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Drilling of a 2000 m borehole for geothermal steam in Iceland

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ABSTRACT

Drilling for geothermal heat has been carried out in Iceland since 1928, when hot water was obtained for district heating in Reykjavík. From that time and in particular in the sixties extensive drilling has resulted in annual utilization of 54 million tonnes of water and 2 million tonnes of steam. Five drilling rigs are used for geothermal drilling with depth capacity ranging from 400 to 3600 meters. Drilling procedures vary extensively and depend on whether a high-or lowtemperature field is being drilled, the main difference being the well-casing program and the blow-out equipment used. A description is given of the drilling and well completion of a 2000 meter borehole drilled with an electrically driven Gardner Denver 700E rig. Such a borehole is typical of wells drilled at the Námafjall and Krafla hightemperature fields, where bottom hole temperatures exceed 300°C and a 1000 meter cemented production casing is required. Factors of importance are the drilling procedure, blow-out equipment, casing and cementing procedure, well completion as well as cost data for a completed well. Initial drilling is done with a percussion drill down to approximately 50 meters and loose surface layers are cased off. Rotary drilling starts at this point. The rotary drilling is carried out with insert bits, 17 1/2" down to 300 meters, 12 1/4" down to 1000 meters and 8 1/2" down to 2000 meters. Directional survey is carried out to assist in drilling vertical. The classification of blow-out equipment and casing program is according to the steam pressure corresponding to bottom well temperature. The 13 3/8" anchor casing is set down to 300 meters and the 9 5/8" production casing down to 600-1000 meters to seal off aquifers in the upper section as necessary. A 7" slotted liner is hung from the lower end of the production casing down to the bottom. The main difficulty in cementing the casing is the loss of circulation, which require stage cementing collar and perforation of the casing. The total cost of the well described was approximately 1 million US dollars in 1980.

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DRILLING OF A 2000 M BORHOLE FOR GEOTHERMAL STEAM IN ICELAND

Introduction

Geothermal drilling for practical purposes began in Iceland in 1928, at a location inside the Reykjavík city limits, near hot springs that had been used for a long time for laundering. The project was successful and led to the first district heating service in Iceland; it was a modest affair involving geothermal hookups to some 70 houses. While exploitation of natural hot water continued, progress in drilling was relatively limited until the 1960s, when a major effort to harness geothermal resources started. Since that time, there has been uninterrupted emphasis on geothermal drilling, with the result that the combined length of boreholes is around 400 kilometers. The annual consumption of geothermal water in Iceland now stands at 54 million metric tons, besides the use of 2 million tons of geothermal steam.

Used mainly in the drilling were the following rigs (all were given Icelandic mythological names)

		Depth capacity
1.	Jötunn (Gardner Denver 700 E)	3,600 m
2.	Dofri (Oilwell 52)	2,000 m
3.	Narfi (Failing 3000 CF)	1,400 m
4.	Glaumur (Wabco 2000 CF)	800 m
5.	Ýmir (Mayhew 1000)	400 m

Drilling at a site called Námafjall in the eastern North provided steam for running a diatomite factory and a 3-MW back pressure power plant, which have operated the last twelve years. Construction work to build a 60-MW geothermal power plant began in 1975 at Krafla, 8 km north of Námafjall. The station house was finished and the associated equipment intalled quite some time ago, but not enough steam is on hand yet though 15 wells have been drilled.

The Námafjall and Krafla areas lie on a swarm of fissures, which has been very active the last five years. ~~At the time of this writing~~, six small volcanic eruptions ~~had~~ occured there since December of 1975, and more ~~were~~ predicted. These events and related developments - earthquakes and cyclical rising and subsiding of the ground - made for serious trouble in the drilling effort as many of the wells got damaged. A well at Námafjall, for instance, discharged ash and spattering of lava one night in September 1977, incredibly enough. Last summer (1980), the National Energy Authority drilled three wells for steam at Krafla and one at Námafjall. ~~A general description of the procedures used in that work follows.~~

The Well Design

The drill sites are on slopes on mountainsides, where the depth to the youngest strata of lava ranges from just a few meters to several tens of meters. The foundation for the rig is roughly 40 by 50 meters, with a cellar of concrete in the center of that space. The first phase of the ensuing work is cable-tool drilling down to a depth of 50 meters. Then the hole, which is 22 inches in diameter, is cased with 18 5/8" surface casing that is cemented in place.

The next step is to move the rig Jötunn to the drill site - a transportation job involving 450 tons of equipment. The initial drilling is for a rathole and a mousehole. A 17 1/2" bit is used in the rotary drilling to a depth of 300 metres, and a 13 3/8" casing is then run in and cemented. After that, there is drilling down to anywhere between 700 m and 1,100 m with a 12 1/4" bit, and this hole is given a 9 5/8" cemented casing. The exact depth depends on the expected pressure at the bottom of the well upon completion; casing down to 700 m is normal in a 2,000 m well. But in the Krafla area, casing down to 1,100 m is called for because of the need to seal off the zone above that level to prevent relatively cold water from entering the hole. The drilling is resumed with an 8 1/2" bit down to around 2,000 m, and the last part of the well then cased with a slotted liner that reaches to the bottom. Cut with an acetylene/oxygen torch, the slots, each 70 by 20 mm, are evenly spaced in circles of three vents; there are ten such rows on each meter of casing, which means that the slots per meter add upp to an area that is 1.6 times the cross section of the casing.

The following table lists the bit and casing sizes and other relevant data.

Cable-tool bit	22"	to 60 m			
Surface casing	18 5/8"	60 m	78 lbs/ft	st 52	welded
Bit	17 1/2"	300 m			
Anchor casing	13 3/8"	300 m	68 lbs/ft	J 55	buttress
Bit	12 1/4"	1,100 m			
Production casing	9 5/8"	1,100 m	43.5 lbs/ft	J 55	buttress
Bit	8 1/2"	2,000 m			
Slotted liner	7"	2,000 m	26 lbs/ft	J 55	buttress

As noted, the depth of casing is determined by the bottom hole pressure - a factor that also dictates the pressure class for the main valves of the well, which are connected to the anchor casing. Typically, there has been use of a (gate-through conduit) W-K-M (10" ANSI 900) as the main valve, and of Sigma gate valves (10" DIN 250 kg) for backup. A kill line unit is positioned as a rule between the two cited valves.

The Rig Equipment and Crew

The rig is Gardner Denver 700E, diesel/electric powered and driven with an SCR unit from Ross-Hill Corp. The derrick is of the type Lee C. Moore, 131 ft high and retractable. Hook load capacity is 393,000 lbs with eight lines of traveling block, which is equivalent to 12,000-14,000-ft capacity with 5" drillpipes. It is customary, however, to say that this rig has a depth capacity of 3,600 metres. The drawwork is Gardner Denver 700E with a 750-hp electric motor. The swivel is Gardner Denver SW-30-300 tons. There are three mud pumps; two Gardner Denver P2-8 triplex units, each with 750-hp electric motor, and one Gardner Denver FO-FXO with 150-hp Caterpillar diesel engine. The drillpipes used are 5"-19.5 lbs/ft grade E and 7 1/4" and 10" drill collars. On hand are two-Cameron blowout preventers (12" Type QRC Ser. 900) with hydraulically operated rams, one Hydrill blowout preventer (GK 12" Ser. 900) and one Grant rotating drilling head

(12" Ser. 900). The cementing unit consists of three storage tanks, each for 48 tons, diesel-driven hopper (mixer) and diesel-driven triplex pump for cement slurry.

As for the crew, there are a leader (tool pusher) and his assistant, who remain at the drill site around the clock except that each has every fourth week off; meanwhile, there is 24-hour standby duty a day for the other. A motorman is responsible for seeing to it that the engines powering the drilling equipment are kept in good working condition. There are four teams made up of driller, derrickman and two rotary helpers - who work in 8-hour shifts. At any given time, one such group is on vacation as the drilling is usually continuous from the start of a well and until it has been completed. A drilling supervisor is present at the site under certain circumstances; he serves as coordinator between contractor and commissioning party, while also overseeing casing and cementing operations. Two men are assigned to the logging truck, and have the extra duty of perforating casings when this is needed.

The Drilling Procedures

Once the rig has been set up, rotary drilling is started by feeding 7 1/4" collars into the surface hole, which is deep enough to allow placing of suitable weight on the 17 1/2" bit. A 50-m-deep hole can accommodate collars adding up to 8 tons, but in this phase of the drilling (down to 300 m) weight on the bit beyond 6 tons is rare. As the topmost strata are soft, excessive drilling rate is apt to make for trouble with the circulation of the drilling fluid; the average penetration rate with the 17 1/2" bit is about 5 m/h. The bedrock in this zone is stratified: varying thicknesses of metamorphic hyaloclastite alternate with basalt layers that are poorly crystallized and fine-grained; hence, big circulation losses tend to occur. One counter-measure is to attempt to seal off the faults with cement slurry, often blended with different materials such as wood chips and mica. Adding perlite to the cement frequently gives good results, too. This portion of the well is sometimes drilled with mud as circulating fluid, but opinions are divided on that approach - apart from the extra cost compared with water. Collapsing, however, may leave no alternative to the use of mud.

When the bit is down to around 300 m, a suitable basaltic layer is selected for the end of the 13 3/8" casing, which then is run in and cemented. Following that, blowout preventers are installed; a standard 14" gate valve is placed at the bottom, directly on the casing flange; next come two Cameron blowout preventers. The Hydrill valve, which is fitted with a rubber bellows, is installed above the Cameron valves. Located highest is the Grant rotating head to prevent a discharge up through the rotary table, in case of a blowout.

These operations over, the drilling is resumed with a 12 1/4" bit coupled with one or two sets of reamers for vertical stabilizing. In the zone below, fine-grained basaltic strata of different thicknesses still alternate with hyaloclastite layers - and, understandably, big circulation losses continue. At the depths in question, that trouble has been persistent, leading to long interruptions of the drilling for sealing work - though the results admittedly have never proved fully satisfactory when it comes to the cementing of the next casing. On the other hand, the leaks rarely slow down the circulation rate to the point of making the drilling difficult, for the faults seem to be wide enough to receive the rock cuttings. Brief periods of drilling with total circulation loss are, in fact, fairly common - but sealing to a degree from the cuttings usually follows so circulation is restored. Recently, there has been a tendency to tolerate circulating losses up to approximately 20 l/sec.

An average weight of some 10 tons is maintained on the 12 1/4" bit, which gives a drilling rate of 6-7 m/h in this zone. At certain intervals, an inclinometer is sent down the string to check for tilt; if there seems to be deviation of more than 2-4 degrees from a vertical line, the weight is reduced for correction. The work continues in the same way until the bit reaches a depth of 700 to 1,100 m, depending on the need to block out inflow of low-temperature water as mentioned before. Once the 9 5/8" casing has been run in and cemented, the final 10" main valve is attached to the anchor casing, and the other valves are installed as before.

From this point on, the drilling is with an 8 1/2" bit down to the ultimate depth of the well, usually somewhere around 2,000 m. In this phase of the operation, the weight on the bit is kept at roughly 12 tons, and the average drilling rate is 7-8 m/h. No heed is now paid to circulating losses, though occasional shots of mud may be called for if caving has been in evidence. In this zone - that is, between 1,100 m and 2,000 m - the same strata alternation as before occures, between basaltic and hyaloclastite layers; the former are poorly crystallized and highly altered, while the latter are now mostly tuff. At a depth of 1,300 m, acidic intrusive rock appears, and more often further down, amid strata otherwise consisting of basalt breccia and tuff. At contacts between layers, circulating loss of 10-20 l/sec is common and sometimes grows to 40-50 l/sec when the bit is not drilling. After the well is down to 2,000 m and the drilling finished, logging takes place. Finally, a slotted liner is hung onto the anchor casing and made to extend to near the bottom.

Casing and Cementing

As mentioned earlier, four types of casing are used - namely, surface casing, anchor casing, production casing and slotted liner. Normally, the cabletool-drilled portion of the well is cased immediately upon completion, and the casing set with sand-cement slurry that is pumped down the annulus between the 22" hole and the 18 5/8" pipe. This is possible as the water level is generally below the bottom of the well. The anchor casing is run down to 300-m depth, with centralizers placed at 30-to-60-m intervals. Cementing is done through the drilling string, which is connected to a float shoe. Before cementing, water is circulated in the hole to clean, cool and measure leakage. Located at the drill site are three storage tanks for cement, each holding 48 tons; the cement is fed from there into a hopper, and the slurry then forced with a special triplex pump to the drilling string. To make for stronger, lighter and better-sealing cementing, the following cement mix is used:

Portland cement:	100	kg
Silica flour:	40	kg
Perlite:	4	kg
Bentonite:	2	kg
Retarder (D-13):	0.2	kg

Added for slower setting, the retarder has been found to extend the process by 40-60 minutes; its duration is critical, especially when the production casing is being cemented. As this 1,100-m-long casing cannot be cemented in one stage, a stage cementing collar is located at a depth of some 700 m. In this case a calculated amount of cement slurry is pumped into the casing, cement plug released and displaced with water. The stage collar is opened and the calculated amount for the second stage pumped into the casing, the closing plug released and the cement displaced with water again. Because of circulation loss the amount of cement slurry used has been 100% in excess of the annulus volume for both cementing stages, but despite this excess it is most usual that the cement does not reach or get above the collar in the first stage and the surface in the second stage. To locate the top of the cement after the second stage, which generally has been between 200 and 300 m the pressure encountered during the displacement and a sonic cement bond logging tool is used. Casing is perforated by shaped charges and cementation completed through these holes. Then the cement and plugs are drilled out to the bottom of the casing and a cement bond log is made. If an uncemented zone is found the casing is perforated again to squize cement behind the casing.

Naturally, the perforation of the casing may cause some trouble in the operation of the well by discharging steam, but that is supposed a lesser evil than uncemented spaces - the biggest single problem in completing geothermal wells.

Logging

Logging during the drilling of wells is chiefly for drift control. Measurements to that end are carried out with a TOTCO inclinometer at intervals of 100 to 200 m, and deviation exceeding 2-4 degrees from vertical line are usually not tolerated. Before casing is run in, there is logging of well temperatures, as also gauging of the borehole diameter with a three-prong caliper device. When the drilling itself is finished but before the slotted liner is run in, a resistivity, neutron-neutron and natural gamma logs are performed - which together offer indications of the nature of the strata, giving valuable knowledge about the reservoir.

After the slotted liner has been run in, a pumpdown test is made. Logging for temperature and pressure is carried out every few days; this is normally the most effective method of assessing the well before a discharge test is carried out.

Well Cost

It is very difficult to assess drilling expenditures, not least because of world inflation and Iceland´s soaring inflation rate in recent years. It is also hard to separate the typical outlay for a well from cost factors associated with the project as a whole. The customary Icelandic practice is that the commisioning party will enter a contract with the National Energy Authority, on a time basis - while buying supplies directly from various other sources. It follows that the main cost items in the cited two-party contract are rit rental and wages. That circumstance has prompted accounting where a line is drawn between outlays for the actual drilling, or time-linked costs, and expenses from drill-site preparations, transportation and materials. The following table gives a rough cost breakdown for Well No. 11 at Námafjall, which was drilled in the summer of 1979, with the sums indicating real values at that time.

Cost of Well No. 11, Námafjall, 1979

Drill-site preparations, roads, cable-tool work:	$ 33,800
Materials (A): bits, reamers, centralizers, casing shoes, cement, mud:	$ 35,400
Materials (B): casings and valves:	$ 138,700
Services: transport of supplies, cement trucks, logging, etc.:	$ 110,600

Drilling:

Rig rental:	3,100 $/day	
Fuel oil, lube:	497 $/day	
Wages:	1,965 $/day	
Maintenance:	384 $/day	
Fares:	162 $/day	
Car rentals:	262 $/day	
Safety valve rent:	300 $/day	
	6,670 by 33 days	$ 220,200
Transport of rig:		$ 72,000
Miscellaneous:		$ 92,000
	Total:	$ 702,700

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