The United Nations University

GEOTHERMAL TRAINING PROGRAMME
Orkustofnun, Grensásvegur 9,
IS-108 Reykjavík, Iceland

Reports 1999
Number 9

COMPARISION OF DRILLING IN GEOTHERMAL FIELDS IN KRAFLA, ICELAND AND TENDHAO, ETHIOPIA

Abraham Muluneh
Ethiopian Institute of Geological Surveys,
Geothermal Exploration Project,
P.O. Box 33414, Addis Ababa,
ETHIOPIA

ABSTRACT

This report compares the drilling of geothermal wells in Iceland and Ethiopia, describing the technology applied and practical activities. For this study, well KJ-32 in the Krafla geothermal field in Iceland (drilled 1998) and well TD-5 in the Tendaho geothermal field in Ethiopia (drilled 1997) were selected. In Krafla 35 wells have been drilled to date and of these 9 wells are directional, as is the case for well KJ-32. The well was drilled from the kick of point (KOP) to final depth with a steerable down hole motor and measurement while drilling (MWD). The target was to produce from the lower reservoir with a temperature of up to 320°C and to reach inaccessible parts of the reservoir below 1100 m. In Tendaho, six wells have been drilled, three deep wells and three shallow wells. Well TD-5 was drilled vertical to a depth of 516 m to intersect a shallow reservoir with a temperature of 240°C. The basic rig parts such as the mast, pumps, and cementing units are quite similar in the two countries and the casing program also. The drill strings make-up and use of logging tools, cementing material and manpower is, however, different. The opportunity was given to me to witness cementing operations at Nesjavellir and at Krafla. This included a three week period on site at Krafla during completion of well KJ-33 and the beginning of drilling well KJ-34.

1. INTRODUCTION

This report is a product of a six months' fellowship awarded to the author to study geothermal drilling technology through the United Nations University, Geothermal Training Programme, at Orkustofnun - the National Energy Authority (NEA) in Iceland. The training programme started on the 30th of April 1999 with a six weeks lecture course on various subjects of geothermal engineering and science. The next four weeks were for special lectures and supervised reading on drilling technology. Special emphasis was placed on well design, casing programmes, cementing, blow-out prevention and safety. Also covered was the specification of the drilling programme, materials and equipment. Furthermore, I had the opportunity to attend two weeks of lectures on well stimulation, geothermal pump installation and maintenance, and instrumentation and control technology. Then there was a five day field excursion to the main geothermal high- and low-temperature fields in North and Northeast Iceland. The trip took us to district heating systems, power generating stations, greenhouses, a fish farm, big and small industries, along with historical places. To this can be added that for three weeks I stayed at the Krafla geothermal power station to witness drilling operations on well KJ-33 and KJ-34.

This paper describes the drilling of a geothermal well in two countries. For this purpose, well KJ-32 in the Krafla geothermal field in Iceland and well TD-5 in the Tendaho geothermal field in Ethiopia were selected. A comparison is made on well design, cementing equipment and the difference in drilling a vertical and a directional well.

2. THE KRAFLA GEOTHERMAL FIELD, ICELAND AND DRILLING OF WELL KJ-32

The Krafla high-temperature geothermal area is located within the volcanic zone of Iceland and takes its name from the hyaloclastic mountain Krafla. The volcanic zone defines the plate boundary where the American and Eurasian continental plates are drifting apart and new land is in the process of being formed. The Krafla area is a part of a volcanic system inside an old caldera. An active fissure swarm crosses the caldera from north to south, stretching for about 100 km. Studies of tephra layers suggest that volcanic episodes occur in the Krafla region at intervals of 250-1000 years, lasting 10-20 years each. The most recent eruption episode started in late 1975 just as production drilling was beginning. By monitoring the area with best known methods at that time, 21 events of ground inflation and subsidence were observed. Nine of the events ended with an eruption, the last one in September 1984. At a depth of 4-8 km beneath the Krafla caldera, there is a magma chamber. During the volcanic episodes the magma flowed into the magma chamber until it reached the stress limit and burst out in an eruption on the surface or formed intrusions within the fissure swarm.

The size of the geothermal area has been identified by geological mapping and resistivity surveys. The main geothermal field is located in the central part of the Krafla caldera and two smaller ones at the southern part of the caldera rim. The surface geology is characterized by hyaloclastite ridges and lava flows. Underneath are two thick hyaloclastite formations, divided by lava formations, extending down to 800-1000 m where the temperature in the so-called “upper reservoir” is relatively low or only 200˚C. Below 1100 m there is the “lower reservoir” where there is a sharp increase in temperature that follows the boiling point with depth curve (BPD) reaching 300-340°C. Well KJ-32 was designed to case off the “upper” reservoir and produce from the “lower” one. The productive part of the reservoir rock consists mainly of basaltic intrusions.

2.1 Description of well KJ-32

The Krafla area (16˚45´W, 65˚02´N, elevation 450 m), is one of the large high-temperature areas in NE-Iceland. The power plant owned by Landsvirkjun (National Power Company) generates 60 MWe in two 30 MW turbines. Presently, wells are being drilled for an expected expansion. A total of 35 high-temperature wells have been drilled to date (see Table 1), with the deepest well 2222 m. Twenty six wells were drilled vertically and 9 directionally (Figure 1).

TABLE 1: Krafla wells, classified according to use Sept. 1999

Description	Number of wells
Wells in use	19
Monitoring wells	5
Injection wells	1
New warming up wells	2
Wells not in use	7
Damaged wells (blow–out)	1
Total number of wells	**35**

Well KJ-32 is located about 1000 m northeast of the power plant. The first stage, pre-drilling of the surface hole, was drilled with a 22" bit to 61.6 m depth. After drilling and casing the surface hole, the shallow cellar was made and the drill site prepared for the large rig. The work continued with the big drilling rig “Jötunn” of the Icelandic drilling contractor Jardboranir hf. A 17½" bit was used and the intermediate part of the well was cased with 13⅜" to 285.8 m. The production casing part of the well was drilled with a 12¼" bit to 1077 m and the production casing run to 1069.49 m. The kick-off-point (KOP) for directional drilling was at 450 m depth where the drift angle would be built up to 30˚ at a build rate of 1.5˚/30 m. The directional work was carried out with a steerable motor, and measurement while drilling (MWD) logging from the KOP to the bottom by Halliburton Sperry Sun (Norway). The well target was to intersect faults at "Hveragil". The final stage of the well was drilled with a 8½" bit and mud motor + MWD to 1875 m. The maximum inclination was 33˚ with the azimuth at 260˚. A 7" slotted liner was run to 1831.5 m. Figure 2 shows the casing profile for well KJ-32.

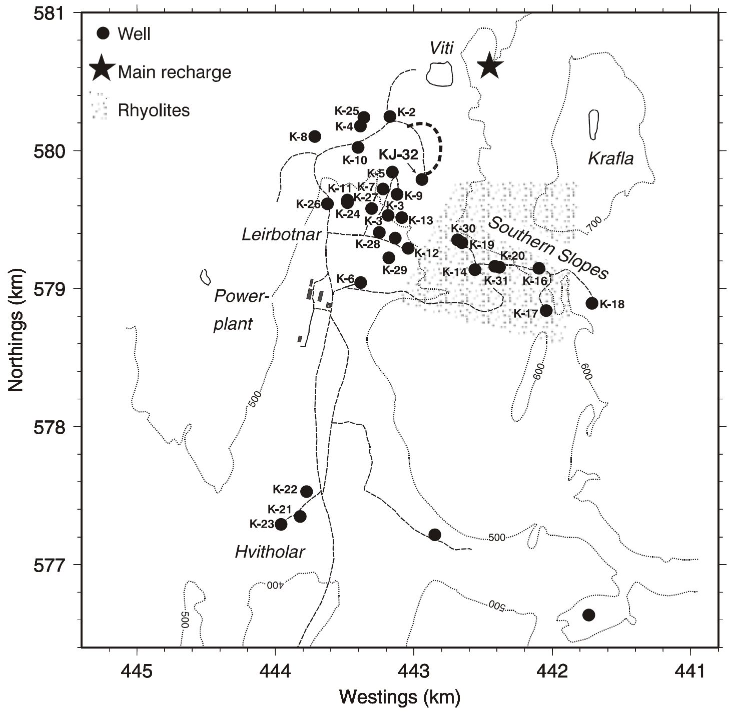

FIGURE 1: The Krafla well field

2.2 Drilling of the surface hole

The first string of casing in a well is the surface casing. Its length will vary in different areas depending upon state or operational requirements. The surface casing serves as a base upon which to fix the well control equipment, protect the fresh water zones and isolate lost circulation intervals. Cementing objectives for this shallow case include:

1. Complete circulation of cement slurry to the surface for full protection.
2. Early compressive strength development so drilling can continue.
3. Long time stability against high temperatures (Evanoff and Harris, 1992).

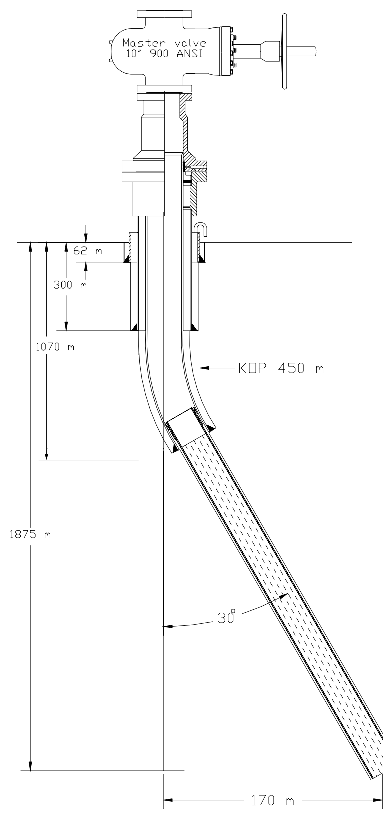

FIGURE 2: The casing profile for well KJ-32, Krafla geothermal field

In Iceland it is common practice to pre-drill the hole and land the surface casing to 60-90 m before the big rig is brought in. This is done to save time on the more expensive big rig and to solve any problems that are common near the surface due to poor hole stability. The big rig is also able to start drilling with enough weight on bit (WOB) as there is room for the drill collars in the hole.

For pre-drilling this well a truck mounted rig (Failing 3000) was used with a mud circulating system. The total time for transporting, drilling, casing and cementing the well to 60.6 m took only 5 days as can be seen in Table 2. The casing was cemented using the rig pumps and the cement slurry was brought in on conventional ready-mix cementing trucks from the construction industry. After removal of the truck-mounted rig, the drill site was prepared and a pre-cast concrete shallow cellar put around the well.

TABLE 2: Drilling of surface hole KJ-32

Day no.	Drilling (m/day)	Drilling (hr/day)	Working (hr/day)	Remarks
1		1.5	10.5	Rig up
2	20.8	10	14.5	Drilling
3	35.3	12	14	Drilling
4	4.5	12	13	Run 18⅝" casing/cementing
5		5	9.5	Rig down

Where there are lavas to the surface or hard rock, air hammers have been used for drilling the surface hole. The air hammer method is not a true rotary method but a percussion method adapted to a rotary rig. A pneumatic hammer, similar in function to a large jackhammer, operates at the down hole end of the drill pipe on 100 psi or higher compressed air. The hammer face has tungsten carbide inserts to provide chipping capabilities. The air hammers are available for bits from 3" to at least 26" in diameter and provide between approximately 800 and 2,000 strokes/min. The drill and hammer are rotated slowly so the inserts continually strike a new surface to provide even penetration and drill a straight hole. Hammer exhaust or excess air or both are directed to clean the chips or carry them away as they are formed. Drilling rates of 50-100% faster than for tricone roller bits are common. When drilling below the static water level, a pressure difference across the hammer must be maintained, and the air pressure is increased to accomplish this. Foams can be utilised to assist in hole cleaning and to reduce the pressure in the borehole. Large hammers require large volumes of air, typically two compressors. Compressors and their operation significantly increase the fuel oil consumption of the rig.

2.3 Drilling of the 17½" intermediate hole section from 60 to 300 m

Drilling of well KJ-32 started on Friday, 14 August 1998, using Jötunn the biggest drilling rig in Iceland. The daily drilling activity is listed in Table 3 and the directional surveys in Table 4 (Franzson et al., 1998)

TABLE 3: Daily drilling activity (60-300 m), well KJ-32

Bit 17½" MS-51ADM	Date	Drilling (m/day)	Drilling (hr/day)	Penetration (m/hr)	Time on bit (hr)	Depth (m)
H 83912	14.08.99	12	3.5	3.4	3.5	80
H 83912	15.08.99	56	22	2.5	25.5	136
H 83912	16.08.99	78	22.5	3.46	48	214
H 83912	17.08.99	74	22	3.36	70	288
H 83912	18.08.99	7	3	2.33	73	295
Total	**4 days**				**73**	**270**

TABLE 4: Inclination of well KJ-32 to a depth of 300 m

Depth (m)	Log (m)	Inclination (°)	Deviation (m)
119	100	0.9	1.6
227	200	0.9	3.2

The 17½" bottom hole assembly was as follows: Bit 17½" MS-51ADM + Stabiliser +crossover + drill collar + stabiliser + 10 drill collars + cross over + drill pipe. The maximum weight on bit was 5-10 tons with 40-60 rotations per minute (RPM). The average penetration rate was 3.1 m/h to 90 m depth. The pump rate was 15 l/s. At 90 m, the well encountered a soft formation where the pump rate was increased to 26-30 l/s to wash and carry the cuttings. A thick bentonitic (Wyoming bentonite) mud was used for this section. The specific gravity of the mud was 1.11-1.14 g/cm^3, March viscosity 75 seconds/qt, pH-6, sand content at shale shaker 2-10%. This well had the loss of circulation recorded at 4 hour intervals and it was negligible or small, or <1.25 l/s. The geological formation at 295 m depth was dominated by pillow basalts. After completing drilling of the intermediate part of the well, it was circulated for cleaning and cooling for two hours. Then a temperature and pressure log was run inside the drill pipe for safety reasons. The well had thick mud and the calliper tool could not pass down beyond 68 m due to mud caking. The calliper tool was removed and a drill bit was run back into the well for a wiper trip to clean and ream the mud from the well down to 102 m. Below that depth the well was clean. The casing was run, and before the cement job, fresh water was circulated to clean and cool the well.

2.4 Calliper logs

Calliper logs are made by a moveable multi arm tool (typically 3 or 4 arms) which measures the well diameter as it is pulled up the hole on the wire line. Cavities in the well are thus measured and located (see Figure 3).

In Iceland calliper logs have been used for a long time:

- To calculated the volume of cement slurry required for casing cementing.
- To interpret the lithological logs.
- To determine the location of open-hole packer for well stimulation.
- To detect casing damages or scale deposition inside the well.

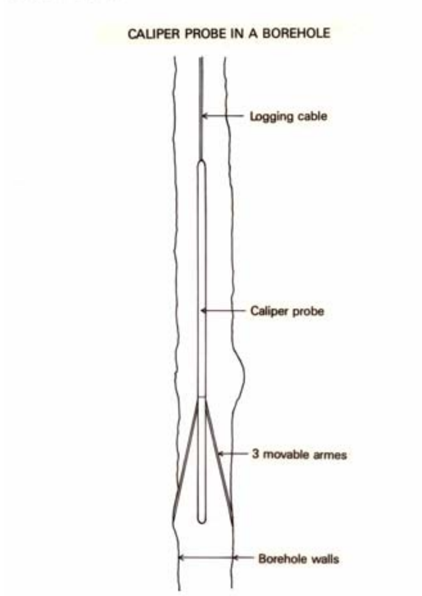

FIGURE 3: A calliper probe in a borehole

Calliper logs are also used to locate where to place cement plugs before cementing of cavities or large loss zones. The calliper log gives the location of cavities in the well. Cuttings will accumulate in all major cavities, causing a potential risk of the drill string becoming stuck in the well. Before that situation develops, the geologist who analyses the cutting has usually noticed the problem. Proper precautions can be taken in this case, including running a calliper log to locate the washout zones and to define the size of the problem. If big loss zones or cavities are found, it is usual to cement that zone, especially in the interval where the well will be cased (Stefánsson and Steingrímsson, 1980).

Before cementing the 13⅜" intermediate casing, certain parameters are calculated, such as the required volume of cement slurry, cement material and water requirements and the time to complete the job. The cement volume determination is based on theoretical volume calculations but also, where available, the actual well volume is determined, based on logs of well diameter made with a calliper tool. The volume, V, calculated from the calliper log is based on summing up the volume of a truncated right cone for each interval, h=0.5 m, logged in the well, using the formula:

$$V = \frac{\pi h}{3}(R^2 + r^2 + Rr) \quad (1)$$

To calculate the theoretical volume the following information is required:

- Annular volume between casing and open hole;
- Capacity of drill pipe;

- Annular volume between two strings of casing;
- Capacity of the open hole.

The calculations give the following:
- Estimating cement volume requirements (100% excess) = 20,863 l x 2 = 41,726 l;
- Displacement with water 2507 l + (12 m x 78.1 l/m) = 3,444 l;
- For the specific gravity of light weight cement, 1.67-1.7 g/cm^3, the slurry yield is 95 l/100 kg;
- The dry cement requirements are thus estimated as: 41,726 l / (95 l/100 kg) = 43,922 kg;
- The rate of pumping during cementing should be at minimum 17 l /s.
-

For the capacity and displacement data the Drilling Data Handbook (Gabolde and Nguyen, 1999) was used. The respective table is noted in Table 5. Surprisingly, an error was found in the new 7th edition of this popular handbook in Table D19 for item 5: the annular volume between two strings of casing which is shown for the 13⅜" casing inside a 18⅝" casing as 29.98 l/m; the 6th edition shows the correct value as 68.94 l/m.

TABLE 5: Cement volume calculation for 13⅜" intermediate casing

No.	Description	DDHB*	Capacity (l/m)	Length (m)	Volume (l)
1	Inside 5" drill pipe	D7	9.15	274	2507
2	Volume between floats in the 13⅜" casing	C70	78.10	12	937
3	Volume of open hole below the shoe	D4	155.2	2	310
4	Volume between 13⅜" cas and open hole	D16	64.5	240	15,480
5	Annular volume between cas.18⅝"-13⅜"		68.94	60	4136
	Total theoretical cement volume 2, 3, 4 and 5				**20,863**

*DDHB: Reference in Drilling Data Handbook (Gabolde and Nguyen, 1999)

Figure 4 shows the actual hole annular volume for well KJ-32 compared to the theoretical volume. Figure 5 shows the inner string cementing method.

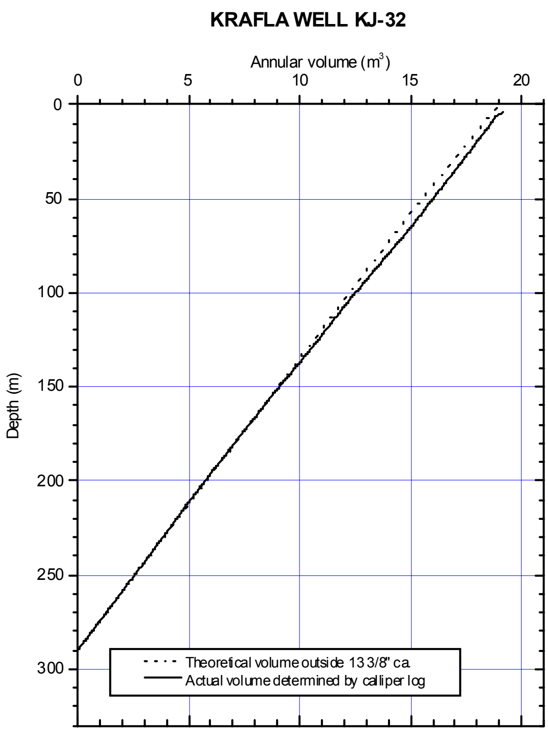

FIGURE 4: Annular volume, 13 ⅜" casing in 17 ½" hole

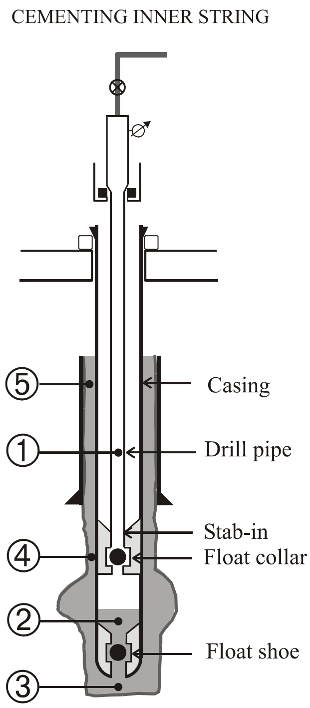

FIGURE 5: Inner string cementing method

2.5 Drilling of the 12¼" hole section from 300 to 1070 m

Drilling continued with a 12¼" bit first by drilling out the float collar and shoe. Below 108 m the drill string MDW tool and bit was cooled periodically while lowering the drilling assembly to the bottom. The kick off point (KOP) is at 450 m and the angle (32° direction N 50 E In) was built up before the casing depth of 1077 m. The daily drilling progress is shown in Table 6. Through the drill string the well was measured for temperature and pressure to the bottom of the hole and monitored for a short time, 30 minutes, before tripping out for reasons of safety. Before running the 9⅝" production casing, the well was logged for temperature, calliper and lithology.

TABLE 6: Drilling progress during second phase of KJ-32

Bit 12¼" MS 51ADM	Date August	Drilling (m/day)	Drilling (hr/day)	Drilling rate (m/hr)	Time on bit (hr)	Depth (m)
H 83912	22	82	7.5	10.93	7.5	377
H 83912	23	273	20	13.65	27.5	650
H 83912	24	273	18	15.17	45.5	922
H 83912	25	155	9.5	16.32	55	1077
Total	**4 days**					**770**

The minimum casing depth for each string is determined by the expected pressure and the temperature in the hole. For geothermal exploration wells, where the reservoir conditions are not known, they are assumed to follow the boiling depth curve (BPD). The depth of the production casing is, thus, based on the expected final depth and also on the geological conditions. For Krafla well KJ-32, the 9⅝" casing design depth was at 1000-1200 m, due to the geological conditions and decisions to exclude water for the "upper" reservoir. This depth is more than enough to insure safety of the well during drilling of the open hole to total depth. The 9⅝" production casing string in well KJ-32 was the following: the top most casing was K-55, 47 lb/ft with buttress, the next 21 joints were K-55, 40 lb/ft with buttress, then a short crossover from buttress to VAM connection casing. The next section consisted of 40 joints of VAM casing L-80, 47 lb/ft then a cross-over again to buttress to one casing L-80 47 lb/ft, and finally K-55, 47 lb/ft to bottom (Gudmundsson et al., 1998a).

The mechanical loads on casing strings in a geothermal well may be of various types, and occur during the running of the casing, during drilling and cementing of a subsequent strings of casing, and after completion of the well during heating up. These loads occur both in the axial direction of the casing or the radial direction. The selection of casing thickness and type of steel is not the subject of this paper. Briefly, it depends primarily on the casing depth and temperature. The most severe loading is from the collapse pressure while cementing with the inner string method, and that usually determines the casing thickness. The material selection is generally based on relatively low strength grades of casing steel such as API K-55 because it is less susceptible to hydrogen sulphide and to stress corrosion cracking and has a low Rockwell hardness that is considered important for corrosion resistance. Also, the K-55 or J-55 material is the highest grade that can easily be welded, as may be required for example on the casing head flange. Material selection is also dependent upon the thermal expansion during heating up and quenching, and the ability to withstand the resulting stresses. The material selection in Table 7 guidelines have been suggested for the 9⅝" casing.

TABLE 7: API steel grade selection guidelines based on temperature (Karlsson,1978)

Weight (lb/ft)	H – 40 (˚C)	J – 55 (˚C)	C – 75 (˚C)	N – 80 (˚C)	P 110 (˚C)
32.3	275				
36.0	284	303			
40.0		313	326	331	
43.5			333	338	> 340
47.0			339	340	> 340
53.5			340	> 340	> 340

2.6 Cementing unit

In Iceland the geothermal cement has for a long time been mixed in the following proportions: for 1000 kg Portland cement 400 kg silica flour (-325 mesh), 20 kg expanded perlite, 25 kg bentonite, 4 kg water loss (CRHT) and retarded according to the expected temperature. Dry mixing is done on the drill site by the drilling crew using the storage tanks. The individual material is layered in one tank in the correct proportions and then transferred back and forth between the tanks pneumatically three times for proper mixing. This mixed cement produces a lightweight slurry due to the effect of expanded perlite. The perlite has also been shown to add good loss of circulation properties (LCM) to the slurry to plug small fissures. A scetch of the cementing equipment used on Jötunn to prepare the cement slurry is shown in Figure 6. The 9⅝" casing was run to 1069.49 m and filled up with water while running in. After landing, the drill string is connected with a slab-in connector at the lower end of drill string to intersect the top of the float collar. Fresh water is circulated to cool the well to the recommended flow-line temperature < 30ºC, and check for any leakage on the cementing line. The estimated cement pumping rate was 1 tonne of dry material per minute and the total pumping estimated to take 45 min. The cement required for this particular job was 41,045 tonnes of cement and 200 kg retarder. Mica LCM flakes (100 kg) were also added to the cement to aid in bridging known loss zones. Cement was, in spite of this, not returned to the surface after the first job.

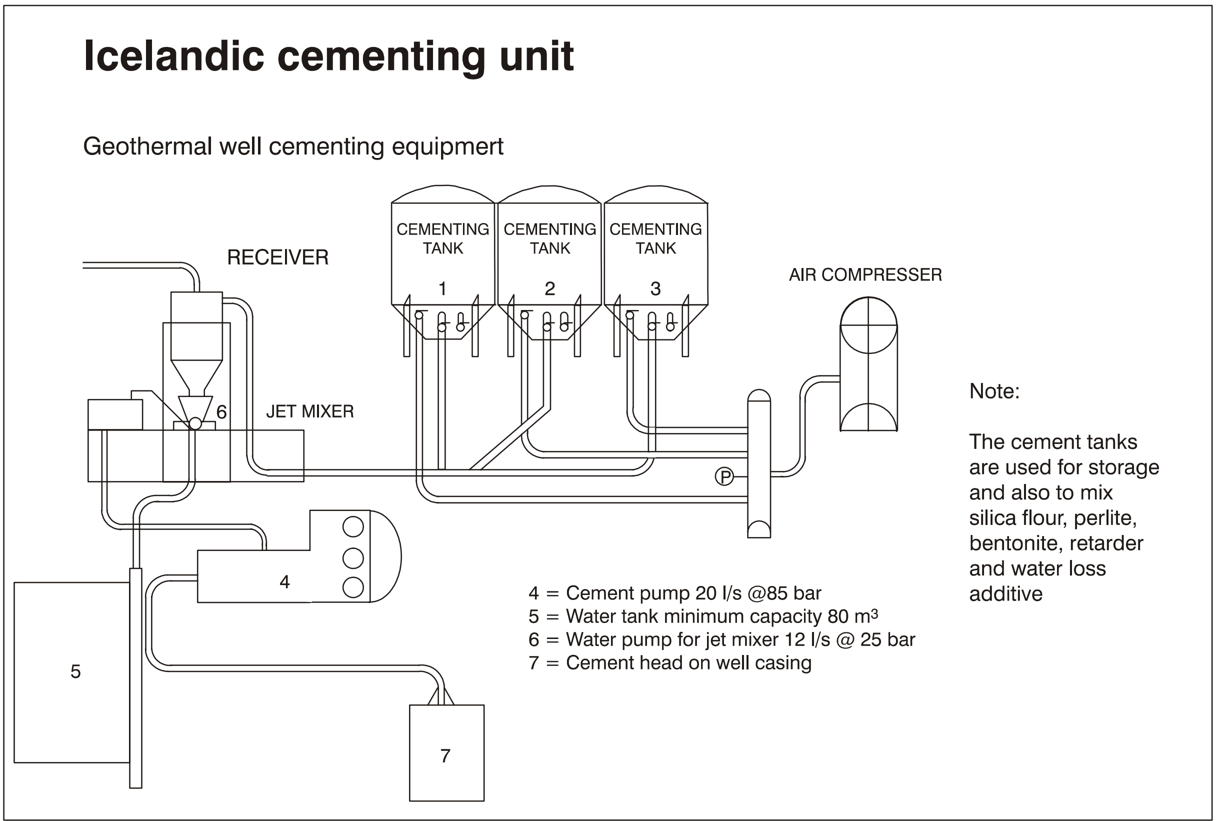

FIGURE 6: Cementing unit used in Iceland

2.7 Cementing bond log

A cement bond log (CBL) is made in order to determine:

- The top of cement slurry in the annulus if there are no returns;
- Cement quality;
- Bonding of cement to the casing and hole wall;
- If the cement has developed the required hardness (Stefánsson and Steingrímsson, 1980).

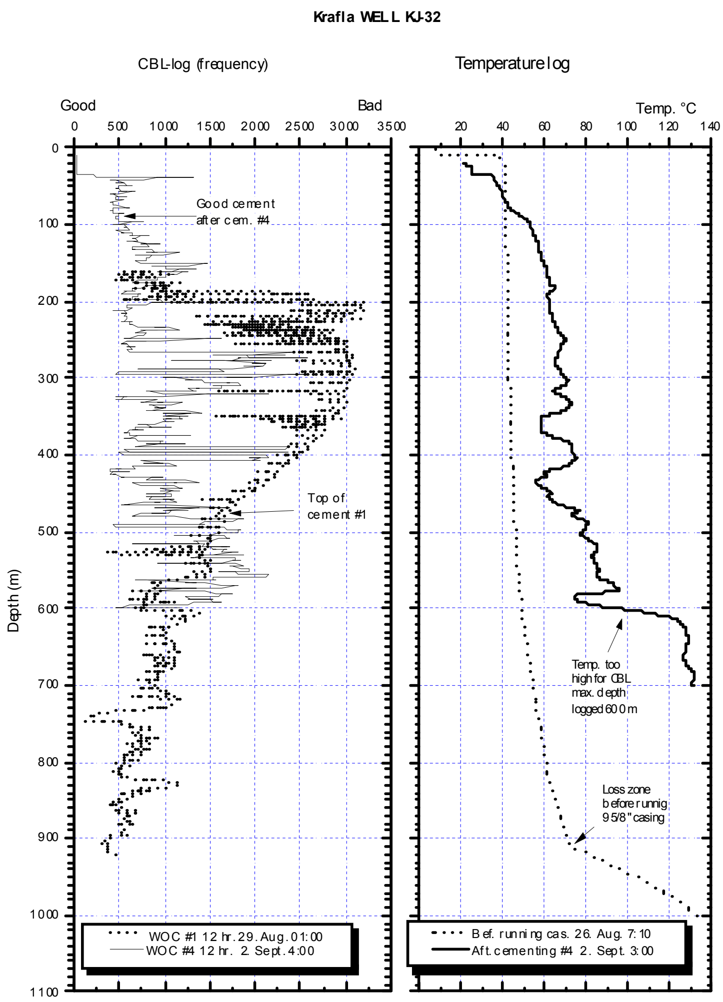

FIGURE 7: Cement bond log and temperature log of the production casing before and after four cement jobs

The CBL is a very important instrument for cementing evaluation due to losses in geothermal wells especially in high-temperature fields. The CBL logging and numerous temperature logs indicated the top of cement behind the casing to be at 550 m. Then a special explosive instrument was twice run into the well to perforate the casing at 550 m, to make holes. Pumping cement for the second time (squeeze cementing) through the perforated holes, the cement came up to 460 m where the cement went into a aquifer. Water was then pumped from above to keep the annulus open down to the loss zone. Only 10 tonnes of cement were used for the second job as it was decided that the cement should only reach up to the large loss zone at 460 m. The cement bond log was run again to determine the top of the cement. This was followed by backfilling of 17 tonnes of cement, mixed with 125 kg mica flakes LCM until the top of the cement reached up to 100 m. Backfilling of 5 tonnes from the top was the fourth and final cementing job. Then the cement was reamed out from inside the casing and a cement bond log (CBL) made full length of the casing. It showed generally good cement coverage except at 400 m and 270-320 m, where less strength had developed. This was, however, not considered enough evidence to proceed with remedial action, as the execution of cementing in these two sections could not explain it. Thus, it was decided to give the cement additional time to harden (increase WOC). The CBL logs of the production casing referred to above are shown in Figure 7.

2.8 Directional drilling programme of well KJ-32 in Krafla

A directional well profile for well KJ-32 had been made by Orkustofnun (consultant) and approved by Jardboranir hf, (operators) and Landsvirkjun (client). The target zone was established and defined as follows: Zones in a straight line in 50° direction +/-15° degrees azimuth from wellhead to the target. The build-up rate was at 1.5°/30 m until 30°was reached from a KOP at 450 m depth.

Procedure: The intention was to drill a vertical hole to KOP (kick off point) at approx. 450 m. Kick of the well from that depth according to the program until 1077 m was exceeded. The operation was performed with BHA (bottom hole assembly) as shown in Table 8 and Figure 8.

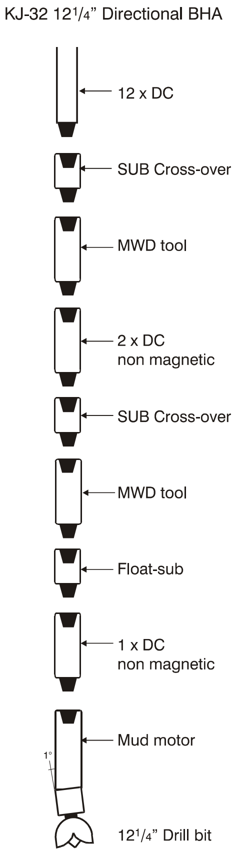

FIGURE 8: 12¼" bit mud motor and measurement while drilling

TABLE 8: Bottom hole assembly for kick-off and directional drilling (BHA). (Gudmundson et al., 1998a)

Item	Description	Length (m)	Total length (m)
1	12¼" Bit	0.34	0.34
2	Mud motor (Halliburton 9.625, F2000S)	8.14	8.48
3	DC (slic non-magnetic drill collar)	2.94	11.42
4	Sub (float sub)	0.62	12.04
5	Measurement while drilling (MWD)	9.24	21.28
6	Sub (cross-over sub)	0.60	21.88
7	DC (slick non-magnetic drill collar)	8.66	30.54
8	DC (slick non-magnetic drill collar)	8.82	39.36
9	Sub (cross-over sub)	0.60	39.96
10	Measurement while drilling (MWD)	9.11	49.07
11	Sub (cross-over sub)	0.56	49.63
12	DC (12 jts, slick drill collars)	110.00	159.63

The drilling procedure resulted in sliding 257 m (28.2%) and rotating 554 m (71.8%). A total of 811 m was drilled for the production casing. Measurement while drilling MWD readings were used to control the direction and inclination, and based on magnetic field measurements. The method was developed in sedimentary surroundings, with little experience of using it in volcanic material. A new method based on gravity sensors (accelerometers), still under development, was added for support. At 1000 m depth a 30˚ inclination had already been reached. At the casing depth the TVD (true vertical depth) was 1018 m with a vertical section 191 m in 50˚direction according to the original program.

2.9 8½" hole section – open hole section from 1070 to 1875 m

The production part was drilled to 1875 m depth. Table 9 shows the daily drilling activity and Table 10 the use of BHA. Finally it was cased with a slotted liner hung from the production casing (Figure 9 shows the liner hanger). As before, the direction and inclination was controlled by measurement while drilling (MWD) based on magnetic field measurements and supported by gravity sensors. After well completion, a giro-survey was run to confirm other readings. Blow-out preventers were used for drilling of each section of the well after the landing of the surface casing. To give an indication of the wellhead and preventer stack, while drilling of the 8½" hole, it is listed in Table 11.

TABLE 9: The 8½" hole section daily drilling activity

Bit 8½" RED TCI	Date Sept.	Drilling (m/day)	Drilling (hr/day)	Drilling rate (m/hr)	Time on bit (hr)	Depth (m)
EHP61ADCP	03	73	6	12.2	6	1150
----------	04	156	11	14.4	17	1306
----------	05	32	2.5	12.8	19.5	1338
----------	06	207	17	12.7	36.5	1545
----------	07	184	19.5	9.4	56	1729
----------	08	146	13	11.2	69	1875
Total	**6 days**				**69**	**805**

TABLE 10: Bottom hole assembly (BHA) for directional drilling with a mud motor and MWD tools (Gudmundsson et al., 1998b)

No.	Tool description	OD (")	Length (m)	Total length (m)	Upper connection	Lower connection
1	8½" bit, Reed, EHP61ADLP	8.50	0.26	0.26	4½ Reg	
2	6¾" Halliburton, F2000S, 5/6, 1.000˚ bend	6.75	7.52	7.78	4½ IF	4½ Reg
3	Float sub	6.75	0.52	8.30	5½ FH	4½ IF
4	Measurement while drilling (MWD)	6.75	9.24	17.54	5½ FH	5½ FH
5	Cross-over sub	6.75	0.59	18.13	4½ IF	5½ FH
6	DC (slick non-magnetic drill collar)	6.75	8.26	26.39	4½ IF	4½ IF
7	HW (heavy weight drill pipe)	5.00	9.07	35.46	4½ IF	4½ IF
8	Cross-over sub	6.75	0.60	36.06	5½ FH	4½ IF
9	MWD (measurement while drilling)	6.75	9.20	45.26	5½ FH	5½ FH
10	Cross-over sub	6.75	0.60	45.86	4½ IF	5½ FH
11	Cross-over sub	0.00	0.47	46.33	N/A	N/A
12	DC (9 slick drill collars)	7.25	81.83	128.16	N/A	N/A
13	Cross-over sub	0.00	0.82	128.98	N/A	N/A
14	Jar	0.00	9.45	138.43	N/A	N/A
15	Cross-over sub	0.00	0.73	139.16	N/A	N/A
16	DC (3 slick drill collars)	7.25	28.30	167.46	N/A	N/A
17	Keyseat wiper	0.00	2.05	169.51	N/A	N/A

The average inclination value was close to 32˚ at 1875 m depth, which resulted in ~1710 m as TVD with the vertical section close to 370 m, due to the spiral path of the well (Figure 10). The slotted liner is usually 7" and either hangs from the bottom of the production casing or rests on the bottom inside the 8½" hole. At Krafla the liner is hung at 1023.5 m inside the production casing (Gudmundsson et al., 1998b). Figure 11 shows progress during the drilling of the production part of well KJ-32.

TABLE 11: Blow-out preventer (BOP) stack

Item	Type	Mark	Size
Cellar		0.70 m down	2.5x2 x1m
Conductor casing		H- 40 casing	24"
Surface casing		K-55	18 ⅝"
Anchor casing		K-55	13 ⅝"
Casing head flange	No side outlets	Weld neck ANSI 900	12"
Expansion spool	No side outlets	ANSI 900	12"x10"
Master valve	POW-R-SEAL	ANSI 900	10"
X–over w. kill line		Two side outlets	3"
Pipe ram	Cameron BOP	API 3000	12"
Blind ram	Cameron BOP	API 3000	12"
Annular preventer	GK - HYDRIL	API 3000	12"
Flow line – T			12"
Rot. drilling head	Grant	API 3000	12"

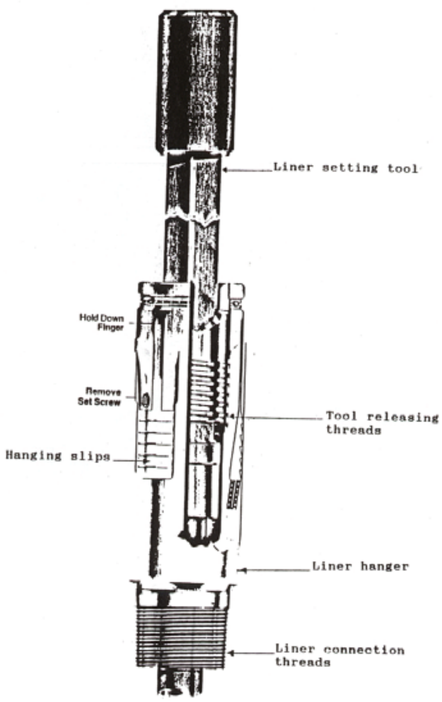

FIGURE 9: Liner hanger

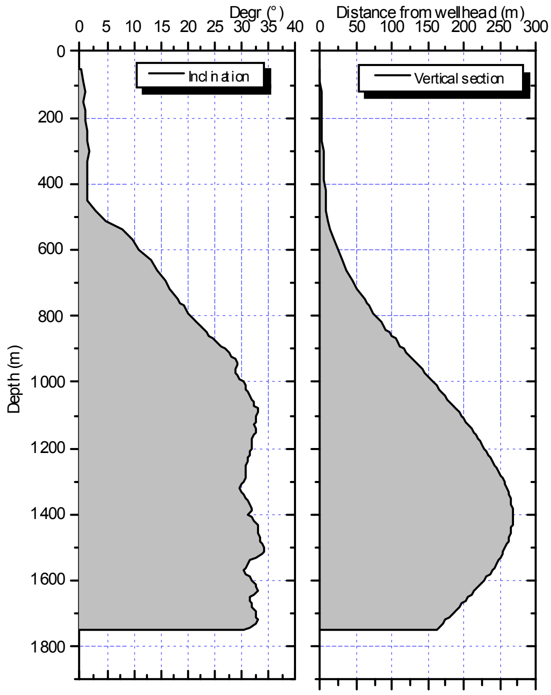

FIGURE 10: Directional survey of well KJ-32

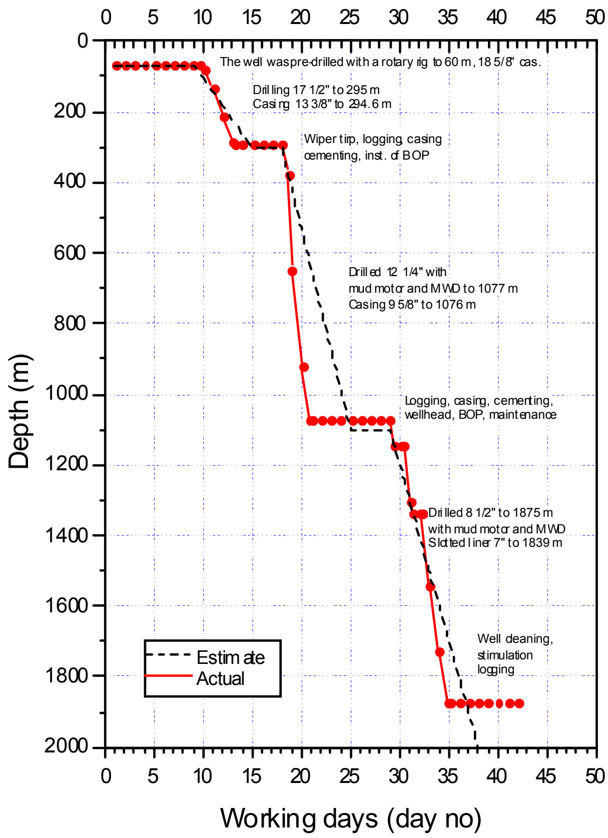

FIGURE 11: Progress curve for well KJ-32

2.10 Drilling fluids

Most high-temperature drilling is done with mud for drilling of the well down to the depth of the cemented casings. Wells usually will not flow, as the static water level is generally very low from a few metres to several hundred metres below the surface. Loss zones are frequently intersected while drilling with mud. To plug the loss zones, so called loss of circulation material (LCM) is added to the mud such as mica flakes or wood chips. For the productive part of the well, 8½" open hole, water only or aerated water is usually used as the drilling fluid. The purpose of the drilling fluid, be it mud or water, is to aid in the following functions:

- Removal of cuttings as they are produced at the drilling face;
- Transporting cuttings up the hole and suspend cuttings during periods of non- circulation;
- Stabilise the hole to prevent cave-ins and reduce drill string corrosion;
- Minimize formation fluid migration into the hole;
- Minimize fluid losses to the formation;
- Lubricate mud pump, bit and annuls between the drill string and the hole;
- Assist in collection and interpretation of samples and borehole geophysical logs;
- Cooling of the drill bit;
- Provide driving force for the mud motor.

2.11 Depth limits for the drill rig Jötunn (Iceland)

As an example of depth limit calculations for a drill rig, the rig Jötunn (Gardner Denver) that drilled well KJ-32 and most of the Krafla wells has been selected. The load distribution is given in Figure 12.

Rotary drilling line. Working load for a single line including the API breaking strength and safety:

$$\frac{API\ breaking\ strength}{Safety\ factor} = \frac{156{,}400}{3.18} = 49{,}182\ lbs \tag{2}$$

From the normal capacity of the mast the load per single line can be obtained as follows:

$$\frac{Nominal\ mast\ capacity}{No.\ of\ line\ crown\ block} = \frac{491{,}100}{10} = 49{,}110\ lbs \tag{3}$$

Comparing values 2 and 3 shows that the drilling line is within safe working conditions since 3 is within the safety range (values are almost equal).

Travelling block. Number of lines through the travelling block is 8 (Figure 12). Thus, the load carried by 8 lines is:

$$Load = 49{,}100 \times 8\ lbs = 393{,}000\ lbs \tag{4}$$

This is the maximum static hook-load capacity with 8 lines. The maximum usable dry drill string weight (no buoyancy effects) should not exceed 75% of the maximum static hook-load. This will allow a reserve pulling capacity of 25% in a dry hole and approximately 37% in a mud field hole (variable depending on the drilling fluid being used). This is equivalent to a safety factor of 1/ 0.75 (1.33). Using the safety factor the usable hook- load will be

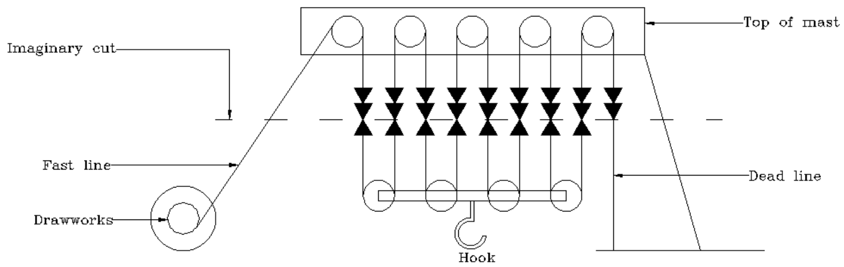

FIGURE 12: Rotary drilling line string-up crown and travelling block

$$Hook\text{-}load = \frac{392{,}800\ lbs}{1.33} = 295{,}339\ lbs \tag{5}$$

This is the safe hook-load to be born in mind when the drilling string is being designed to drill a well using this particular rig.

When drilling the previous wells, 12 drill collars, each 7¼" in diameter, weighing 119.9 lbs/ft and 31 ft long 19.5 lbs/ft drill pipes were used. The weight of hexagonal Kelly (6" OD) and travelling block are 2414 and 9000 lbs, respectively. The total fixed weight of the drill string then becomes equal to the sum of the collar (44,602 lbs), travelling block and Kelly weight. This sum becomes equal to 56,016 lbs. Subtraction of this dry weight from (4) gives a balance for the drill pipes, stabilisers, bit and so on. This rig can thus support a drill pipe length given by (Njee, 1986):

$$Pipe\ length = \frac{(295{,}338 - 56{,}016)\ lbs}{19.5\ lbs/ft \times 3.18\ ft/m} = 3745\ m \tag{6}$$

The total length of drill collar is 112 m and adding this value to the drill pipe length gives the total well depth rating as 3852 m. Figure 12 shows the rotary drilling line string-up crown and travelling block.

2.12 Witnessing of Krafla field drilling operations of wells KJ-33 and KJ-34

As a part of the training, the author stayed at Krafla for three weeks to witness the final days of drilling well KJ-33 and the transport and rigging up at well KJ-34. The trip to Krafla was very interesting and nice. The pilot said our flight would take one hour and that there was sunny weather at Mývatn. Five minutes after take off from Reykjavík airport and still, below 10,000 ft, we were inside the clouds. It started off as a terrible flight with a lot of air turbulence. After a few minutes the flight was stable and relaxing. The pilot explained about nature and the stratigraphy of land and names of mountains and the key features in the landscape. The land looks different at altitude. The geographical vision from top to down has gorges, deep steep-sided river valleys, and the land is covered with a lot of water. After a one hour flight we arrived at Mývatn airport. An Orkustofnun staff member was there to receive me. And then we drove off to the Krafla base camp (10 km) and I went to the drill site. There was a problem at well KJ-33 with the drill string stuck at a depth of 2011 m. These are exercises from my notebook:

July 30 1999: Tried to pull drill string with over 350 tons, but it was not possible to move. Pumping water through the drill string at 40 l/s, the down hole motor started working and there was vibration.

July 31-August 1 1999: Several temperature logs were run in order to determine where the drill string was stuck. Water was injected into the annulus at a rate of 30 l/s. The temperature logs showed that the injection cooled the well to the bottom. Temperature peak was, however, seen at 1975-1980 m depth at the location of the stabilizer in the drill string. It seemed that the injected water was not flowing all around the stabilizer, indicating that the stabilizer was the sticking point. Some irregularities where also seen in the temperature logs between 1850-1890 m depth, the interval just above X-over sub. Sticking at this depth interval could explain why the jar did not work. Determination of the free point can be made by the stretch method. Then the following formula applies (Ng'ang'a, 1982; Gabolde and Nguyen, 1999):

$$L = \frac{2.675 \times W \times I}{P' - P} = \frac{2.675 \times 31.06 \times 1584}{70} = 1880\ m \qquad (7)$$

where L = Length of free pipe [m];
W = Weight per meter of pipe [kg/m];
I = Differential stretch [mm];
$P' - P'$ = Differential pull [000 s daN].

In this way the sticking point was calculated to be at 1880 m.

August 2 1999: The shooting adapter was repaired on the morning of 2 August. Then it was decided to try to back-off (unscrew) at the drill collar joint at 1962.5 m depth. There were two drill collars above the drilling motor in the drill string. A back-off bomb (15 strings, 2.2 m long of 85 grain hexacord) was lowered to 1962.5 m depth and exploded without succeeding in backing off the joint. This meant that the sticking point (the free point) was higher up on the drill string. Probably above the X-over from drill collars to drill pipes. Therefore, it was decided to do the next back-off at 1856 m. There were three drill pipes (1 stand) above the X-over and near the top of the interval where the irregularities were seen in the temperature logs. A back-off bomb of 8 strings at 85 grain hexacord was lowered to 1856 m and exploded after 3 trials. The back-off was successful. After back-off at 1856 m the drill pipes were pulled out.

August 3 1999: Fishing string with jar, bumper sub and intensifier were lowered into the well and connected to the fish. Pulling with 320 thousand pounds and jarring lifted the fish. The pulling force decreased gradually to 220 thousand pounds but when the fish had been lifted 15 meters, the drill string snapped. The travelling block flew up the mast and hit the draw works and damaged the sheaves at the top of the mast. The breaking point on the drill string turned out to be only at 100 m depth in the well.

August 4 1999: The damage on the sheaves was repaired. Then fishing resumed. First by connecting with an overshot to the broken drill pipe at 100 m depth and by jarring again. Pulling force was 220 thousand pounds for the first 5 m but after that the drill string was free. The weight indicator at the rig did not, however, show the weight of the whole drill string. So it was clear not all fish were being landed. This was confirmed when the fish came out of the hole. The drill string had broken half a drill pipe length above the X-over leaving all the drill collars and the bottom hole assembly in the well.

August 5-10 1999: Meetings all day with people from the insurance company discussing further fishing operations. At the same time the injectivity of the well was studied. These tests showed high injectivity indicating that well KJ-33 would be a good producer. With this information in hand it was decided to stop further fishing and leave the collars and the bottom hole assembly in the well and proceed with the planned completion program of the well, starting with geophysical logging to study the lithological units of the well. Then the 59 joints of 7" slotted liner 787 m casing were run into 9⅝" production casing. Finally, a 10 hour injection test was carried out to determine the hydrological parameters for the well. The drilling work on well KJ-33 was completed on August 10 when work started on moving the drilling rig started to the next drilling site (well KJ-34).

August 11 1999: Breaking down drill string travelling block and Kelly assembly from the floor. The other drilling crew group started to relocate the water line through the mountain to the new drill site. The water line size was 6 3/4" high density polyethylene plastic pipe and the connection clamps were made from aluminium.

August 12 1999: The 43 m high rig mast was lowered to the supporting stand. The drill pipes and collars were removed from the rack, BOP bolts disconnected, and the wire line from the mast and all fittings disconnected.

August 13 1999: Substructure disconnected and ladder walkways, water/mud tanks, mud pumps and other rig accessories.

August 14 1999: The new well site for well KJ-34 is approximately 5 km from KJ-33. The drilling progress curve is shown in Figure 13. On this the first day of transportation with six big trucks, starting with the substructure frame, the following needed to be done before assembly of substructure in the exact place:

a) Checking the level of the ground according to specification;
b) Checking the centre of the well through the rotary at the top substructure with levelling instrument;
c) Measure the distance of the rack before laying the substructure.

The centre of the well and rig was over the previously drilled 18⅝" surface casing. Afterwards, the nine frames of the substructure were laid down. The BOP was put on a skid plate with rollers for the second phase of drilling.

August 15 1999: Transportation of the mast, two mud pumps, 21 tons each, and mud tanks. The rig equipment loaded and unloaded with a 35 tonne hydraulic crane and a forklift. All the drillers took part in the transport and they know what to do without instructions.

August 16 1999: The cementing unit moved. The cement silo was placed in the proper place and at the same time the mud pumps were connected to the tanks. The

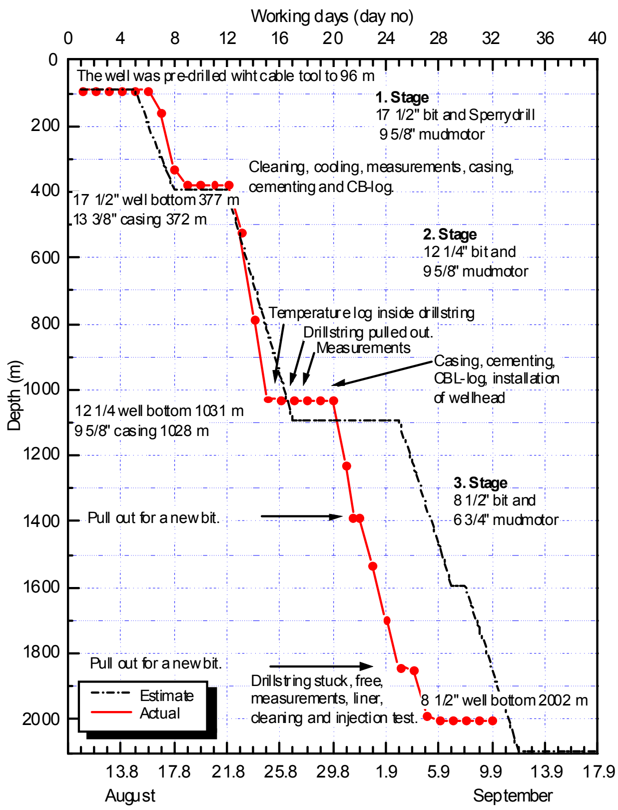

FIGURE 13: Drilling process diagram for well KJ-34

other group prepared the cat line crown and travelling block wire ropes to raise the mast.

August 17 1999: Start of installing the walkway racks and moving the offices. Everything ready within four working days to start drilling, Rig-down to Rig-up.

August 18 1999: The BOP device was installed.

August 19 1999: The 12 m deep rat- and mouseholes were drilled. Drilling of well KJ–34 started. I was on site for the second stage of drilling of well KJ-34, while drilling for the intermediate casing. The drilling of this well went very well and the job was completed on September 10 in 25 days. The well was drilled vertically with mud motors to 2002 m depth.

3. TENDAHO GEOTHERMAL FIELD, ETHIOPIA

Ethiopia is one of the few African countries with a large geothermal energy potential. Geothermal resources of the country are primarily formed in the main Ethiopian rift valley and Afar depression, covering an area of about 150,000 km^2 (see Figure 14). This region is a part of the great East-African rift system. Exploration for geothermal energy in Ethiopia was jointly initiated in 1969 by the Government of Ethiopia and the United Nations Development Programme (UNDP). The early objectives of geothermal exploration in Ethiopia were to investigate and identify the potential geothermal prospects and to recommend further detailed investigations. The geothermal reconnaissance survey covered the main part of the Ethiopian Rift valley and upper depression. The survey consisted of geological, geochemical and geophysical investigations. Identification of five locations as target areas for deep drilling was one of the main outcomes of these surveys. One of these was the Tendaho geothermal area which is located in the centre part of the Afar Depression inside the Tendaho graben which is about 50 km wide and 100 km long, coordinated in a NE-SW direction.

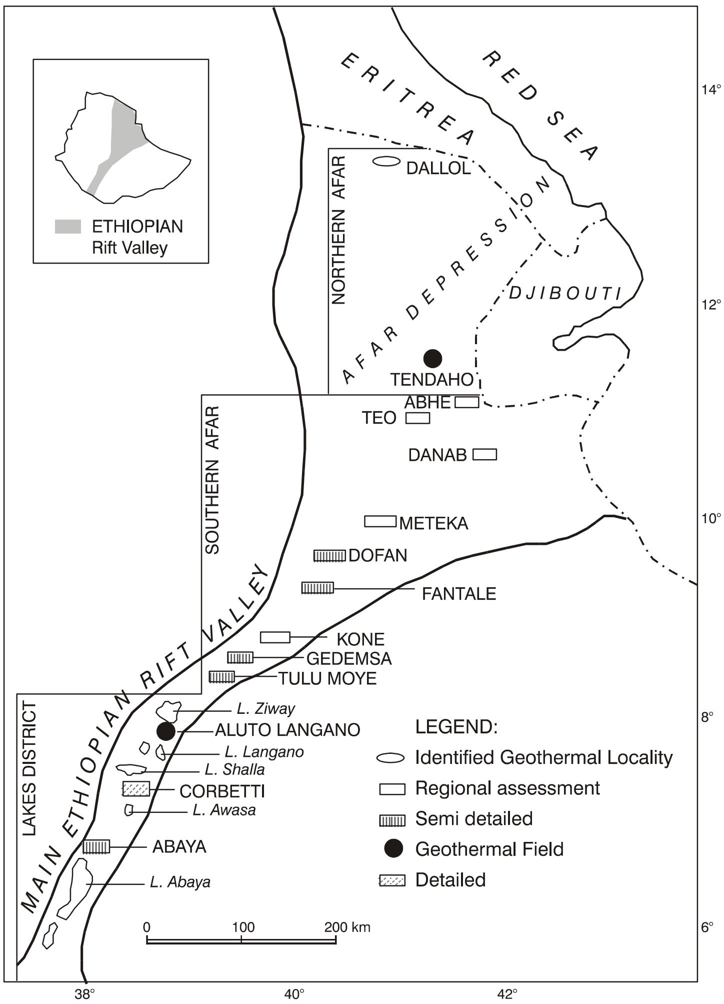

FIGURE 14: Geothermal fields in the Ethiopian rift valley prospect

The Tendaho field is located approximately 630 km northeast from the capital, Addis Ababa. The base camp is 21 km from the drill site. The geography structure is plain sand and soil. With high winds, the temperature sometimes reaches 35°C.

Geothermal exploration of the Tendaho geothermal area in Afar Regional State has been underway since 1971 based on the recommendation of the UNDP (1973). Reconnaissance survey and geothermal exploration was organised and financed by the Ethiopian and Italian governments. The results of these surveys was drilling of shallow temperature gradient boreholes and six geothermal wells. Of these, four wells produce from water-dominated reservoirs at a temperature of 240°C. Presently, the Ethiopia government is looking for a financial source to develop the field and to drill additional production wells. The intended use is for long-term electric power generation and /or direct heat use. Except for well TD-3, the drill sites are located close to the Tendaho cotton plantation. The others are located 500-1500 m apart. The deepest well measures 2196 m and the shallowest one 466 m. Four of the deep exploration wells are suitable for utilisation for electric energy generation (TD-2, 4, 5 and 6). Well TD-5 was drilled in 1997, it was spudded on Dec. 20 and drilled to a final depth of 516 m in Jan. 13 1998 (Table 12).

TABLE 12: Data on well TD-5, Tendaho

Well	Tendaho 5 (TD-5)
Prospect	Tendaho
Region	Afar Regional State
Country	Ethiopia
Location	Inside the Dubti plantation, about 500 m northwest of well TD-6; East = 31558, North = 130298, elevation (m a.s.l.) 366.3
Total depth	516 m
Rig type	Massarenti-7000

3.1 Site preparation and rig mobilisation

Before mobilising the rig equipment and tools, all maintenance work and service required on the rig engine, cementing unit, and other auxiliary had been accomplished by the rig mechanics and drillers. The working time on-site is eight hours per day with three shifts. One drilling crew has 13 persons, not including the engineering department and geoscientists. The shift changes at two months intervals. Preparation work for well TD-5 consisted of such work as levelling and compaction for stability of the rig, installing the cellar and 30" conductor, and preparing and fencing the approximately 90 x 50 m site. The site had a concrete ramp, water disposal pond and suction pit. Road construction of a 15 km gravel road with red ash was also required. Water for drilling of the first well TD-1 was a major problem. A 19 km 6" steel with pipe connections bolted with clamps and rubber seals was laid down from the Awash river to the site. The water was pumped with two Revote water pump engines. The water pumps were run at a maximum of 1800 RPM for 24 hours a day. For TD-5, drilling activity water was, however, obtained from the TD-4 discharge pond, requiring the laying down of a 6" water line pipe a distance of 3 km, in this case reducing the time and material required. Transport and mobilisation of the rig equipment from the Semera warehouse to the site took 20 days because the rig is very bulky and requires a crane to load and unload. Shortage of machinery and the site distance contribute to the mobilisation time.

3.2 Overview of drilling activity of well TD- 5

19-11-97 Drilling started with mud and a 17½" drill bit, later opening the hole with a 24" reamer to 40,6 m.
22-12-97 The 20" surface casing landed and cemented.
28-12-97 The 13⅜" intermediate casing landed in the 17 ½" hole and cemented to122.2 m.
03-01-98 The 9⅝" production casing landed and cemented at 214.0 m.
14-01-98 Drilling to a final depth of 516 m and 7" perforated liner set to a depth of 501.6 m. During the course of drilling, partial circulation losses were acquired at the depth

intervals 27-301 m and 460-487 m. Recovery of the cores at two different depths. During drilling, fall-off injection test were made. Rigging down the mast completed. The rig telescopic mast was retracted and some maintenance work accomplished on the derrick floor before the final rigging down of the mast.

27-01-98 Disassembly of the rig equipment and transporting the rig from TD-5 to TD-6. Installing the master valve to well TD-5 and completing the well. The total time for drilling and other activities on well TD-5 was 23 working days. The drilling progress curve is shown in Figure 15.

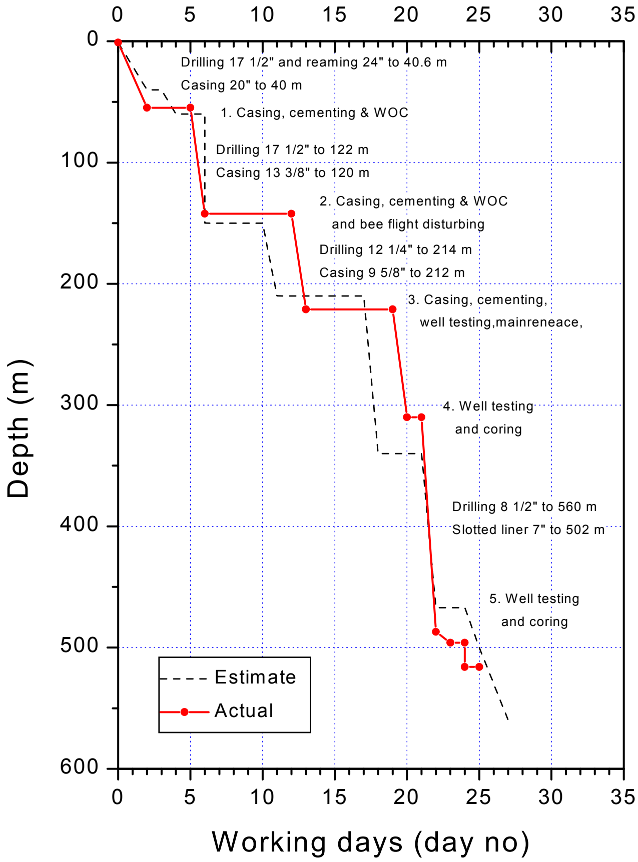

FIGURE 15: Drilling progress curve for well TD-5

3.3 Borehole geology and lithological description of well TD-5

0-97 m: Sediment, the formation is characterized by fine- to medium-grained siltstone cemented by carbonate. Sand, silt and clay compose the uppermost 15 m.
97-101 m: Basalt, dark micro-porphyritic basalt with unaltered phenocrysts of plagioclase and clinopyroxene.
101-129 m: Sediment, fine- to medium-grained brown sandstone cemented by carbonate.
129-149 m: Basalt, dark sub-ophitic/intergranular basalt with unaltered phenocrysts of plagioclase and clinopyroxene.
149-245 m: Sediment, fine- to medium-grained brown sandstone cemented by carbonate characterizes the formation. Brown siltstone is seen at the interval 195-205 m depth. Secondary minerals occurring in the grain and as interstitial fillings of the sedimentary grains are zeolites, calcite and quartz.
245-252 m: Basalt, dark gray aphanatic basalt with calcite deposition in the fractures.
252-280 m: Sediment, brownish siltstone with intercalation of light brown silty clay.
280-301 m: No cuttings because of circulation loss.
301-516 m: Sediments, the formation is characterized by fine- to medium-greenish gray sandstone cemented by carbonate. Few 5-10 m thick siltstone layers are seen. Secondary minerals are zeolites as laumontite, calcite, quartz and clay. In the deeper part wairakite and anhydrite occur and zeolites are replaced by quartz (Gebregziabher, 1998).

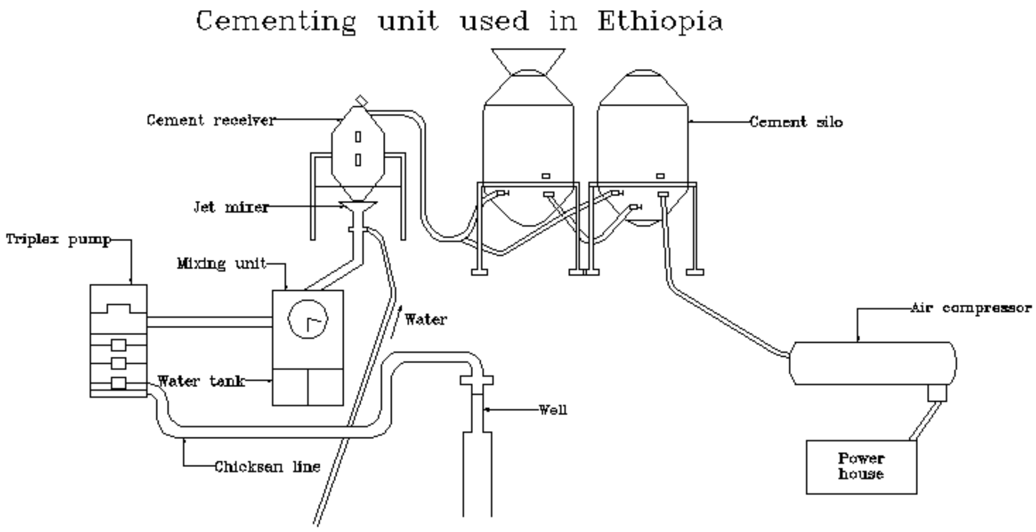

FIGURE 16 : Cementing unit used in Ethiopia

3.4 Drilling of the 24" surface hole section to 40.6 m

The well was drilled with bentonite mud to a depth of 40.6 m, first with a 17 ½" bit and then reaming with a 24" bit using the following bottom hole assembly (BHA): Bit 24"+ near bit 24" +1 drill collar 8" + stabilizer 24" + 1 drill collar 8". The bit was the RR# 1-26 –Y11-REED equipped with 3 +22/32" nozzles. The hydraulic parameter was for flow-liters per minute (LPM) and pressure (P) bar: LPM 3200 - P 50 bar. The Totco surveys were not run for inclination. Before running the casing, the casing threads were cleaned, and the inside diameter of the casing measured with a calliper, and the length of the casing measured with a tape. If the casing calliper could not pass through inside the casing pipe, it was thrown away as being under gauge. The threads were protected with rubber clamps. On the casing shoe, a Baker Lock thread glue is applied to prevent unscrewing. Each thread joint is re-greased and tightened until it meets the triangular stamp mark on the upper casing. While running the casing, it is filled with water to overcome bouncy effects. Four lengths of 106.5 lb/ft J-55 steel grade buttress threaded 20" casings were screwed together to place the shoe at 40.6 m. The hole was flushed with water followed by a geothermal cement slurry with a density of 1.8 kg/l. The cementing was done on 22nd December 1997, using the KREMCO 600 cementing equipment shown in Figure 16. Every cementing job starts with the calculation of the volume of cement slurry that will be required and hence the cement and water that has to be on-site. The slurry volume is the sum of the annular volume between two casing volumes behind the casing and open hole; the volume between the float collar and guide shoe and estimates for losses in the formation (a safety factor of 100%). The safety factor depends very much on experience, ranging from 50% to 120%. The cement material used was an imported geothermal cement mix from Italy delivered in 15 ton big bags. The inner string cementing technique was used. Immediately after pumping the cement, it was displaced from the inner string 5" drill pipe with 366 l volume of water. Full return to surface of cement slurry was obtained and a total of 21 tonnes of geothermal cement used. The 20" casing was cut 1 m below the rotary table and a 10" flow line connected to the shale shaker. No blow-out preventers or valves were installed on the casing. For a density of 1.8 kg/l, the cement yield was 85.3 l/kg, resulting in the actual cement volume used 17,913 l. The actual excess required was 186%.

3.5 Drilling of the 17½" intermediate hole section from 40.6 m to 122.2 m

The well was drilled with bentonite mud and a medium hard formation rock bit by using the following BHA: 17½" Bit NB 17½"+ short DC 8" + Stabiliser 17½" + 8" DC 2 + Stabiliser 17½"+ 8" DC. The bit used was RR # 2 17½"- S2IG REED equipped with 3 x 18/32 nozzles. The hydraulic parameter was: LPM = 2000-1600, P = 10-15 bar.

The well was drilled without interruption to 79.6 m: Then there was a big leak in the water supply pipeline. The drill string was pulled up, mud circulated, and welding repairs made. After the line was repaired, the well was drilled down to 112.2 m and the inclination measured to be 0.4˚, with the Totco survey tool. The well was washed and water circulated for 20 minutes, then everything was ready for running the casing. Ten joints of 13⅜" 68 lb/ft J-55 steel grade casing with Antares threads were screwed together to place the shoe at 121.4 m. A float collar was placed one length above the float guide shoe. Two centralizers were placed on the bottom and then at every third socket. The hole was flushed with water and then the casing cemented with geothermal cement having a slurry density of 1.8 kg/l. The cement was returned to the surface. Then, immediately the cement was displaced with water from the inner string 5" drill pipe. From the top, fill-up was performed through a macaroni string 1¼", run to 20 m down the annulus using 1.5 tonnes of geothermal cement. A total of 17 tonnes of geothermal cement was used. For a density of 1.8 kg/l, the cement yield was 85.3 l/100 kg resulting in a cement volume of 14501 litres and the excess cement is, thus, 70%. The 13⅜" casing was unscrewed 0,60 m above the cellar floor and a 13⅜" x 3000 PSI buttress threaded casing head screwed on and welded. The casing head assembly was made by WKM and has two 2" flanged side outlets. Then a drilling spool and the 12" ANSI 900 Breda master valve was installed. The welding strength was tested at 35 bar. Then the BOP´s were nippled up, the 13⅝" x 3000 PSI double ram and annular preventers.

3.6 Drilling of the 12¼" hole section from 122.2 m to 214 m

The cement from 122.2 m milled out and then drilled with bentonitic mud using the following BHA (Figure 17): Bit 12¼" +NB 12¼" +short drill collar 8" + stabilizer 12¼" + 2DC 8" + stabilizer 12¼" + drill collar 8"+ 6 Heavy weight drill pipe. The bit was the new # 3 12¼" – REED HP21G, equipped with 3 x 16/12" nozzles (Aquater, 1995).

During the drilling operation the hydraulic parameters were the following: LPM=1600, P=35 bar. The well inclination was checked with a Totco survey # 2 at 214 m and the result was 0°. Twenty one joints of 9⅝" 43.5 lb/ft J-55 buttress threaded casings were screwed together to place the shoe at 213.7 m. A float collar was placed one length above the guide shoe and casing centralizers were placed on every third socket. The cementing was done on the 3rd of January 1997. The hole was first flushed with water then cemented with 9,800 litres of geothermal cement slurry at 1.8kg/l density. The inner string 5" drill pipe was flushed with water. During the cement setting time, a macaroni string was run in hole with galvanised tubing to check the top of the cement between 13⅜" and 9" casing. This resulted in pumping 250 litres of cement slurry at 1.9 kg/l density. The primary cementing used 12 tonnes of geothermal cement. After 12 hours, WOC was disconnected and BOP´s 12" gate valve and the drilling spool picked up. The 9⅝" casing cut at 0.58 m from the casing head. After checking the top of the cement, fill-up was performed with 0.32 tons being used for backfill, making a total of 12.32 tons for this string. For the density of 1.9kg/l, the slurry yield was 75.8 l/100 kg (Gabolde and Nguyen, 1999, Table I6) the cement volume required for

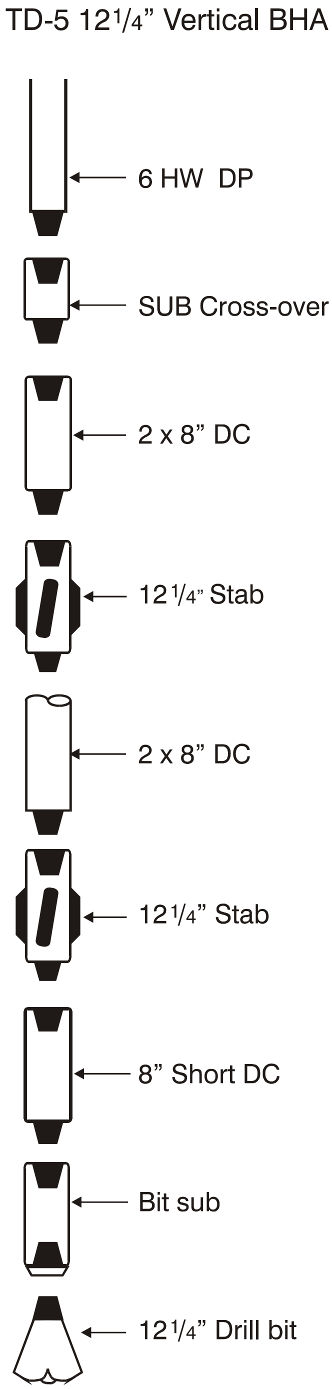

FIGURE 17: 12¼" vertical drilling (BHA)

this means that the actual volume was 9,338 l, or an excess of 32.6% over the theoretical volume (Table 13). After cementing the 9⅝" casing there was a problem in the well between the 30" conductor pipe and the 20" casing, due to the escape of hot water and steam from the annular space. The annular space between the 20" casing and conductor was cleaned down to 0.70 m below the cellar floor. Then a slotted 2" pipe was run down the annulus and the space filled with 0.50 m of gravel and 0.20 m of fine sand and cemented up to the cellar floor. This did not stop the water and steam flow from the annular space. This leakage has continued to this date and is causing problems for the logging crews. Other shallow wells at Tendaho have the same problem. The exact path of the steam and its origin is not known, but it is expected to have a shallow origin. Poor cementing has been suggested by some. However, cementing operations were successful with returns, adding the fact that the leakage started in TD-5 while the well was in a quenched condition, which does not support that idea. Consolidation drilling and injection of grout near to the wells is one method being considered.

TABLE 13: Cement volume calculation for the 9⅝" production casing of TD-5

No.	Description	Drilling data Hb.*	Capacity (l/m)	Length (m)	Volume (l)
1	Inside 5" drill pipe	D7	9.15	200	1830
2	Volume inside casing shoe	C60	38.84	12	466
3	Volume of 12¼" hole below shoe	D4	76.04	2	152
4	Annular vol. 12¼" hole x 9⅝" casing	D16	29.1	90	2619
5	Annular vol. 13⅜" cas x 9⅝" casing	D18	31.16	122	3802
	Total theoretical volume 2, 3, 4 and 5				**7039**

*(Gabolde and Nguyen, 1999)

Estimate of required cement volume (100% excess) = 7,039 x 2 = 14,078 l or 14 m^3.

Displacement with water at the end of cementing job No 1 and half of the capacity between the floats. The geothermal dry cement requirements for a slurry density of 1.8 kg/l are calculated based on a slurry yield of 85.3 l/100 kg dry cement (Gabolde and Nguyen, 1999). Dry cement requirement = 14,078 l / (85.3 l/100 kg) = 16,504 kg. Water requirement = 16,640 kg x 53.6 l/100kg = 8,846 l.

3.7 Drilling of the 8½" hole section from 214 to 516 m

The cement and floats were milled out using water, from 202 m inside the casing float collar and shoe and drilled down to 214 m without weight on bit (WOB). The rock bit used for the milling out of cement was bit # 3 8½" REED HP21G equipped with 3 x 15/32 nozzles. Then the following stabilized bottom hole assembly was run for this hole section: Bit 8½" + near bit + short drill collar 6½" + stabilizer 8½" + 2 drill collar 6½" + stabilizer 8½" + 8 DC 6½" + 6 HW drilled pipe down to 302 m. Partial loss of circulation of 10 l/s was registered at the depth interval 271-301 m. Then the geologists decided to take core #1 in the well at a depth of 301 m. The coring string was equipped with the 8½" x 4"– CB 23 core shoe capable of taking a 9 m long core. Core #1 had a recovery of 61%. Core # 2 was taken with the same equipment from 487 to 496 m, with a recovery of 55%. The core was cut with 10 tons WOB at 70 RPM and pumping 1500 LPM at 45 bar pressure. After the second core the well was drilled down to 516 m where there was a total loss of circulation. The drilling was stopped at 516 m and a 7" slotted liner run, grade J- 55 32 lb/ft. The 7" liner was landed close to the bottom of the 9⅝" casing at 195 m. The liner has 16 perforated joints, 5 slotted joints and 3 plain joints down to 502 m. Figure 18 shows the casing profile of TD-5. The perforated liner has 20 mm drilled holes, 1600 holes per pipe. After removing the rig, the BOP´s were taken off the well and the final wellhead assembly with an expansion spool installed (Figure 19). It consists of a WKM expansion spool with adapter flanges 12" x 3000 and 10" x 2000. The spool has an erosion shield and two 2" flanged outlets. The production master valve is made by Foster type Pow-R-Seal 10" API Class 600, Trim FT/3.

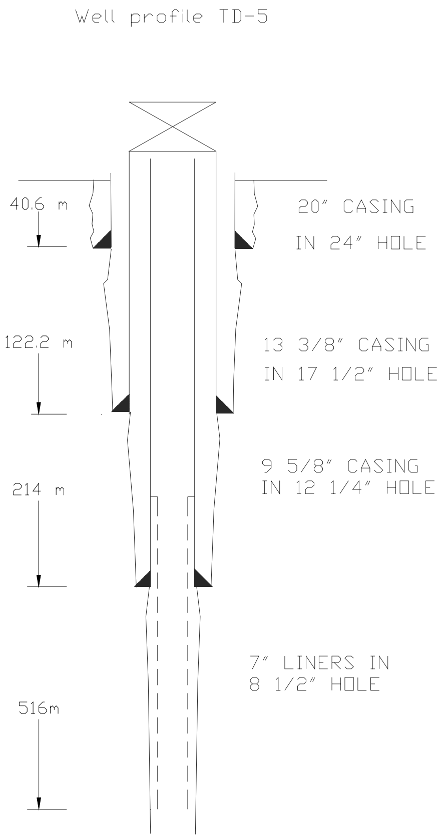

FIGURE 18: Casing profile of well TD-5

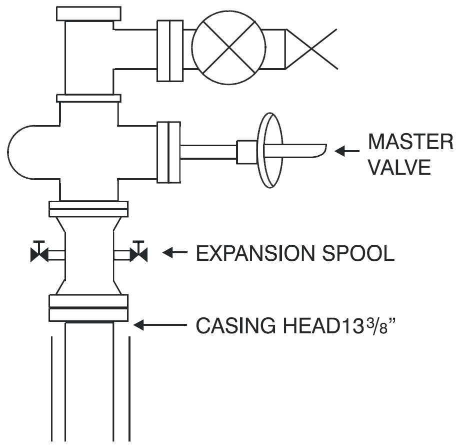

FIGURE 19: Well head assembly for TD-5

The total use of mud chemicals for drilling of well TD-5 was the following:

Bentonite	12,000 kg
Lignite	75 kg
FCL	25 kg
I.D.F Flr	150 kg
Caustic soda	125 kg
I.D.F High temperature	50 kg
I.D.F thinner 500	700 kg

Temperature and pressure profiles measured while drilling and after completion of the well TD-5 during heating up and flow testing are shown in Figures 20 and 21 (Amdeberhan, 1998).

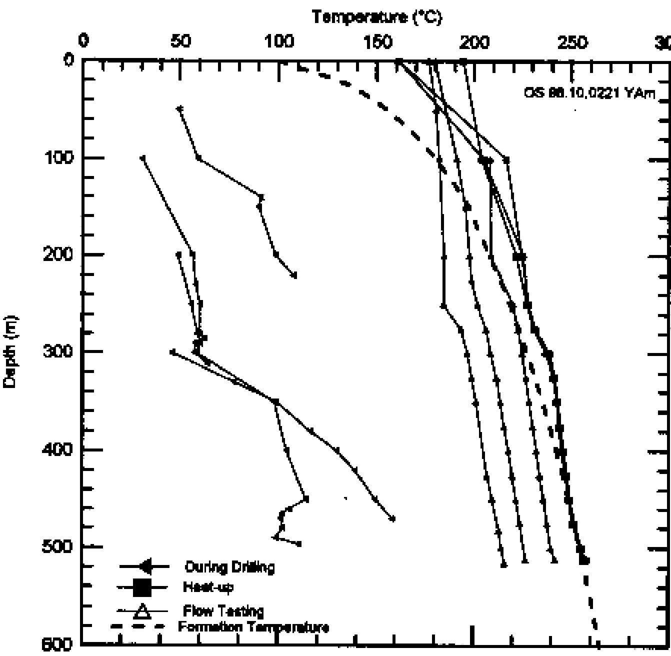

FIGURE 20: TD-5 temperature profiles

3.8 Drilling time analysis

The drilling of TD-5 took 23 days but the overall job took approximately two months. The time was broken down into activities as shown in Table 14. A pie chart shows the same data and highlights the fact that the actual drilling hours with bit on bottom were only 8.36% of the total, taking 52.08 hours (see Figure 22).

3.9 Comments about the rigs and well problems

The Massarenti rig performed reasonably well. There were no major problems with it but several small problems such as in one triplex power pump system which needed minor repairs, especially on

TABLE 14: Drilling time analysis, well TD-5

Description	Duration hours	%
Drilling	52.1	8.4
Tripping	108.8	17.3
Hole opening	2.0	0.32
Circulation	29.9	4.8
Preparation of rig	100.5	16.1
Running casing	54.1	8.7
Cementing job	5.3	0.85
Waiting on cement	56.0	9.0
Cleaning	20.2	3.2
Drilling cement	0.7	0.11
Wellhead assembly	37.0	5.9
Coring	12.3	2.0
Well testing	64.9	10.4
Mechanical problems	36.4	5.8
Other maintenance	43.4	6.9

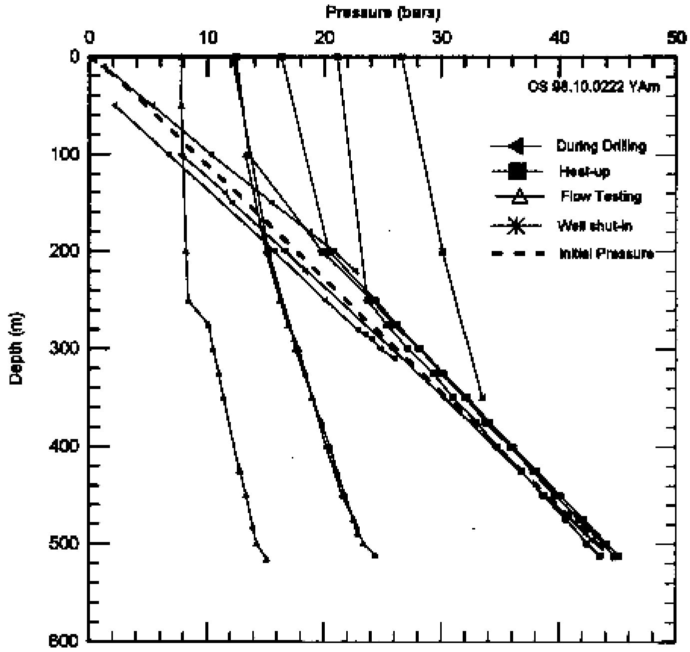

FIGURE 21: TD-5 pressure profiles

the valve seat. For future use, the valve compartment needs to be replaced. This rig has drilled a total of 7570 m in six wells in Ethiopia. The maximum depth capacity a of rig with a 5" drill string is 3000 m.

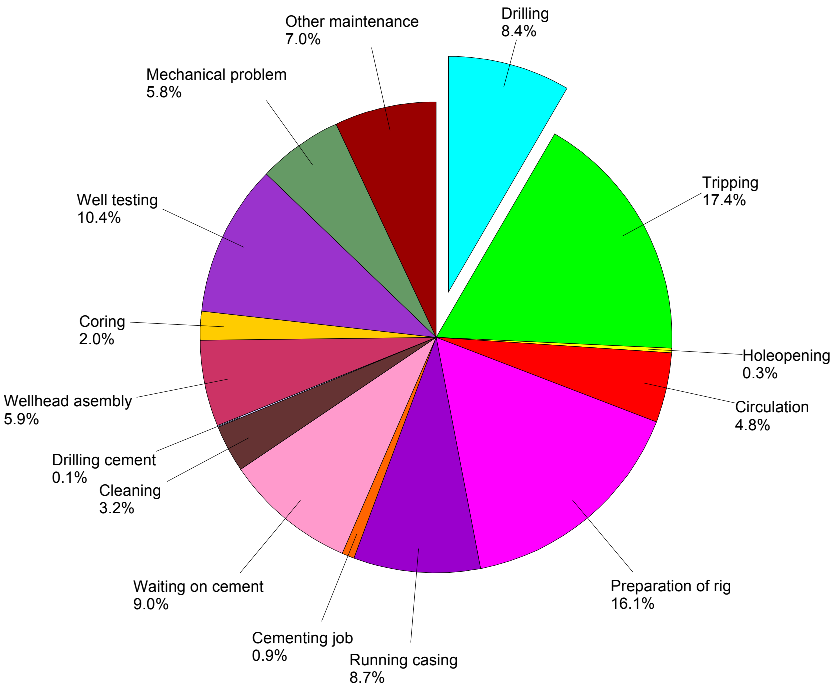

FIGURE 22: Time analysis chart for drilling of well TD-5

Basically, consolidation grouting of a well is necessary for two reasons: to keep the rig and accessories stable while in operation and also to divert uncontrolled flows of emitting fluids away from the cellar area and mud tank. Grouting can be ignored depending on the condition of the drilling site which, so far in drilling at Tendaho, has proven a soft unconsolidated formation in the first 30 m. It is evident that grouting was necessary for the shallow completion wells such as TD-5 and others. Because the maximum depth of these shallow wells is 520 m, at this time hot gases come out around the cellar floor, forming wide cracks due to the hot pool created. This makes the working area difficult. Chemical corrosion and silica deposits shorten the service life of side and master valves. Because of this, consolidation grouting in the last three shallow wells must be done before big damage is done to the wells.

4. CONCLUSIONS

Pre-drilling of wells in Iceland for the surface casing before moving in the big rig has several advantages. The large drilling rig and equipment used in Iceland and Ethiopia are quite similar and both rigs have a rotary table and their own cementing unit. The vertical well TD-5 in Ethiopia was targeted to produce from a shallow well and was drilled to 560 m. But well KJ-32 in Iceland was drilled directionally to a depth of 1875 m. Cementing equipment and placement technique (inner string) is similar, but in Ethiopia the geothermal cement material is imported. In Iceland the mixing with additives is done on-site and uses local Portland cement. Calliper logs are used to plan the cementing operation and CBL logs to evaluate the quality. These tools are not available in Ethiopia. If returns are not obtained, the casing is sometimes perforated with an explosion to fill up the annulus. CBL logs and temperature logs are used to determine the top of cement (TOC). The technique is not in use in Ethiopia. Coring two times was almost equal to the actual drilling time, and the time and extra cost were very high. In Iceland, cuttings are collected at 2 m intervals depth and analyzed with microscope. Sometimes they use coring in new drilling areas. The time required for rig transport and rigging up takes much longer in Ethiopia than Iceland where it only takes 5 days from rig-down to rig-up.

The staffing of the rig crew is 13 persons in Ethiopia and working hours 8 (3 shifts) vs 6 persons and 12 hours with 2 shifts in Iceland. Directional drilling and measurement well drilling (MWD) is used to full depth in Iceland resulting in high penetration rates. The wells require tools and specialist directional drilling experts. Fishing operations were required in Iceland. Fishing equipment was on site but was not required in Ethiopia. In both countries mud is used for drilling of the casing part of the well, but only water used for the production part. Completion tests with step injection and fall-off are similar in both countries.

ACKNOWLEDGEMENTS

I would like to thank everyone who in one way or another, helped me during the course of training and preparation of this paper. I would like to express my gratitude to the United Nation University UNU for the sponsorship to come to Iceland, and to the Geothermal Training Programme director, Dr. Ingvar B. Fridleifsson, and to Mr. Lúdvík S. Georgsson, the deputy director. I thank Mrs. Gudrún Bjarnadóttir for her help and kindness. I wish to especially thank my supervisor, Mr. Sverrir Thórhallsson, for sharing his excellent technical experience without hesitation. Also I thank Mr. Ísleifur Jónsson for the special lectures. I want to thank Mr. Ásgrímur Gudmundsson, the Orkustofnun reservoir geologist, for his discussion about geology and I am grateful to the Orkustofnun engineering and scientific staff members.

I want to express my gratitude to the Ethiopian Institute of Geological Survey for giving me the opportunity to receive this training. I wish to give my thanks to the Icelandic government and Jardboranir drilling company for demonstration of drilling techniques, and to Mr. Haraldur Sigurdsson and Mr. Dagbjartur Sigursteinsson, drilling supervisors, and all the drilling crew. And thanks to the Krafla power station staff members for good co-operation during my stay at Krafla. Finally, I am grateful to the other UNU-fellows for our time together. I dedicate this report to my dearest wife, Aynalem Eshete, and my two children for their infinite kindness.

ABBREVIATIONS

ANSI: American National Standards Institute
BOP: Blow-out preventer
CBL: Cementing bond log
CSG: Casing
DDHB: Drilling Data Handbook (Gabolde and Nguyen, 1999)
FH: Full hole
IF: Internal flash
LCM: Loss circulating material
MWD: Measurement while drilling
NB: Near bit
RPM: Rounds per minute
SPM: Strokes per minute
TD: Total depth
VAM: Type of casing thread
API: American Petroleum Institute
BPD: Boiling point depth curve
DC: Drill collar
DP: Drill pipe
HW: Heavy weight drill pipe
KOP: Kick of point
LPM: Liter per minute
NA: Not available
OH: Open hole
RR#: Bit run #
Stab: Stabilizer
TVD: True vertical depth
WKM: Brand name of Cameron
WOC: Waiting on cement

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