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NEW DEVELOPMENTS IN GEOTHERMAL DRILLING

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1. INTRODUCTION

There have been considerable advances in geothermal drilling technology and improving the output of wells over the past decade. This paper mentions some of the advances so that non-technical persons with interest in geothermal development can appreciate the state of the art in this important field. Geothermal well costs typically make up 30-40% of the total project cost for electric generation. The main interest is in technology that can lower the cost of geothermal wells both for exploration and production. This goal is a worthy one and at the present time two international efforts are under way to explore the possibilities. Actual well costs have, however, over the past few years not gone down, but increased rapidly mainly due to market forces and the cost of new technology. Drilling costs have also gone up because more challenging wells are being drilled going deeper and deviating from the vertical ("directional drilling"). The other way to lower the overall cost of geothermal development is to drill very productive wells. Considerable progress has been made in this respect. Once several wells have been drilled in the same geothermal field the results become more predictable and also how to deal with the drilling problems. Nevertheless one must remember that geothermal wells are remarkably different, even inside the same field. The new technology adds to the costs but in balance it is hoped that the overall cost of geothermal development can come down in time and lead to more reproducible results.

2. LOWER THE COST

In the past, the geothermal production wells cost was around 1000 US$ per meter in depth of hole, but because of inflation and the fall of the dollar plus other cost increases, it is now almost 2000 US$ per meter. High temperature wells thus typically cost 4-5 US$ million now and the high cost has been a disincentive for geothermal development. Recent large increases in energy prices in general have lessened this and now geothermal drilling is in high gear. Because of the cut-backs in drilling effort in the past, there is now a severe shortage of drilling rigs for geothermal drilling.

2.1 IEA and ENGINE, cost and drilling effectiveness

There are two international programmes looking at the cost issues and how to improve the drilling effectiveness. One is by the International Energy Agency (IEA) "Advanced Geothermal Drilling" (GRC 2006) and the other is a coordination action by the European Union, called ENhanced Geothermal Innovative Network for Europe - ENGINE (GRC 2006). Direct comparison of drilling costs has been shown to be difficult but an effort is being made to identify the technology that can help to this end. Both programmes plan to produce a "Best Practices Handbook" where the "Stae of the Art" will be described as well as the technological gaps and opportunities. The geothermal drilling industry is a small one and not much development is taking place for that industry alone. Most of the technology is adopted from the oil well drilling industry and from freshwater drilling to some extent.

The drilling industry and geothermal companies are generally not interested in making cost data available, preferring to keep it confidential, and this means that the most cost effective drilling methods and technologies are more difficult to identify. In some cases the drilling contractors are owned by the government utilities. All this complicates such an analysis. By keeping this data confidential the geothermal industry is likely to be at a disadvantage in deciding which technology to apply and moreover puts the geothermal companies at a disadvantage when it comes to pricing in general.

2.2 Faster drilling

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-up and down, to install and cement casings, installing valves, logging, operations to solve drilling problems related to loss zones, instable formation or for “fishing” when the drill string becomes stuck or breaks. A good way to assess what the problem may be is to look at a curve potting depth vs. days that the job has taken for each well. Any “flat spots” where there is no advance in depth for several days shows clearly up and will indicate that there may be a problem. The technology is now such that a production well can usually be drilled to 2500 m in 40-60 days. In the past drilling 40-100 m/day was considered quite respectable, but now drilling up to 200 m/day is not uncommon.

2.3 Mud motors

The main reason for faster drilling is the use of down-hole mud motors. There the motor which sits just above the drill bit, and driven by the hydraulic power of the circulated drilling mud, turns some 200 rounds per minute (rpm) and when the drill pipe rotation is added the final bit speed is around 250 rpm, quite a bit faster than the 50-70 rpm of conventional rotary drilling. The mud motors are required for directional drilling, but after they were found to improve the drilling rate so much, they have also been cost effective when drilling vertical holes. The mud motors have rubber parts and can not take high temperatures, but this is not really a problem as the drilling fluid cools the well so efficiently that a temperature of say under 100°C can be maintained in a 2000 m deep well even though the reservoir temperature is over 300°C. Effective cooling of the well also allows Measurement While Drilling (MWD) tools to be run deep in the hole. This information transmits information on the azimuth and inclination and aids the steering of the bit. The MWD is, however usually taken out of the string after a certain depth has been reached due the danger of loosing the tool and having to pay a very high “lost in hole charge”. The Bottom Hole Assembly (BHA) has also seen changes. The BHA is the lowest 100 m or so of the drill string. In the past there was the drill bit and on top of that the drill collars to exert pressure (by their own weight) to the bit and then there were stabilizers to keep the string in the middle of the hole. Now the BHA usually contains a shock absorber, the mud motor, the MWD tool, a non-magnetic collar for magnetic orientation, a hydraulic jar to free the string should it get stuck and then a few heavy walled drill pipes to smooth the transition over to the normal drill pipes. The new BHA has rental equipment costing almost one million dollars, if lost in hole, far more than the old one.

2.4 Long life bits

The life of drill bits has steadily improved especially the journal bearing types with hard metal “teeth”. These are considerably more expensive, but can be rotated over 1 million rounds and drill up to 1000 m without being replaced. Fewer round trips and having to pull out of the hole only once to replace the bit for the last section of hole is very valuable. Polycrystalline diamond bits (PCD) have found some use in geothermal drilling. They can drill fast even without a mud motor, but the torque is usually higher and life shorter than for a good tri-cone bit. For drilling the surface hole air-hammer drilling has been applied up to a diameter of 28”.

2.5 Automation

The new rigs have automatic pipe handling to add drill pipes as the well becomes deeper and “iron roughnecks” to screw and unscrew. Most of these, however, handle only a single 13 m long drill pipe (“singles”) and not the 3 x 9 m long pipes (“drill pipes”). The work is much easier for the crew and safer but the tripping speed is in the range of 250-400 m/hr.

2.6 Geologic information

The geology of the given area plays a major role in how fast a well can be drilled. The on-site geologist can provide valuable advice and identify problem zones. Large loss zones and fractured rock may cause delays, but then these formations are really what you are seeking to obtain good production! It is sometimes said that a well that has been easy to drill, will not be a good producer.

2.7 Contracting

There are several ways of contracting drilling jobs. In the past for many countries the drilling was done by the government utilities themselves but private drilling contractors were active in others. Now as a result of energy sector restructuring more of the drilling work goes out for competitive bidding to a single general contractor or a series specialized of contractors. The drilling operations have been spun off and these companies then bid for the work, even when they are owned by the utility. Most of the contracts are based on day-rates for crew and equipment plus the cost of materials. Some “turn-key” contracts were made in the past where there was a lack of drilling expertise and where investors were involved. Because of the current tight market day-rates for rigs are the norm but there are some differences in how many independent contracts are made. For complex drilling operations many independent contracts are made covering: drilling rig and crew, directional drilling, bits, casing, wellhead, cementing services, mud services, logging services, geological services (mud logging). In Iceland a mixed structure is used, whereby the drilling contractor is the lead contractor and he subcontracts most of the required services, except for consultancy and logging. That contract is partly based on unit prices such as cost per meter drilled and unit prices for materials, but fixed rates for certain tasks. This form gives the drilling contractor a certain incentive to improve his operations, but gives the developer less control of the work.

2.8 Quality control

To insure good practices and quality, documentation at drilling projects has improved and the way the work is monitored. Non-destructive inspection of the drill string and other quality measures reduce the chance of failure.

3. FEWER STOPS AND PROBLEMS

The most common reasons for high costs or cost overruns are drilling problems either related to the geological and reservoir conditions or the drilling equipment itself. Qualified drillers and good equipment sometimes make all the difference in avoiding the “flat spots” that cause extra working days.

3.1 Human resources

Drilling can be taught in special courses and such courses are essential, especially in teaching how to control steam eruptions, so-called “Blow Outs”. Mainly the drillers learn on the job by working their way up the ranks on the rig over a period of 3-5 years. The driller must focus on the down-hole condition by reading the gauges and other observations. Losses or gain in drilling fluid, changes in mud temperature, drill string vibrations, sound and such are important indicators of pending trouble.

Drilling in volcanic formations in geothermal areas is not the same as drilling in the sediments in the oil industry. Large circulation losses, avoid getting stuck, drilling in fractured rock causing vibrations, not drilling too fast in soft formations are some of the challenges. For this reason it is essential that the drilling contractor have experienced drillers and that he is able to retain them. One way is through a programme of training and by offering good working conditions.

3.2 Information systems

The old-time drillers did not think much of modern computer monitoring systems and at first considered it to be an infringement. Younger drillers are accustomed to use computers through games and their IT knowledge. All modern rigs have such systems and they are easy to fit to older rigs. This provides high resolution data to analyse past problems and trend plots and other indicators provide the driller with much better information than in the past. These both allow more aggressive drilling where possible and also help to avoid problems when such conditions arise. Such on-line information during drilling can be shared by a larger group of experts giving additional support to the drilling effort.

3.3 Cementing

Problems relating to cementing shows up in most drilling jobs. Long sections of casing pipe that has to be cemented, good cementing is one of the more critical and time consuming operations. Zones of circulation losses were treated in the past by stopping and cementing to heal the loss, taking 1-3 days, but now many drillers bypass these zones. Good cementing is nevertheless obtained by inner-string cementing up to the loss zone. Flow of water from top down the annulus keeps the loss zone open and then the annulus is filled up by “squeezing” cement down to the loss zone, thus achieving a continuous sheath from bottom to top. Recently “reverse” cementing where the cement is pumped down the annulus, has been tried in problem wells and also “foam” cement to lessen the slurry density and cement with loss of circulation material to plug the losses. Cementing long casing strings in stages or using tie-back casing strings are other methods used. The cement has to withstand the temperature and chemical environment and to that end 40% silica flour is added to Portland cement or special fly-ash cement is used. Highly specialized cementing companies are usually employed for cementing of geothermal wells. To reduce cost some drilling contractors carry out the cementing with their own equipment and use local cements.

3.4 Drill string inspections

There is a lot of wear and tear on the drill string and thus the life of the drill string can be anywhere from 3-6 years. Cracks, corrosion and loss of outside diameter on the tool-joints due to wear are the main problems. Some of the new methods, such as aerated drilling, result in shorter life due to the corrosive effect of oxygen higher torque and extra wear on the tool-joints. Regular non-destructive tests are usually called for to “grade” the drill string. As failure of the threaded connections on the drill collars are common some contractors inspect the threads each time the collars come out of the hole. Accurate pressure gauges and monitoring can sometimes detect a crack or a hole in the drill string before it parts. 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. Such fishing or sidetracking operations where the un-retrieved section of the drill string is left in the hole are all too common.

3.5 Use of logging tools to solve drilling problems

By using the electrical logging tools it is possible by temperature logging to locate the loss zones and detect by calliper survey where there are caves or “washouts” in the well. 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). In an extreme case explosives are used to cut the drill string to retrieve a part of the drill string. Now the well condition can also be evaluated by an acoustic televiwer 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. 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 reach surface to detect the top of cement in order to plan remedial actions.

4. NEW RIGS

Top drive rigs have a hydraulic or electrical motor riding high in the mast to turn the drill string. This has several advantages over the conventional “rotary table” rig as the drill pipe can be turned as it is being tripped out of the hole, lessening the chances of becoming stuck. Water can also be pumped while the drill pipe is being lowered into a hot hole to avoid heat damage on the bit and motor. Such top-drive units are on all new rigs and can be retrofitted to older ones.

4.1 Hydraulic hoisting, automation

The hoisting of the drill string in the past 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, thus keeping the rate of penetration high. A rig with a hook load rating in the range 250-350 tonnes is usually sufficient for most geothermal drilling, but larger rigs are quite often found at geothermal sites. Automation has entered the rig floor and now the only manual work for the “roughnecks” is to apply the grease to the connections. The drill pipe is automatically brought into position and the “iron roughneck” tightens the threads to the predetermined torque. The driller controls all of this from inside his “doghouse” where he is allowed to sit comfortably in a chair. In the past the driller stood outside and was not allowed to sit, less he fall asleep! Modern rig instrumentation insures the driller has the most recent measurements at his fingertips, plotted in such a way as to ease interpretation.

4.2 Rig transport

The new rigs are designed to be highly mobile with wheels fitted to the large parts so they can be towed away quickly and other equipment is in container size modules for easy transport. Still it takes 40-45 truckloads to move a rig, but the time do so has been reduced to four days.

5. IMPROVING WELL OUTPUT

Rather than to reduce the cost of each well the overall cost of the project can be brought down by improving the well output (power). There are several examples of how this can be achieved, as will be mentioned here.

5.1 Careful targeting

As the information gained at each site the future wells can be targeted more precisely. With this information in hand the well siting and trajectory can be optimized. The targeting of geothermal well is not and does not have to be as precise as for petroleum wells, but still there are zones with attractive permeability that can be picked out.

5.2 Larger diameter casings

If wells intersect good permeability the mass flow may become limited by the diameter of the production casing. There are, however, cases, especially were 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” production 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. The rigs are generally big enough so that the larger diameters are not a problem and the time to drill such wells is not appreciably greater. The output is, however, proportional to the cross sectional area of the pipe, thus the larger wells can potentially produce twice as much. The larger casing also has the advantage that it does not clog as quickly by scaling and should a well require repairs later on there is room for a 9-5/8" casing inside. By standardizing on two to three casing program sizes the inventory of drilling tools becomes simpler and the practices become routine. This in time contributes to lowering costs.

5.3 "Barefoot" well completion

For very permeable wells (in Iceland the criteria is Productivity Index >5 (l/s)/bar) and where the boiling point is within the cemented casing, wells have successfully operated without a slotted liner, so called "barefoot" completion. There is a cost advantage as a liner is not required and also the well is easier to clean of any deposits.

5.4 Balanced drilling

Usually the pressure within the geothermal reservoir is low, so a well full of drilling fluid will loose the fluid once a fracture is intersected. The cuttings from the drill bit will hence go to the formation and may in time plug the fracture. Lately methods to overcome the formation damage have been used by what is called "balanced drilling" (aerated drilling) or sometimes "underbalanced drilling". Then 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. This has been successfully applied in several countries, but is rather costly due to the large air compressors required and almost doubling of the oil consumption. Remarkably the rate of penetration goes up as well, offsetting in part the increased cost. On average these wells are reported to have up to twice the output of conventionally drilled wells in the same field.

5.5 Well stimulation

Hydraulic stimulation is used at the end of drilling by pumping large quantities of water into the well to clean out mud, cuttings and whatever. The flow can be large 60 l/s and the pressure 100 bar but this pressure is not enough to fracture the rock. The problem with this method is that most of the water exits the hole at the first fracture below the casing shoe and does not stimulate the whole open section. Thermal cycling whereby the well is first cooled by water pumped through the drill pipe that reaches the bottom and is then allowed to heat up several times, is known to open up fractures and increase the "losses", but it does not always produce a permanent improvement.
Another method used, especially where mud is used for drilling, the productive interval is to inject large volumes of acid (ca. 200 m3) to do what is referred to as acid stimulation. This is known to improve the permeability especially where carbonate is found in the veins. Very many geothermal wells are drilled with water only in the open interval and it is generally considered that it causes less formation damage, especially when coupled with balanced drilling (aerated drilling).

5.6 Multilateral wells

If the well is a very poor producer or has suffered damage or a collapse, one possibility is to drill a sidetrack, even drilling out of the cemented casing. When both sections of the hole will remain open afterwards it is referred to as a multilateral well. The multilateral technology is also found in petroleum drilling, but the cost of such operations is substantial.

6. ENVIRONMENT AND SAFETY

Now most countries have in force environmental laws that require environmental audits of geothermal drilling operations and environmental impact assessment (EIA) of some sort are made prior to drilling. This has resulted in modifications in some past practices, but has also put drilling on hold in new areas that had been targeted for exploration. Drilling licences in protected areas has been especially difficult to obtain. The construction of access roads and platforms are the most common issues together with land use.

6.1 Many wells from the same platform

In part as an answer to the issue of surface construction and land use more wells are now drilled as directional wells. Up to six wells from the same drill pad are drilled, spaced some 6-20 m apart but heading in different directions. In many geothermal areas around the world up to half of all wells drilled are now directional with an inclination of 30-45°. Such wells have proven easy to drill but the cost is higher, partly offset by shorter surface pipelines and less civil works. An effort has been made to decrease the size of the drill platforms and for a single well the size is down to 40 x 50 m, almost half of what is was at times.

6.2 Safety

Many rigs now have “iron roughnecks” to screw the drill pipes and automatic pipe handling. Both methods increase the safety of the drilling crews. Personal safety gear is now mandatory such as hard hats, safety shoes, and bright coloured overalls with light reflectors, ear and eye protection and gloves. Safety classes, material safety sheets and HSE rules set by the drilling contractors have contributed to safer working practices. Drilling did not have a good safety record but this has greatly improved.

6.3 Handling of waste

Now most drilling rigs have oil catchments around the rig and many collect the cuttings in containers for transport to dedicated disposal areas. Used drilling mud is in places no longer disposed to a nearby earth mud pit but is trucked away and water is reinjected to shallow wells. Sorting of solid waste on the drill site in closed bins for garbage collection is common. Septic tanks or collection of human waste is the rule. Noise abatement is also a factor with regulations in place and demands from neighbours that the drilling operation be as quiet as possible. These changes have also resulted in a better working environment for the drilling crews.

7. CONCLUSIONS

Considerable advances have been made in drilling practices and the equipment and technology employed for geothermal drilling. Many of these changes have increased the cost of drilling each well but the extra cost has in part been offset by less civil construction on surface and increased productivity of the wells. There are many factors that impact the cost and performance of wells and due to the high variability it is difficult to pick a clear winner in terms of which technology or practices to employ. This comparison is in part also hampered by the lack of reliable performance and cost data. The good news is that the drilling industry is now able through directional drilling and MWD to drill wells to access parts of the reservoir previously inaccessible. Also there are methods to lessen formation damage and even improve wells with poor productivity. Finally the working environment has improved due to more automation, instrumentation and better practices. All of this is important if the geothermal drilling industry is to retain highly qualified workers and grow in the years to come.

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