so good.

5. CEMENTING

Problems relating to cementing show up on most drilling jobs. Long sections of casing pipes have to be cemented in place and during drilling there are loss zones that have to be healed. Cementing is one of the most critical operations of the drilling effort. Zones of unwanted circulation losses were treated in the past by stopping soon thereafter and cementing to heal the loss, taking 1–3 days, but now it is common practice to bypass these zones – all but the largest. Good casing cementing can nevertheless be obtained by the so called inner-string cementing method up to the loss zone. Flow of water top down in the annulus then keeps the loss zone open until the annulus is filled up by "squeeze cementing", by pumping cement slurry down the annulus to the loss zone. Recently "reverse" cementing where all the cement is pumped down the annulus, has been successfully applied. In some countries "foam" cement is used to lessen the slurry density and loss of circulation material, e.g. mica flakes, added to block the losses. Cementing of very long casing strings is done in stages (e.g. 2-stage) by a tool that opens ports to the annulus after the first stage. An inflatable packer is at times located just below the stage tool, especially in wells with high losses. At times a hung liner is cemented in place, either to create a "pump chamber", or a second section of casing reaching the surface is installed, a so called "tie-back" casing string.

The cement has to withstand the high-temperatures and the chemical environment. To that end API grade G cement with 40% silica flour added (ground quartz, -325 mesh) is most commonly used. The silica gives the cement temperature resistance and there are also cases where slag or fly ash cement is being used. Specialized oil-field cementing companies are usually engaged to carry out the well cementing operation. They bring in their own mixing and pumping equipment and materials required for the job. In order to reduce the cost some drilling contractors carry out the cementing operation with their own equipment and use local cements. Additives such as temperature retarders, fluid loss, friction reducer and antifoam, are then selected based on the required pumping time which is a function of the temperature, size of job etc. In Iceland expanded perlite (a volcanic material by origin that expands like pop-corn when heated rapidly) has been used to reduce the cement slurry density to 1.7 g/cm^3 and in other countries glass "microspheres" or "foaming" the slurry by injection of gas or air are similarly used. This is done to reduce the collapse pressure exerted on the casing from the cement column and to lessen the chance of fluid going into the formation.

6. MAIN CHALLEGES

There have been considerable advances in geothermal drilling technology and also improvements in well output. Geothermal well costs typically make up 30–50% of the total project cost of geothermal projects, be it for district heating or for generation of electricity. There is a large interest is any technology that could lower the cost of geothermal wells. Actual well costs have, however, over the past few years not gone down, but increased rapidly mainly due to higher material costs and the cost of new technology. The cost has also gone up because ever more challenging wells are being drilled, by going deeper, having larger casings and by the added cost of directional drilling. Another way to lower the overall cost of geothermal development is to improve the productivity of the wells. Considerable progress has been made in that respect, i.e. by well stimulation (Axelsson, 20076). Advances in exploration and more precise targeting also play an important role. Once several wells have been drilled in the same geothermal field, results become more predictable and so do the ways to deal with drilling problems (Stefansson, 1997). Nevertheless one must remember that geothermal wells can be remarkably different in flow and enthalpy, even within the same field.

Application of new technology may add to the well cost but improved output may offset that. In balance it is hoped that the overall cost of geothermal development can be lowered in the future through better drilling efficiency and higher well yields. There are now two international projects that focus on technology that could lower the drilling cost. One is under the International Energy Agency, Geothermal Implementing Agreement, Annex VII, Advanced Geothermal Drilling Techniques (2007, Mongillo). The European Union has supported the ENGINE program, ENhanced Geothermal Innovative Network for Europe, where the best drilling practices was one of the subjects. (http://engine.brgm.fr)

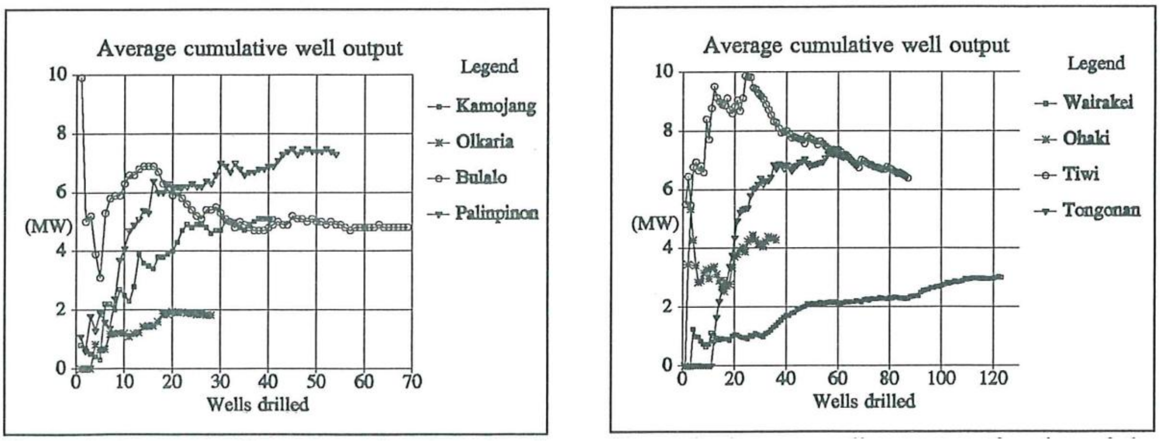

FIGURE 3: Improvements in well output as more wells are drilled. (Stefansson, 1997)

The most common reasons for high costs or cost overruns are drilling problems related to the geological and reservoir conditions. Large loss zones and fractured rock may cause delays in drilling, but then these formations are really what you are looking for in order to obtain good production! Thus it is sometimes maintained that a well which has been easy to drill, will not be a good producer.

Problems with break-downs of the drilling equipment itself are usually not serious because of built-in redundancy, extra generators or pumps that can carry on.

Technology exists that allows most wells to be drilled successfully. Although improvements are expected in equipment and materials the better knowledge and experience as to how to deploy the technology and solve drilling problems is equally important. To explain a little what the problems are, the following figure lists some of the drilling challenges faced in geothermal drilling in Iceland.

There are countermeasures available for most of the listed “drilling challenges” in Figure 5. Only very rarely does a well have to be abandoned due to insurmountable problems. For directional drilling the high torque required to rotate the drill string sometimes dictates how deep it is possible to drill. The target depth may also not be reached due to fill-in making adding a drill-pipe difficult and too high risk of getting stuck. This can occur, for example, after the well has been drilled “blind”, that is with total loss of circulation for several hundred meters. That does, however, not pose a problem as having reached total loss indicates that the well has intersected very permeable formations and can thus be expected to become a good producer.

Drilling technology can be taught in special courses, and such courses are essential, especially as regards how to control steam eruptions, so-called “Blow Outs”. Most often, the drillers acquire the skills on the job by working their way up the ranks in the drilling crew over a period of 3–5 years. The driller should focus their mind on the down-hole condition by monitoring the gauges for any changes in mud loss, rate of penetration, torque, weight on bit, rpm of bit, colour of the mud being returned, sensing the vibrations etc. These provide warnings of impending trouble but are also used as guideposts on how fast it may be possible to drill. Existing drilling equipment allows very rapid drilling and thus adequate cleaning of the hole becomes an issue. For that reason “time drilling” is the norm, where the rate of penetration is fixed, say at 10 m/hr, as is the case in Iceland. Drilling can proceed faster but after each drill rod the extra time to make up an hour is used to circulate the hole to clean the bottom before adding a new drill pipe.

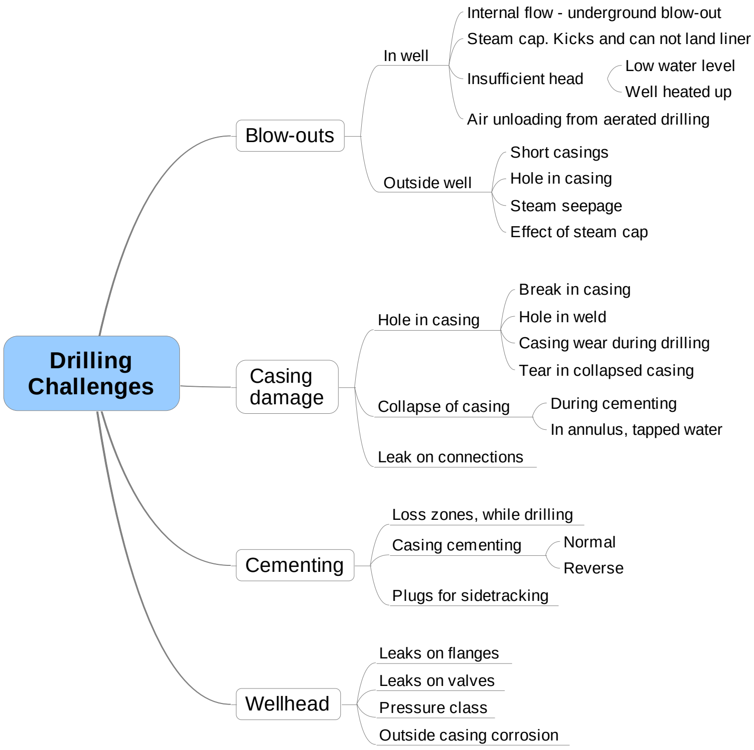

FIGURE 4: Map listing the challenges faced in HT drilling in Iceland.

There is a lot of wear and tear on the drill string and thus the its life can be anywhere from 3–6 years due to cracks, corrosion and loss of outside diameter on the tool-joints. Some of the new methods, such as aerated drilling, result in shorter life of the drill pipes due to the corrosive effect of oxygen higher torque and extra wear on the tool-joints. Regular non-destructive tests are called for to “grade” the drill string. As failure of the threaded connections on drill collars are common and some contractors ultrasonically inspect the threads for cracks each time the collars come out of the hole. Accurate pressure gauges and monitoring by the driller can detect a crack or a hole in the drill string before it breaks. All of this is done to avoid very costly fishing jobs or sidetracking (exiting the hole and drilling a new well beside the old one) operations that have to be made, if the drill string breaks.

Information provided by down-hole logging is very useful in tackling drilling problems. By using electronic logging tools it is possible to measure temperature and locate the loss zones or detect by calliper survey (measuring diameter) where there are caves or “washouts”. The well condition can also be evaluated by an acoustic televiewer that shows the diameter and any fractures. At times after pumping clean water into a hole a video camera can be sent down for inspection. Logging tools are also required to aid in fishing operations, to locate the top of the fish, where stuck and for unscrewing the drill pipes (back-off with explosives). In an extreme case explosives are used to cut the drill pipe to recover the free part of the drill string. To confirm the well trajectory readings from MWD, a gyroscopic survey is made. Cement Bond Logs (CBL) are also used to confirm integrity to the cement and if it does not return surface to detect the top of cement in order to plan remedial actions. The on-site geologist can also warn of impeding drilling problems from his analysis of the drill cuttings and knowledge of the stratigraphy.

7. DEEP WELL GEOTHERMAL PUMPS

The majority of low temperature wells require pumping as the water level is usually below the ground level and also to increase flow by inducing a draw-down that brings in more water. There are several ways to pump the wells but now it is done by multi-stage centrifugal pumps placed down in the well. These pumps were originally designed for the supply of fresh water for general use and for irrigation water, but have been modified to suit the geothermal conditions. The pump is made up of individual stages, consisting of the pump impeller and housing, where the diameter has the greatest effect on the maximum flow that can be pumped. Each stage has a certain hydraulic lift capability, say 15 m of water. The pump has to have the appropriate diameter for the required flow and as many stages as are required to achieve the desired lift, e.g. 10 stages to achieve a 150 m lift. The small size pumps are rotated at 2900 rpm and the large ones at 1450 rpm. This is done by an electric motor that either is on surface and is connected to the pump via a long shaft, called shaft driven pumps (Figure 6), or the motor is directly below the pump in the well, called submersible pumps (Figure 7). The electric motor used on the shaft driven pumps has a hollow shaft through which the long pup shaft extends and on top of the motor sits the thrust bearing. Now most pumps have a variable frequency controller (40-60 Hz) on the 3-phase electricity to fine tune the motor speed to the desired flow rate, thereby saving electricity when there is low demand. This is important as the pumping requirements must follow the heat load, which is highest when it is cold. The early pumps used in Iceland had rather short lifetime due to the use of an open shaft and rubber bearings. Oil lubricated copper bearings inside an enclosing tube did not work well either. Finally a pump was designed, referred to as the “Icelandic geothermal pump” evolved after 1964 (Zoega, 2004). Here the shaft rotates inside a stationary enclosing tube and the shaft bearings, spaced 3 m apart, are made of graphite impregnated Teflon which are lubricated by the filtered geothermal water itself. These pumps have proven to be very reliable and can last 5-10 years without requiring overhaul. Most of the Icelandic geothermal pumps are either 8" in outside diameter, having a capacity of 40 l/s at 2900 rpm, or 12" with a capacity of 90 l/s at 1450 rpm. In Iceland the total lift is anywhere from 100 m to 250 m and water temperatures up to 130°C are handled, but the most common temperature is around 80°C. Because of the good service of these pumps they are also selected as surface booster pumps for the district heating network. In small rural district heating systems the use of submersible pumps is becoming popular due to their lower price and ease of installation. For submersible pumps the temperature rating and size of the motor are the limiting factors. Inexpensive submersible motors that can operate at temperature above 100°C are becoming available and it is expected that submersible pumps will dominate the market in the near future.

The above mentioned pumps originate from the water pumping industry but submersible pumps (ESP – electric submersible pumps) from the oil industry have also been used for geothermal wells. These pumps can go deeper and tolerate higher temperatures as well. Then the down-hole motors are driven by high voltage motors and at greater speeds. Only one such pump is in use in Iceland due to their greater cost.

The pump selection starts with knowing what the water level in the well will be and future predictions, for the desired flow. Each well needs to have the productivity index (PI: (l/s)/bar) determined from pump tests. From that the desired flow rate is determined and resulting draw-down estimated. From the desired flow (l/s) the pump diameter is selected and the number of pump stages for hydraulic lift (bar). The intake of the pump needs to be several meters below the expected water level to avoid boiling (cavitation). Just how deep in the well depends on the water temperature and Net Positive Suction Head (NSPH) of the selected pump. Sometimes gas bubbles can be formed which influence the required submergence, thus knowing the gas partial pressure (e.g. of CO_2) is important. For deep setting depths the pump may require several stages of thrust-balanced impellers to lessen the axial force. Such impellers have additional seals on the back face, similar to the one on the suction side. Finally the motor size (kW) has to be determined, based on the flow, lift and type of pump selected.

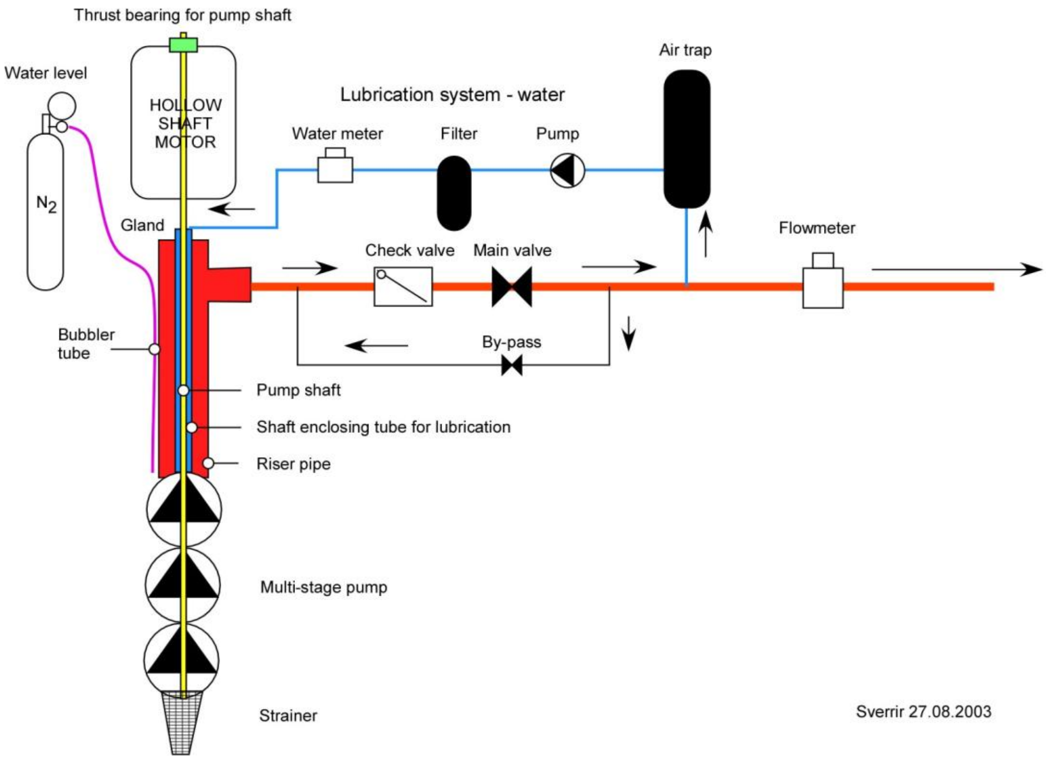

FIGURE 5: Shaft driven pump. Note the water lubricated shaft inside the enclosing tube. This design is sometimes referred to as the Icelandic geothermal pump.

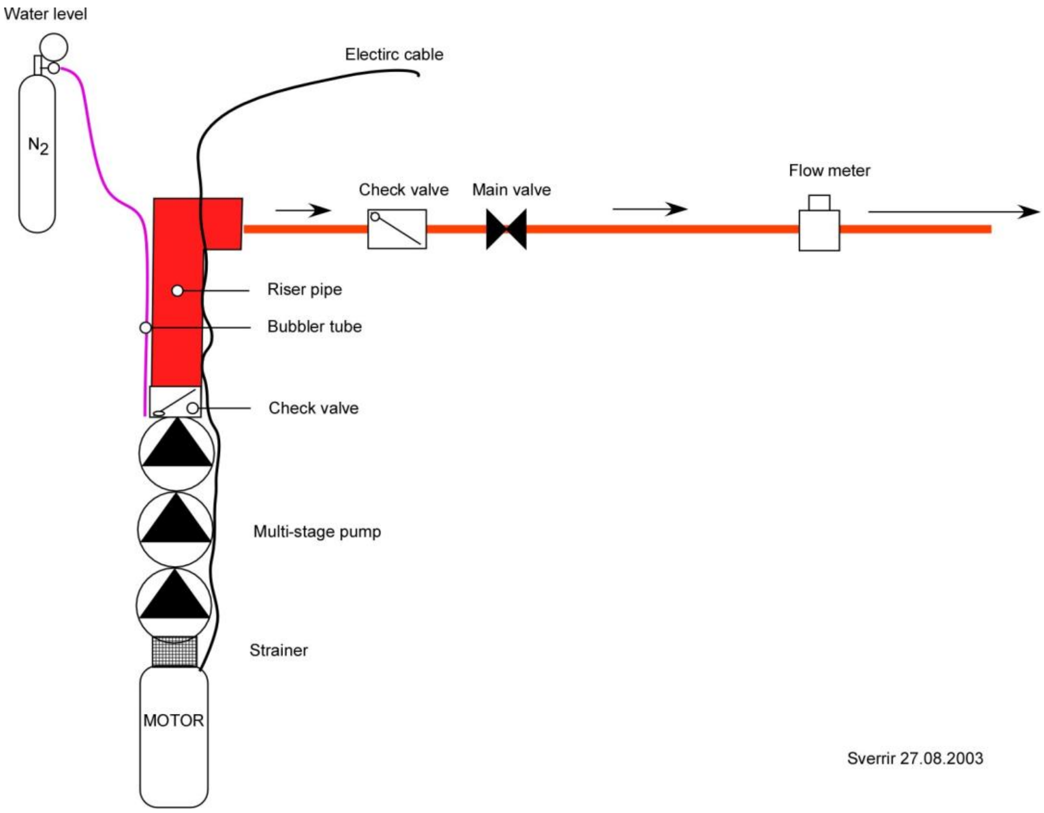

FIGURE 6: Submersible pump in a geothermal well.

To monitor the wells it is customary to install a small diameter air-bubbler pipe down to the top of the pumps so that the water level (m) can measured at all times. Nitrogen gas is frequently used to purge the pipe and its back pressure (1 bar = 10 m) tells what the water level is. Also the flow rate (l/s) is measured at surface by a magnetic flow meter. The power that the motor draws (Amp) and motor speed (frequency, Hz) is logged plus the wellhead pressure (WHP) and temperature (WHT). Such data is stored on site in modern data storage devices or transmitted to a central location. This allows close monitoring of the production and also condition monitoring of the pump. An indication on wear of the pump is an increase in the Hz to achieve the same flow rate.

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