DRILLING OF WELL NJ-17 IN THE NESJAVELLIR HIGH TEMPERATURE GEOTHERMAL FIELD (SW-ICELAND).

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ABSTRACT

This report describes the drilling activities observed by the author while on seven weeks practical training attachment to Rig Jötunn in the Nesjavellir high temperature geothermal field. The description covers the procedures used in drilling the different hole diameters, bit cost analysis, casing and cementing operations, and some aspects of rig selection.

For the casing programme, two methods for determining the minimum casing depth in a geothermal well have been illustrated quantitatively with reference to well NJ-17. An analysis of rig time distribution has been carried out on well NJ-17 and compared with the time taken to drill an average well in Nesjavellir to check the efficiency of the drilling programme.

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1. INTRODUCTION

1.1. Scope of work

This report is a product of a six months fellowship awarded to the author by the United Nations University to study "Geothermal drilling technology" through the UNU Geothermal training programme, at the National Energy Authority (NEA) of Iceland.

The training commenced with 5 weeks of introductory lectures on various disciplines in geothermal science and engineering. The lectures covered borehole geology, geochemistry, geophysics, well discharge measurements, reservoir engineering, surface geology, wellhead equipment, casing design, cementing and geothermal energy utilization. The main objective was to give the trainees a broad view on how the various disciplines are integrated to locate a geothermal reservoir, tap and utilize the earth's buried energy.

To commence a specialised study in drilling technology after the introductory lectures, the author was attached to Rig Jötunn for 7 weeks to acquire practical training in the Nesjavellir high temperature field. Besides acquiring the field experience, the author covered 2 weeks attending lectures on casing design and wellhead equipment selection from professor Thorbjörn Karlsson from the University of Iceland. The last two months were spent in the UNU premises learning how to use the IBM personal computers, literature survey and preparation of this report.

1.2. Geothermal well drilling

Geothermal well drilling is the process of sinking a hole either vertically or directionally into the earth to tap the energy stored in a steam or hot water reservoir. The drilling technology used has been borrowed from the oil industry to a great extent. Rotary drill rigs are used for deep hole drilling while cable tool rigs are occasionally used for shallow depths (surface hole).

Proper planning is a major factor to successful drilling of a well. A competent well plan should include decisions on the casing, bit, drilling fluid programmes, water supply, site preparation and suitability of the drilling equipment. Inadequate planning may result in downtime, delays, inefficiency and uncontrollable blow-outs. A geothermal well may cost anywhere between 1-2 million dollars depending on the total depth and in particular on the number of days taken to complete the job.

In this report the most critical parameters that heavily affect the drilling progress such as casing, bit, drilling fluid programmes and blow-out prevention system have been discussed in reference to well NJ-17 in the Nesjavellir high temperature geothermal field.

2. DRILLING OF WELL NJ-17 IN NESJAVELLIR

The Nesjavellir high temperature field is situated in the northern sector of the Hengill central volcano, within the volcanic rift zone of SW-Iceland. The uppermost 600 m of the geological strata is composed of several basaltic and hyaloclastite formations, while the basaltic lava series, with sparser interbedded hyaloclastite formations, characterize the lower part of the reservoir (Franzson et al, 1986).

2.1. Drilling programme

The drilling programme for well NJ-17 consisted of the following elements:

a) Site preparation:

The drill site should be levelled with gravel and compacted.

b) Pre-drilling of surface hole:

The cable tool rig to be used to drill the surface casing hole with a 22" hammer bit to 62 m. The surface casing should then be set and cemented.

c) Rotary drilling:

The surface casing must be pressure tested with water at 15 bars. The intermediate hole has to be drilled with a 17-1/2" diameter tri-cone insert bit and cased to a depth between 200-300 m (see Figure 1). The production casing hole to be drilled using the 12-1/4" tri-cone insert bit and cased to a depth between 600-800 m. The slotted liner section of the well has to be drilled with 8-1/2" diameter tri-cone insert bit to a depth of 2000 m. While drilling this (8-1/2") phase three cores should be taken at different locations. The completion tests should then be carried out.

d) Cementing:

Portland cement to be blended with the following additives; 30 % silica flour, 2 % API bentonite and 2 % perlite (percentages by weight of dry cement). The cement bond logs should be run for any unsatisfactory job and the casing to be perforated where necessary and cement squeezed into any empty spaces noticed.

e) Casing and liner specifications:
Surface casing; 18-5/8" o.d., 87.50 lbs/ft, Grade K-55 with no couplings but to be welded.
Intermediate casing; 13-3/8" o.d., 68 lbs/ft, range 3, Grade K-55 with buttress thread couplings.
Production casing; 9-5/8" o.d., 47 lbs/ft, range 3, Grade K-55 with buttress thread couplings.
Slotted liners; 7" o.d., 23 lbs/ft, range 3, Grade K-55 with buttress thread couplings (API specification 5A).
f) Drilling fluid:
The drilling fluid to be used is mainly water.
g) Drill string:
The drill string to be made up using 5" o.d. drill pipes, 19.50 lbs/ft, IEU grade E and 7-1/4" o.d., 119 lbs/ft drill collars.

2.2. Pre-drilling

It is customary in Iceland either before or after site preparation to drill for the surface casing with a cable tool rig. In well NJ-17 the first 65 m were drilled using this type of rig and the time spent (212 hours) in this phase is shown in Table 1 and Figure 3. In the cable tool drilling a heavy hammer bit 22" outside diameter was used to crush the rock through a pounding action. The rock fragments were being mixed with water and bailed out.

It is not possible to exert optimum weight on bit while using the rotary rig within the first 60 m or so in the surface hole. The cable tool rig saves expensive rotary drilling time and requires only two men to operate. Among the limitations of this drilling method are the slow penetration rate and lack of blowout prevention equipment.

2.3. Drilling of the 17-1/2" diameter hole

After drilling the 22" diameter hole with the cable tool rig and cementing the surface casing, the largest rotary drill rig in Iceland (Rig Jötunn) was moved in and erected in preparation for deep hole drilling. This rig is capable of drilling slightly over 3600 m depending on the drill string design, see calculations in section 4.1.

Drilling of the 17-1/2" hole was commenced on the 12-06-1986 from a depth of 65 m. Pressure testing of the surface casing was performed as specified in the drilling programme but no leakage was observed. The average penetration was 3 m/h and it took about 66 hours (rotating time) to drill down to 271 m. The weight on bit was being adjusted between 12000 - 20000 lbs. The pumprate of the drilling fluid used (water) was maintained at about 30 l/s. This pumprate results in an annular return velocity of 0.5 m/s.

The circulation loss measurements were being taken after every 4 hours from the mud tanks. Drill cuttings were collected after every two metres drilled. The cuttings were being collected and analysed on site for alteration minerals so as to give an indication of what kind of formation was being drilled through and to understand the geological structure of the Nesjavellir geothermal reservoir. The whole span down to 271 m indicated presence of hyaloclastites (cemented volcanic tuffs) formed sub-glacially. From 65 m to 190 m the average circulation loss was 2 l/s but between 190 and 220 m it increased to 10 l/s. Between 220 and 271 m, the average circulation loss decreased to about 4 l/s.

The drilling programme had specified that the intermediate casing be set between 200 and 300 m. After confirming from the cuttings that the sorrounding rock was strong enough to support the casing,and the minimum surface casing depth (calculations in section 4.2) had been attained, drilling was stopped at 15.05 hrs on 15-06-1986 at a depth of 271 m. The drill string was lifted 20 m off the hole bottom to facilitate cleaning out the cuttings. The rotary speed was reduced from 65 rpm to 28 rpm but the pumprate was maintained at 30 l/s. Cleaning with plain water was unsuccessful in lifting out some 19 m of cuttings and this was overcome by mixing the water with 3950 kg of API bentonite.

2.3.1. Cementing of the intermediate casing

Before running in the casing string, caliper and temperature logs were taken to check the hole diameter and temperature respectively. A hole with large cavities indicates some possibility of an unsuccessful cementing job or usage of too much cement while high temperatures calls for adequate hole cooling prior to cementing to prevent occurrence of blowouts during the cementing.

The casing tally measurements and inspection were carried out and the casing string sunk without any problems. It took 6 hours to run in 22 lengths of the 13-3/8" outside diameter casing. The centralizers were placed two at the bottom and one after every three joints.

Portland cement was blended as specified in the drilling programme and the actual quantity used was 50,000 kg. The calculations of the theoretical volumes required is given in section 4.3.

Pumping time of the cement slurry is dependent on the pumprate, slurry density and the slurry volume to be used. It took about 47 minutes to complete the job using the stab-in cementing method (see Figure 11). The average pumprate was 900 litres of slurry per minute. Proper planning of the cementing job prior to commencing is very vital in order to pump in the slurry before it sets.

Slurry density was being controlled by ensuring proper cement to water mixing ratio. The specific gravity and slurry pump discharge pressure values were being recorded during the cementing operation to assist in controlling the mixing ratio (see Table 2a).

As cement returns to the surface were achieved, no cement bond log was taken but after 10 hours the cement level had dropped by 65 m. This was refilled from the top of the annulus by 6,000 kg of cement and this is a clear indication that excess bulk cement should also be stored on site for such losses.

Water availability is another important aspect in cementing operations. Besides being used for slurry mixing, water has to be used for displacing the cement from the drill pipes and cleaning up the cementing equipment immediately after job completion. The rig Jötunn has tanks with a water storage capacity of 76,000 litres which was in excess of what was required.

2.4. Drilling of the 12-1/4" diameter hole

This commenced by drilling out the bakelite material from the float collar, the float shoe and the cement between them. This was done with care to avoid damaging the casing joints due to vibration and too much tensile loading from the drill string. On reaching the hole bottom at 273 m, fresh formation drilling was commenced still with water as the drilling fluid.

At a depth of 585 m, a deviation measurement was taken using a drift indicator. This instrument records the angle on a disc made from a specially chemically treated paper with eight preprinted concentric circles. Each circle from the centre of the disc, represents one degree of inclination of the actual hole to the true vertical hole. There exists a plumb bob vertically above the disc that produces a circular dot on the treated paper when the instrument is at rest depending on the inclination. The deviation was found to be only 0.2° at this depth corresponding to 1.70 m off the true vertical position. This was found to be a negligible deviation and therefore no modifications were made to the drill string to counter balance the deviation.

The drilling was being carried out using a tungsten carbide insert bit IADC code 6-2-7 type FP-62 from the Reed Company. This had journal bearings and gauge protection and is suitable for drilling medium hard formations with high compressive strength. The weight on bit was being maintained between 30-50 % (13000-22000 lbs) of the drill collar weight. The rotary speed was being maintained between 65-75 rpm and the consequent average penetration rate was about 6 m/h. The maximum weight on bit allowable is 2/3 of the drill collar weight (Chuji, 1979). This is not always applicable because other factors affect the weight and rotary speed to be used. It is usually a matter of monitoring the behaviour of the bit downhole in relation to the formation characteristics (hardness, softness, cavities, drilling fluid lifting capacity) in order to reach a compromise on how to obtain an optimum penetration rate.

The drilling programme had specified that the production casing be set between 600-800 m, but it was necessary to ensure that all cold aquifers were drilled through and cased off. The aquifer temperatures at depth were being investigated through microscopic analysis of cuttings for alteration minerals. Chlorites (existing at temperatures 145°C and above) were first identified at about 680 m. The concentration of the chlorites increased with depth and epidote (existing at 255°C and above) was observed at about 750 m. At 773 m, a decision was reached to run in the production casing since a high temperature aquifer over 200°C was by then evident. Also it was undesirable for the production casing to be very deep due to cementing problems.

Prior to running the casing, the well was cleaned of the cuttings using 4,000 kg of API bentonite down to 772 m. Before tripping out, a temperature measurement was taken through the drill string. After tripping out, a caliper log was taken to check the hole diameter but there was very little hole enlargement which promised of a successful cementing job for the production casing. Other measurements taken were a) Gamma-Gamma, for rock bulk density determination, b) Neutron-Neutron, for rock

porosity determination, c) resistivity log and d) a second temperature log.
It is worth mentioning that the logging instruments used have a downhole temperature limitation due to the electronics and insulation material used in their construction (about 100 - 150°C), (Steingrimsson B. et al, 1981).

2.4.1. Cementing of the production casing

The casing specifications were as indicated in the drilling programme. The casing was run carefully using all the precautions necessary as formerly done for the intermediate casing and no mishaps were encountered. The centralizers were placed two at the bottom and one after every three joints.

The Portland cement was blended with additives as previously done for the surface casing and the theoretical cement slurry requirements were as shown in section 4.3. The actual amount of cement used was 49,900 kg at an average specific gravity of 1.68. The stab-in cementing method was used.

After waiting on cement (w.o.c) for 6.5 hours the level drop was found to be 6.6 m in the annulus. This uncemented portion was not refilled from the top of the annulus but it was regarded to be negligible compared to the properly cemented production casing depth. It is the authors feeling that it was vital to cement this portion even with an ordinary cement-sand mixture to prevent casing corrosion. The whole cementing job took 47 minutes to achieve the returns at the surface, and the specific gravity variation of the slurry taken during the cementing is shown in Table 2b.

2.5. Drilling of the 8-1/2" diameter hole

This was commenced on the 28-6-1986 from 773 m after drilling out the cement. The bit used was a J-44, IADC code 6-2-7 8-1/2" in diameter from Hughes Tool Company. The rotary speed was 70 rpm and weight on bit was always between 30-50 %

(13000-22000 lbs) of the total drill collar weight (44,602 lbs) while the resulting average penetration rate was 4 m/h.

At 876 m depth normal drilling was stopped at 13.00 hours on the 2-7-1986 to commence coring preparations. This was the first core to be taken in this well down to 880 m. After taking the core, normal drilling was continued again to 1003 m from where a second core 7 m long was taken. Three cores had been specified in the drilling programme and the last one was taken between 1447-1454 m. From 12-7-1986 no further drilling was pursued upto the 11-8-1986 since the drilling crew went for its annual summer vacation.

During this vacation period, the well had stopped being cooled and was bound to undergo some thermal recovery. When the crew resumed duties, a decision was made not to commence drilling using the ordinary tri-cone bit, but to use a new type of drill bit for the first time in Iceland, the Razorback 3. The reason for this decision was to avoid damaging the elastomer seals of ordinary tri-cone bits due to elevated temperatures.

The Razorback 3 was a Reed Company manufactured bit with diamond inserts fitted in a tungsten carbide matrix and has no bearings. Drilling commenced from 1454 m with 13,000 lbs weight on bit, 105 rpm and the resulting penetration rate was about 3 m/h after which it decreased to 1.3 m/h. Since this was an uneconomical penetration rate, it was tripped out at 1674 m and a tungsten carbide insert bit IADC code 6-2-7 run in, which continued the drilling to the total depth of 2100 m. However, from 1650 m, blind drilling started when a total circulation loss of 35 l/s occurred down to the maximum depth of the well. This was rather risky because the drill cuttings can easily cause the drill string to get stuck.

After striking the targeted depth of 2100 m on 21-8-86 at 18.30 hours, hole deviation measurements were taken. They revealed drifts of 0.5° at 1000 m, 4° at 1500 m, and 7° at 2000 m. These drifts when expressed as distances from the true vertical hole position are 6, 27 and 75 m respectively (calculated using the minimum curvature method). A close look at these values clearly shows that the kick-off was caused by the use of the special Razorback 3 bit at 1454 m and the normal tri-cone bit followed the same profile. If a drift measurement had been taken while changing over from the Razorback-3 to the tri-cone at 1674 m, the drift could have been noticed and the string adjusted by fitting stabilizers where necessary.

Completion tests (injection, fall-off, logging) were carried out to assess the well transmissivity.

2.5.1. Slotted liners

A study of high temperature geothermal utilization in various areas of the world, such as Iceland, Italy and New Zealand, reveals that drilled wells are generally of the same diameter; 13-3/8" intermediate casing, 9-5/8" production casing, and 8-1/2" open hole or with 7" slotted liners, (Karlsson T. 1982).

The function of the liner string is to prevent collapse of the hole within the uncased production zone but to allow inflow of steam from the reservoir into the wellbore through the slots. The string is usually hung from the production casing using a Liner Hanger with an overlap of two blind lengths. Hanging the liner is preferred as setting (see Figure 2) it on the bottom could result in buckling, particularly in the elevated temperatures in the geothermal reservoir.

In well NJ-17, the liner used had the following specifications; 7" outside diameter, 23 lbs/ft, Steel grade K-55, Buttress threads couplings and Range 3. The slotting had been done (15 slots per metre) using oxy-acetylene flame with dimensions as 100 mm long by 20 mm wide. The slots can also be machine cut in which case the stress concentration factor is lower than in the flame method and therefore reduces chances for stress corrosion, (Teshome, A. 1983).

During the running operation, the string could not go down past 1968 m. This was thought to have been caused by the kick-off at 1500 m or due to the cuttings from the blind drilling that could have fallen back into the well. The liner string was therefore hung at a depth of 1965 m with an overlap of 90 m and expansion clearance of 3 m from the bottom of the well.

2.5.2. Blow-out prevention

A blowout is an uncontrolled flow of fluids from a well. In geothermal wells, blowouts can cause losses of life, lost well and serious damage to the drill rig. They are caused by unbalanced pressure between the wellbore and the formation. When the wellbore pressure is lower than the formation pressure, the geofluids flow into the bore towards the surface and may escape from the well at a high uncontrollable pressure.

The blowouts can be controlled by installation of properly rated blowout preventers (BOP), good casing design and use of the appropriate drilling fluid. There should be no attempts to pursue drilling in the absence of blowout preventers or with a faulty blowout prevention system.

During the drilling of well NJ-17, the BOP system installed on the different casings was the following (numbered from the Casing head flange-CHF):

a) Surface casing (18-5/8" (o.d.)

1) Master gate valve, ANSI series 300.
2) An Annular BOP ANSI series 600, size 21-1/4"(i.d.). The Annular BOP is capable of closing on any shape of object that passes through it.

b) Intermediate casing (13-3/8" o.d.)

To drill for the production casing, the following equipment was installed on the intermediate casing.

1) Master gate valve ANSI series 900, size 12" (i.d.).
2) Blind ram BOP (manufactured by Cameron) for closing the open hole.
3) Pipe rams BOP (manufactured by Cameron), opening size 12" diameter. This was fitted with two rubber rams with a 5" semi circular opening to close around the 5" diameter drill pipes used in the drill string.
4) An Annular BOP ANSI series 900 and 12" diameter.
5) The rotating head BOP was always in place to divert any blowing geofluid away from the drilling crew working on the deck. The Accumulator system for rig Jotunn has a hydraulic fluid storage capacity of 160 gallons(US) at 2000 psi operation (charge) pressure.

2.6. Coring

Coring in a geothermal well is done to collect samples of the reservoir rock for geological, geochemical and geophysical analysis in order to understand the reservoir rock at known depths. This has not been a common practice in Iceland but instead intensive analysis has been carried out on cuttings from the wells. This year three cores were taken from well NJ-17 in the Nesjavellir high temperature field. In this report, the coring procedure and requirements have been given in reference to the first core from 876-880 m.

Generally core barrels either regular or wireline with diamond bits are used. In most cases, cores are taken with a diameter of 2-1/8" or 4-3/8" in an 8-1/2" diameter hole. The diamond bit cost is high since many diamonds are required in a hole of that diameter (about 300-400 carats), (Thorhallsson S., 1986).
During the coring operation, the factors that influence the quality of the core are weight on bit, rotary speed and fluid circulation. The best combination can be obtained while the operation is in progress by plotting in situ the core length

against coring time for small increases of weight on bit. This gives a clear indication about the weight on bit at that particular coring rotary speed to yield a good penetration rate and a good core. The core bit manufacturer usually specifies the weight on bit required, rpm and also the suitable fluid circulation rate but this may not always be the best combination due to variations in formation characteristics.

Below is a set of instructions that were being followed prior to the coring operations to clean the well.

a) withdraw the 8-1/2" diameter bit from the hole and run in a junk basket (fishing tool) to retrieve out any metallic debris from the hole bottom,
b) without exerting any weight on the bit, set the drill string rotation at 30 rpm and a pumprate of 10 l/s (water) for 5 minutes,
c) increase the pumprate to 15 l/s for 15 minutes at the same rotary speed,
d) trip out.

Core barrel

The procedure for running the core barrel and bit into the hole were also as follows;
a) while at 3 m above the hole bottom, circulate for 3 minutes 11 lb/gal API bentonite mud (low viscosity) at the rate of 15 l/s, b) approach the bottom slowly until the bit is at about 50 cm off the bottom and maintain a pumprate of 15 l/s for 10 minutes,
c) lower the core bit and drill the first 15 cm at 15 l/s , 30 rpm and 2,000 lbs on bit,
d) increase the rotary speed to 52 rpm and weight on bit gradually by 1,000 lbs intervals up to 13,000 lbs (or to a value of optimum penetration rate) but maintain the mud circulation at 15 l/s. The coring is estimated to take 5 hours.

The instructions were closely followed but the maximum weight on bit reached was 10,000 lbs. This was not increased further because an adequate penetration rate was obtained at 10,000 lbs for that rotary speed within that particular formation. The parameters that were being closely observed during coring were weight on bit, pumprate, standpipe pressure, rotary speed, viscosity and temperature of the mud.

The standpipe pressure is very important because it gives an indication of the bit-core behaviour downhole. After taking a core 419 cm long, the standpipe pressure suddenly rose to 600 psi indicating core blockage and the job was stopped. After tripping out, 70 % of the core was recovered while the rest had been washed away by the circulating mud.

The rotation of the core bit on the bottom was only for 190 minutes but the total time taken from when normal drilling was stopped in preparation for the coring to when it was commenced again was about 20 hours. In those 20 hours, only 4 m were drilled at the expense of 80 m in normal drilling at the common penetration rate for Rig Jötunn of 4 m/h. Coring therefore takes alot of rig time, high bit costs and therefore requires diligent planning and preparation before commencing the job. The cost of the coring operation in dollars per metre can be seen in Table 3.

This first core was taken using a tungsten carbide bit though the initial plan was to use a diamond core bit. The substitution was undertaken because the bolts that hold the rubber on the rotating head had broken and fallen into the hole prior to the coring preparations. The junk basket lowered only managed to retrieve a few milled pieces and since it was unknown whether the well was clean it was a risk to run in the expensive diamond bit. The coring data and time versus core length graph are shown in Table 4 and Figure 4 respectively.

2.7. Inspection of drill collars

Its a common practice in Iceland to inspect drill collars, crossover subs and stabilizer joints (box and pin ends) for fatigue cracks. This is done to avoid "fishing" (the driller's evil) of broken collars from the wells.

After completion of well NJ-17, all of the drill collars (12) used in the drill string, 2 crossover subs and 3 stabilizers were inspected using an Ultra Sonic Flaw detector type Krautkrammer UMS2. The inspection was done by first calibrating the instrument for pulse penetration using a measured length of 125 mm. A penetration range of 250 mm was then selected from the instrument. The joints faces were then cleaned and all sharp edges or high spots filed out. An electronic sensor from the instrument was then brought into contact with each face of the joints and moved along the periphery with an oil film between the sensor and the face. The oil film was to ensure efficient transmission of the sound pulses into the steel. The waveform resulting from the echo of the pulses, was being observed on an Oscilloscope screen. Cracks were identified through careful observation of the waveform discontinuities. Four drill collars and one cross-over sub with internal cracks were identified. The crossover sub had a crack 125 mm from the box end while the drill collars had cracks 110, 112, 115 mm from the box end and 100 mm from the pin end respectively. These defective parts were taken to a local machine shop for re-cutting.

3. OPTIMIZATION OF DRILLING OPERATIONS

3.1. Bit programme

The drill bit programme in well NJ-17 comprised of 3 tri-cone insert bits from the surface casing shoe. Their diameters are 17-1/2", 12-1/4" and 8-1/2" for the intermediate, production casings and production liners respectively.

3.1.1. Classification

According to the International Association of Drilling Contractors Code (IADC), drill bits are classified as milled tooth bits or insert bits. In setting up the classification system, the IADC selected a three numerical system which classifies bits as 1-for milled tooth or insert, 2-for formation hardness, 3-designation to describe certain mechanical features such as gauge protection. A designation of 5-1-7, would for example be an insert bit (5) to drill soft formations (1) and has journal bearings and gauge inserts (7).

The size selection of drill bits is based on the casing programme and the desired cement wall thickness. There are different ways in which the bits can be used to make the hole, namely:
a) drilling with a full size bit,
b) piloting the hole with an undersize bit and opening later with the full size bit,
c) simultaneous piloting and opening.

Each of these ways has its own merits and demerits and the choice of any of the methods may depend on the field experiences and economic considerations. At Nesjavellir, full size bits were used to drill all the phases in well NJ-17.

3.1.2. Penetration rate

During drilling the penetration rate is heavily dependent on the following factors, a) type of drill bit, b) weight on bit, c) rotary speed and d) pumprate of the drilling fluid (see Figure 5).

It is possible to determine the optimum combination of weight and rotation speed of the bit in the field by performing a "Drill off test" as described below:

a) select a practical rotary speed,

b) place maximum practical weight on bit (consider bit specifications and drill collar weight),

c) lock the brake,

d) record the time required to drill off weight in 2000 lbs increments. If the penetration rate makes this increment impractical, use 4000 or 5000 lbs increment. The shortest time increment will indicate the optimum weight on bit for that rotary speed.

It is important to realise that the optimum condition obtained should be considered against other factors like rate of cuttings removal before it is adopted to avoid fishing problems.

3.1.3. Bit record, selection and cost analysis

Bit record keeping including a good dull bit evaluation is very essential for optimizing drill bit selection.

Bit selection should be based on past bit records, known geological information, well logs from past wells. The best way to assess drilling is to calculate costs in dollars per metre from bit records. This can be achieved through the relationship below:

$$\text{cost/m} = \frac{(HRC)(DT + TT) + (n)(BT)}{MD}$$

where HRC = hourly rig cost

DT = drilling time, hrs

TT = trip time, hrs

BT = drill bit cost, $

MD = metres drilled by that bit

n = percentage of bit usage (from dull bit evaluation).

This type of cost analysis was performed for all the bits used in well NJ-17 and the results are shown in table 3.

3.2. Rig time breakdown

The time taken to complete a geothermal well is influenced by such factors as formation hardness, ease of access to the site, the power and efficiency of the rig, bit type, quantities of casing required, well diameters, cores to be taken and the depth to the productive aquifer. All the above factors can be optimized for fast drilling by proper planning and equipment selection.

As time is one of the most influential factors in determining drilling costs, the use of expensive but efficient tools e.g Tungsten carbide insert bits, may often prove to be worthwhile. In well NJ-17, expensive insert bits were used and it took 47 days to complete the 2100 m deep well. This period includes rig transportation and erection to well completion. The planned and actual drilling progress was as shown in Figure 6. Table 6 shows rig time breakdown for some wells drilled with rig Jötunn in the Nesjavellir field. It is evident that well NJ-17 was completed on schedule and this can be attributed to proper planning, suitable bits and of course limited drilling problems.

Figure 15 shows a comparison of rig time distribution between well NJ-17 (2100 m) and an average well 1800 m deep in Nesjavellir. An average well in Nesjavellir geothermal field takes about 872 hours from rig transportation to well completion while well NJ-17 took 1128 hours to complete. This well took more time than average due to coring, extra trips due to Razorback 3 bit change, more time for transportation and erection and of course it is deeper. However, overall comparison of this well with the average one in the same field shows that the drilling progress was good.

4. SOME DRILLING CALCULATIONS

4.1. Rig selection

The depth a rig is capable of attaining is of major concern to the well designer when deciding on a drilling programme. The question of a rig's depth limit requires a great deal of calculations and discussion, and it is only after all the rig components have been carefully selected that a satisfactory answer can be obtained.

The factors briefly mentioned below are important when selecting the rig and most manufacturers offer optional components to match the drilling requirements.

a) Exact mast rating

The exact rating of the mast should always be determined because the gross load, gross nominal rating or just mast rating do not give the necessary information. What is most important is the hookload ratings based on corresponding string up of the travelling block. Any attempts to modify the crown block to carry extra lines can ruin it. This can also damage the mast by creating load imbalance to the mast legs. The gross load rating represents the maximum load exerted onto the mast through the crown block.

b) Drawworks

The clutch is the main factor in determining the maximum single line pull of the drawworks. The brakes are usually matched to the single line pull. The load and speed of pulling determine the horsepower expended.

Stringing up more lines to the travelling block (depending on the number of sheaves designed) will increase its hoisting capacity but at a reduced hoisting speed. To avoid overloading the drawworks, shock loading must be avoided at all times.

c) Rig pumps

Correct rig pumps selection can be achieved only when the full drilling requirements like the hole diameters, depths, diameter of pipes and all related equipment are known.

The return velocities required for the drilling fluids to be used are a necessary consideration in this selection. A minimum return velocity in the annulus should be 0.25 m/s. The selected return velocity in combination with the area of the annulus will help in calculating the drilling fluid volume in litres per second. In general, for a high volume and low pressure pump, the duplex double acting piston pumps can be suitable for drilling a large diameter well. On the other hand, a low volume high pressure triplex pump may used when drilling small diameter deep wells with small drill pipes.

In both cases different liner and pistons are available to accommodate the best hydraulics suitable for the well to be drilled. Its also worth mentioning that the selection should include the consideration of adequate power to drive the pump - an electric motor or a diesel engine.

d) Air compressors

Selecting an air compressor is just as critical as selecting a rig pump. This is of major concern in drilling programmes where air and foam are to be used as drilling fluids. A minimum return air velocity of 15.0 m/s is needed for proper hole cleaning while a return air velocity of 25.0 m/s is considered good and will prevent the bit from crushing the same cuttings over and over again, (John L'Espoir 1984).

The proper compressor can be chosen only when the type of formation and the hole size are known.

e) Auxiliary equipment

Besides the above mentioned components, there exists other backup equipment such as standby pumps, compressors and also rig electric power generating sets. In addition, a rig must be equipped with instruments so that the driller can observe the hook load, weight on bit, standpipe pressure, controls air pressure, rpm, torque and strokes per minute of the pumps.

4.1.1. Depth limit for Rig Jötunn (Iceland)

As an example of depth limit calculation, the rig Jötunn has been used. The depth limit calculation will require specifications as given in appendix A.
The load distribution is as given in Figure 7.

Calculation

Rotary drilling line:

Working load for a single line including the API safety factor

$$= \frac{\text{API breaking strength}}{\text{safety factor}}$$

$$= \frac{156{,}400}{3.18}$$

$$= \underline{49{,}182 \text{ lbs}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

From the nominal capacity of the mast, the load per single line can be obtained as;

$$= \frac{\text{Nominal mast capacity, lbs}}{\text{no. of lines on crown block}}$$

$$= \frac{491{,}000 \text{ lbs}}{10}$$

$$= \underline{49{,}100 \text{ lbs}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Comparing values (1) and (2) shows the drilling line is within the safe working condition since (2) is within the safety factor range (values are almost equal).

Travelling block:

No. of lines through the travelling block = 8
Thus load carried by the 8 lines = 49,100 * 8 lbs

$$= \underline{393{,}000 \text{ lbs.}} \;\; ....(3)$$

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 mud filled hole (variable depending on the drilling fluid being used). This is equivalent to a safety factor of 1/0.75 (1.33). Therefore using this safety factor the usable hook-load will be;

$$= \frac{392{,}800 \text{ lbs}}{1.33}$$

$$= \underline{295{,}339 \text{ lbs.}} \;\; ....(4)$$

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

When drilling well NJ-17, 12 drill collars each 7-1/4" diameter weighing 119.9 lbs/ft and 31 ft long and 19.5 lbs/ft drill pipes were used. The weight of the hexagonal kelly (6" o.d.) and travelling block are 2414 and 9,000 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 weights. This sum becomes equal to 56,016 lbs. Subtraction of this dry weight from (4) gives a balance for the drill pipes, stabilizers, bit and so on. So the rig could have supported a drill pipe length given by;

$$\text{pipe length} = \frac{(295{,}338 - 56{,}016) \text{ lbs}}{(19.5 \text{ lbs/ft})(3.28)}$$

$$= \underline{3740 \text{ m.}} \;\; ....(5)$$

The total length of drill collars is 112 m and therefore adding this value to the drill pipe length gives the total well depth as 3852 m. As mentioned above the depth limit a rig is capable of attaining requires reasonable discussions before approving a drilling programme and purchasing of a rig.

4.2. Casing programme and wellhead equipment selection

In geothermal wells, commonly two or three concentric casing strings are run and cemented in the well before the target geothermal reservoir is reached. The principal functions of casing are to;

a) seal off cold unwanted aquifers and therefore prevent fluid migration,
b) prevent hole collapse,
c) provide anchor for the wellhead and blowout prevention equipment,
d) provide a good outlet conduit for the geofluid.

A casing programme is heavily dependent on formation lithology, aquifer depths and economic factors. Its very necessary for the casing to maintain the strength requirements during drilling, running, cementing operations and of course during the service life of the well within the elevated temperature environment.

4.2.1. Casing design

The casing for a geothermal well normally represents 20-30 % of the well cost. Thus casing is a major well cost. The design of the casing strings is therefore a critical element for the economics of a geothermal project (Nicholson, R. Robert, 1985).

Casings currently being used in the geothermal industry are mainly designed for the oil wells to withstand;

a) Tension, from longitudinal loading,
b) collapse, from unbalanced external pressures,
c) burst, due to unbalanced internal pressures.

The API specifications furnish no minimum strength requirements at elevated temperatures, but tensile strength in cold conditions are given in Table 5.

However tests have been carried out at elevated temperatures on various API casing from different manufacturers and the results are as shown in Figure 8. The relative changes in yield strength are shown in the shaded area. The relative change in tensile strength turns out to be fairly consistent for all grades of casing as seen from the figure. Its therefore safe to assume from this that the tensile strength of the casing is unchanged upto a temperature of about 350°C, (Karlsson T., 1978).
The API casings are designed according to the formulas available in the standard API document entitled "Bulletin on formulas and calculations for casing, tubing, drill pipe and line properties".

4.2.2. Minimum casing depth

The minimum casing depth is determined by the pressure to be expected from the aquifer through which the well is to be drilled. It has been customary in Iceland, to assume that the boiling pressure around the well bottom reaches up the wellhead. The casing depth is then determined in such a way that the formation pressure around the well at the bottom of the casing string is higher than the well pressure at that depth. The formation pressure is determined by assuming an average formation specific gravity of 2.0.

Since this is rather a very severe assumption, a new approach has been suggested by Professor Thorbjörn Karlsson from the University of Iceland. This approach assumes that water at a temperature and pressure corresponding to the boiling with depth curve for water (Figure 9) enters the well bottom and starts ascending. Part of the water flashes into steam with the dryness fraction increasing with elevation while the temperature and pressure decreases.

The maximum pressure will be expected when the well is closed. The pressure variation in the wellbore ignoring inertia effects and assuming constant specific enthalpy can be expressed as:

$dp/dz = {}_{m}g$ ....(1)

where z = minimum casing depth, m,

${}_{m}$ = steam / water mixture density, kg/m^3,

g = acceleration due to gravity, m/s^2.

The ${}_{m}$ may be approximated from Figure 10 as:

${}_{m} = \alpha \exp(\beta P)$ ....(2)

in the interval $P_o/2<P<P_o$, where P_o is the well bottom pressure.

The smallest pressure drop or the maximum pressure occurs in a closed well and the solution to equation (1) can written as:

$\exp(-\beta P) - \exp(-\beta P_o) = g\alpha\beta(H - z)$ ....(3)

or $P = - \ln(\exp(-\beta P_o) + g\alpha\beta(H - z))/\beta$ ....(4)

where H = total depth of the well, α and β are functions of P_o and are chosen such that equation (3) gives correct values for $P=P_o$ and $P=P_o/2$. Equation (3) can be solved by trial and error method.

The two methods for minimum casing determination have been used in this report for well NJ-17 and the results obtained were compared with the actual cased depth (see Figure 11).

METHOD 1

Based on boiling pressure at the well bottom reaching up the wellhead.

Production casing

Total well depth = 2100 m

From the boiling with depth curve, for this depth the bottom hole temperature T_o = 342°C

P_o = 149.76 bars.

From the steam tables, the specific volume of steam $v_g = 0.010367$ m^3/kg, and the steam density $_g = 1/v_g = 96.46$ kg/m^3.

Assuming the well to have a steam column from the bottom to the wellhead, the pressure P_z at a depth of z m below the surface is found by subtracting the pressure exerted by a column of steam extending from the bottom to depth z.

Therefore $P_z = P_o - \ _g g(H - z)$, ...(5)

$= 149.76 - (96.46)(9.81)(10^{-5})(2100 - z)$

$= 129.89 + 0.00946z$.

Therefore the minimum casing depth was obtained by equating this pressure P_z to the formation pressure at the production casing shoe depth. Taking the rock density $_r$ as 2000 kg/m^3, the minimum production casing depth was calculated as;

$$z.\ _r.g = z(2000)(9.81)(10^{-5}) = 129.89 + 0.00946z$$

$$z = \underline{696}\ m.$$

This procedure was repeated using the 696 m, as the new total depth of the well and used similarly to recalculate the depth of the intermediate casing which resulted in 288 m. Once again, the 288 m was regarded as another new total depth of the well to find the extent of the surface casing downhole which was found to be 131 m,.

METHOD 2

Superheated or saturated water enters the well bottom flashes into some steam and the steam-water mixture starts ascending with the dryness fraction increasing with elevation , (Karlsson, T. method, 1978).

Production casing

At a total well depth of 2100 m, T_o = 342°C, P_o = 149.76 bars. The specific enthalpy of the water h_f = 1610.0 kJ/kg, specific volume at this temperature v_f = 0.0016567 m³/kg,

water density $_f = 1/v_f = 603.6$ kg/m³

At P = $P_o/2$ i.e approximately 75 bars, and assuming adiabatic conditons, the dryness fraction will be obtained as,

$$
\begin{aligned}
h_f\ (149.76 \text{ bars}) &= h\ (75 \text{ bars}) \\
&= h_f + xh_{fg} \ \ldots\ldots(6) \\
1610.0 &= 1292.7 + x(1474.1) \\
x &= (1610.0 - 1292.7)/1474.1 \\
&= 0.215.
\end{aligned}
$$

The specific volume of the steam-water mixture was obtained as:

$$
\begin{aligned}
v_m &= v_f + xv_{fg} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(7) \\
&= 0.0013678 + 0.215(0.025323 - 0.0013678) \\
&= 0.006518 \text{ m}^3/\text{kg}.
\end{aligned}
$$

The mixture density $_m = 1/v_m = 153.42$ kg/m³. Using equation (2) and solving it simultaneously for pressures 149.76 (P_o) and 75 ($P_o/2$) bars respectively, resulted in values for $\alpha = 38.82$ kg/m³ and $\beta = 0.01832$ bar⁻¹.

The formation pressure $P_f = z\,.\,_r\,.g = 0.1962z = P$ ......(8)

Substitution of this expression for P together with α and β values in equation (3) and solving for z by trial and error methods yielded a minimum production casing depth of 485 m.

Using this value as the total depth of the well the same kind of analysis as above was carried out and the results were 148 m for the intermediate casing while the corresponding values of α and β were 11.94 kg/m^3 and 0.10035 bar^{-1} respectively. Again to get the setting depth of the surface casing, the 148 m were taken as the next total well depth and this was found out to be 54 m.

The minimum calculated casing depths can now be compared with the actual cased depth as shown in Figure 11.

4.2.3. Wellhead equipment selection.

The assumption that the pressure (150 bars) at the well bottom reaches the wellhead would mean selecting an ANSI (American standards) series 1500 master valve from the selection curves given in Figure 12. The value 1500 means that this master valve can withstand a pressure of 1500 psi (104 bars) at 400°C.

Using the wellbore pressure distribution expression from Karlssons approach (eq. 4), and setting $z = 0$ i.e. at the surface, gives a wellhead pressure of 85 bars at 300°C. From Figure 12 it is found that the suitable master valves for this condition are ANSI series 900 and ND160.

In well NJ-17 the actual master valve installed was a 12" ANSI series 900 which is a suitable selection.

4.2.4. Casing care and handling

Casings need to be handled with care to avoid failures during running, drilling operations and most important in the productive life of the well. The mishandling can arise from the areas mentioned below.

a) Transportation: During transportation by truck or by any other means, the thread protectors should always be in place to prevent thread damage.

b) Preparation and inspection before running: The threads should be cleaned and inspected visually for injurious defects at the well site. The casing pipes used in well NJ-17 had all the threads cleaned with pressurised water and inspected but none of the buttress threads was found defective.

The length of each piece of casing pipe should be measured prior to running. These measurements should be taken from the outermost face of the coupling to the position on the externally threaded end where the coupling stops when the joint is made power tight. On round thread joints, this position is to the place of the vanish point on the pipe; on buttress threaded casings, this position is to the base of the triangle stamp on the pipe; and on the extreme line joints, to the shoulder on the externally threaded end.

c) Running: Its always safe to remove the thread protectors just before stabbing at the rig floor and applying the correct antiseize compound over the entire surface of the threads. Stabbing is successful only when the casing pipe is vertical and in this case there was a rig crew member up on the mast to align the casing lengths. Another important aspect to bear in mind is that after stabbing the casing should be rotated very slowly at first to ensure that the threads are engaging and not cross-threading.

For well NJ-17, all the casings were being lifted and lowered into the well slowly with much care while setting the slips to avoid shock loads. This is because dropping the string even a short distance may loosen the couplings at the bottom of the string. It is worth realising that the whole length of the casing string has more flexibility than a single length of casing pipe. This therefore means that resting the string on the well bottom would result in casing buckling particularly where the well is heavily enlarged. In this connection the casings were never allowed to rest on the well bottom even during the cementing operations.

Definite instructions were being followed such as where to fix the centralizers, the float collar and recording the casing tally. To facilitate running and ensure adequate hydrostatic head, water was being added periodically into the string. There are a number of factors that affect the frequency of refilling namely weight of the pipe in the hole, drill fluid specific gravity, reservoir pressure and so on.

4.2.5. Causes of casing troubles

In general the more common causes of troubles include the following:

a) Improper determination of casing depths to cope with the reservoir pressures to be encountered.
b) Insufficient inspection of each casing threads.
c) Abuse in mill, transportation and field handling.
d) Non-observance of good rules in running and pulling casings.
e) Improper care in storage.
f) Excessive torquing of casings.
g) Rotary drilling inside casing particularly when drilling out cement.
h) Buckling of casing in an enlarged, washed out, uncemented cavity due to dropping or due to thermal stresses.
i) Burst and collapse due to water pockets entrapped in cement between to casing strings and hydrostatic pressure imbalance.

Besides building the casing string using the round thread, buttress threads and extreme joints, welding is also used in some cases. The selection of steel for use in casing is governed by important considerations dictated by the service the casing must perform. Steels most suitable for welding do not have those performance properties. Therefore, field weldability cannot be of primary consideration in the selection of steel for the manufacture of casings. As a result, unless precautions are taken, welding may have adverse effects on many of the steels used in all grades of casings, especially J-55 and higher, (due to carbon content increase thus influencing formation of brittle martensite). Field welding procedures are available in Appendix B of API std. 6A (Specification for wellhead equipment).

The heat from welding, may affect the mechanical properties of high strength steels. This may cause poor resistance to burst, collapse and thermal stress during the service life of the casing. Cracks and brittleness are likely to occur in the heat affected zone. The welding of joints to prevent backoff must be done carefully with the necessary and recommended procedures.

In well NJ-17 the surface casings was welded but the intermediate and production casings and slotted liners were all made-up using buttress thread couplings. Casings are identified through a colour code usually denoted by some colour bands on the casings. All the casings used in NJ-17 had two green bands signifying the K-55 steel grade.

4.3. Cementing in geothermal wells

Cementing casing strings in geothermal wells is performed in order to:

a) support and hold the casing firmly to the ground,
b) prevent cold geofluid migration to the hot desired aquifer,
c) seal off loss of circulation zones and
d) protect the casing string from corrosion.

Besides casing string cementing, the open hole can also be cemented for the following reasons;

a) combating loss zones greater than 20 l/s,
b) sidetracking around an obstruction,
c) plugging abandoned wells and in some cases
d) temporary plugging during repairs or removal of wellhead equipment.

A number of cement placement techniques are in existence and the most common are:

a) inner string or stab-in method (see Figure 11),
b) conventional method or cementing through casing and displacing the cement with water and plug.
c) multi-stage cementing for casing strings greater than 700 m.

In the stab-in method, a stab-in seal nipple (see Figure 13) is used to couple the drill pipes to the float collar by means of left hand threads. The cement slurry is then pumped through the drill pipes (see Figure 11). When the slurry reaches the float collar, the ball check valve (that allows only downward flow) opens and allows the slurry to flow down towards the float shoe. If the float shoe also has a ball check valve (some types do not have) it opens and allows the slurry to flow into the open hole from where it rises up the annulus to the surface. This method has the following advantages over the conventional method:

1) allows better control of the cementing operation,
2) cuts down the possibility of cement setting in the casing,
3) when the returns appear, only the volume in the drill pipes that to be displaced.

Before the cementing job is commenced, a cementing programme is always necessary and may include the following:

a) calculation of slurry volumes and dry cement requirements,
b) calculation of slurry yield and density,
c) determination of pumprate to complete cementing job before thickening,
d) bulk cement blending programme,
e) determination of pump pressure for the inner string method,
f) decision on the clearance between the hole bottom and casing shoe,
g) decision on the casing hardware to be used e.g centralizers, float shoe and collar, stage tools.

4.3.1. Some cementing problems

Cementing problems in geothermal wells may arise due to the reasons explained below.

i) Thermal conditions

Above 110°C all cement slurries undergo a retrogression of compressive strength. As the compressive strength retrogresses, the cement permeability increases and no longer prevents geofluid migration as desired. This can be improved by blending the cement to be used with about 40 % silica by weight, (Cigni et al, 1975).

ii) Water pockets and hydrostatic pressure

If there is improper fillup of cement particularly between two casings the water pockets may be formed. During the service period of the well, the water heats up and expands exerting a very high pressure which can go beyond the collapse pressure of the inner casing or the burst pressure for the outer casing. Proper design assures that the latter occurs first.

Casing collapse may also be encountered around its bottom section during cementing. Assuming the annular space between the casing and open hole to be filled with slurry while the inside is filled with water (for the stab-in method water occupies the annular space between the drill pipe and the casing), the collapse pressure P_c can be obtained from the expression;

$$P_c = hg(\ _c - \ _w) + P_p \ldots\ldots\ldots\ldots\ldots\ldots\ldots(9)$$

where h = hydrostatic head, g = acceleration due to gravity, $_c$ = cement slurry density, $_w$ = density of water and P_p = Pump pressure. For the production casing in well NJ-17, the average slurry density was 1680 kg/m^3 and therefore the collapse pressure can be expressed as;

$P_c = 9.81*771*(1680 - 1000)*10^{-5} + P_p$ bars

$= 51.43 + P_p$ bars.

After a cementing job has been carried out unsatisfactorily it is necessary to check for the uncemented sections using a cement bond log. The casing should then be perforated and cement squeezed through the holes to fill up the uncemented portions.

4.3.2. Slurry volume calculations

Before cementing the 13-3/8" and 9-5/8" diameter casing, Portland cement was blended with the following percentages (by weight of dry cement) of additives; a) 30 % silica flour, b) 2 % Perlite, c) 2 % API bentonite. Silica stabilizes the cement compressive strength at the elevated temperatures encountered in geothermal reservoirs. Perlite reduces slurry weight for efficient pumping and prevents formation fracturing which may cause slurry loss zones during cementing and c) API bentonite decreases the water loss.

The theoretical volumes required were calculated using the relationship,

$V = q * d$

where V = Volume of slurry in litres,

q = capacity of drill pipes or annular volume in litres per metre,

d = depth, m.

a) Intermediate casing volumes (13-3/8")

The notation of the different volumes for the two casing strings is as shown in Figure 10. The intermediate casing calculations were as follows;

1) drill pipe volume,

   $V_1 = 9.16$ l/m * 229.48 m = 2102 l

2) annular volume between 18-5/8" and 13-3/8" diameter casings,

   $V_2 = 68.94$ l/m * 62 m = 4274 l

3) annular volume between 13-3/8" casing and 17-1/2" open hole,
   V_3 = 64.4 l/m * 194.52 m = 12527 l
4) volume between float collar and float shoe,
   V_4 = 79.37 l/m * 25.81 m = 2049 l
5) volume below guide shoe,
   V_5 = 155.2 l/m * 1 m = 155 l

Thus the total slurry volume, V = 21107 litres. To cater for any loss within the hole, 100 % excess was allowed and thus the slurry volume with 100 % excess was 42214 litres.

The calculated theoretical specific gravity for the blended slurry was 1.74. The yield was 90.6 litres of slurry per 100 kg of dry blended cement while the water requirements were 57.1 litres per 100 kg of dry blended cement.

The theoretical dry cement requirement was therefore equal to 42214 l * 100 kg/90.6 l = 47,000 kg. The actual cement usage was 50,000 kg which is more than initially anticipated. The average measured specific gravity of the slurry was 1.66. The sp. gr. may have differed from the theoretical one due to inhomogeneous additives-cement mixing or innacurate mud balance readings due to air entrapped in the slurry.

<u>b) Production casing (9-5/8")</u>

Cement amounts used were as shown below;
V_1 = 9.16 l/m * 742.13 m = 6798 l,
V_2 = 30.98 l/m * 267.50 m = 8287 l,
V_3 = 28.94 l/m * 495.55 m = 14341 l,
V_4 = 38.19 l/m * 26.06 m = 995 l,
V_5 = 76.04 l/m * 1 m = 76 l.

Thus the total theoretical volume of slurry was 30,497 litres. Again to cater for losses, 100 % excess was allowed for resulting in 60,994 litres of slurry. The theoretical amount of dry cement required was 60,994 litres * 100 kg/90.6 litres = 67,322 kg. The actual usage was 49,900 kg at an average sp. gr. of 1.68. In this case the actual usage was less than the theoretical value because the well never had big loss zones (as previously indicated by the caliper log).

4.3.3. Cementing equipment

The cementing system for rig Jötunn comprises of;

a) Two bulk cement silos

These are used for bulk cement storage and blending. Each has a storage capacity of 36.8 m^3 and can withstand a maximum internal pressure of 60 psi. They are manufactured by the Byron-Jackson (BJ) International Services Incorporation. During operation they require 450 CFM of air to discharge out the cement.

b) Cement blending tank.

This is a 0.7 m^3 tank in which the calculated amounts of cement additives are added and then discharged into the bulk silos using air at 40 psi.

c) Air compressor.

The compressed air used for the cementing operations is from a single air compressor from Ingersoll Rand type DXL-855 with a capacity of 850 CFM at 100 psi.

d) Halliburton unit.

This is one of the best cementing units (Figure 14) today for the drilling industry. It is composed of a slurry displacing pump, cement-air cyclone separator, stab-in seal nipple (Figure 13) and a mixing skid.

Compressed air at 40 psi, is usually passed into the bulk cement silos through a 3" diameter hose pipe fitted at the base of each silo. This air disperses the blended cement and forces it through two 5" diameter hoses into a 0.6 m^3 cement-air cyclone separator. Here the air fraction is vented to the atmosphere. The cement is then passed through a master valve into a slurry make-up unit. This consists of two 5MD DEMING centrifugal pumps with ceramic coated shaft sleeves, a 1272 litres tub, two screw pump driven stirrers and a set of control valves. The two pumps are located on the same base. One of the pumps is used for recirculating the slurry through the pre-mix compartment of the tub to build up the desired specific gravity. The second is used for pumping water from the storage tanks into the tub. They are powered by a GM 3-71 diesel engine through a Chelsea 4700A split power take-off gear box.

After the slurry has acquired the desired sp.gr., the slurry displacing pump sucks it from the tub and pumps it through the drill pipe down to the float collar (stab-in method, see Figure 11) and seal nipple. The float collar has a ball check valve that enables the slurry to be pumped into the annulus without any backflow. This pump has three 6" diameter plungers, 8" stroke and is driven by a GM 12V-71 series engine via a CP-HT400 Halliburton transmission unit.

5. CONCLUSIONS

The conclusions drawn from the experience acquired from the drilling of well NJ-17 are as follows;

a) Prior to commencing the drilling of a geothermal well, a clearly defined programme is very vital. All the materials and tools specified that will be required during the drilling process should be available in adequate amounts. These include things like bits, cement and its additives etc. The drilling programme should be a flexible one in order to cope with the drilling problems that may be encountered in the field.

b) Proper bit records and cost analysis in terms of cost per metre drilled (as done for well NJ-17) can provide a good basis for bit selection. Even though formation hardness may differ in various geothermal areas large savings of time (which translates into money) can be achieved by use of insert bits with journal bearings. These bits are more expensive than the milled tooth bits but their performance and durability are higher.

c) Regarding cementing techniques, the stab-in cementing method (Figure 11) is superior to the conventional method of pumping the slurry directly into the casing string and chasing it with water and a plug. In the stab-in method, it is possible to pump more slurry volume even beyond the calculated value so long as it does not set.

d) Frequent inspection of drill collars (and the rig mast) for internal cracks as mentioned in this report is a necessary precaution to avoid downtime that may arise from fishing jobs.

e) Rig instrumentation is an area of great concern since it enables monitoring of all the necessary parameters that affect drilling operations. The instruments such as suitable pressure gauges, weight indicator and so on should always be maintained in an operational condition.

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REFERENCES

Abera Teshome, 1983: Planning and drilling a Geothermal well, UNU geothermal training programme, report 1983-7 46 pp.

Chuji Araki, 1979: Utilization of geothermal energy in Japan, Geothermal energy research and development company, 25 pp.

Cigni U., Fabri F. and Anselmo G., 1975: Advancement in cementation techniques in the Italian geothermal wells, Second United Nations Symposium on the development and use of geothermal resources 1975, 1471 - 1482 pp.

Franzson H., Asgrimur G., Guðmundur O.F. and Jens Tömasson (NEA): Nesjavellir high temperature field (SW-Iceland) reservoir geology. Fifth international symposium on water rock interaction,1986.

Halliburton cementing tables 1980, section 230.

Institut Francais Du Petrole, 1978: Drilling data handbook.

Karlsson T., 1982: Optimization of geothermal well diameter, International conference on geothermal energy (Florence Italy May 1982).

Karlsson T. 1978: Casing design for high temperature geothermal wells, Geothermal Resources Council Transactions 2, 355-358 pp.

Lynes catalog 1978-79: Inflatable packers, inflatable speciality tools and formation testing, 4431 pp.

Moore, L. Preston: Drilling pactices manual, 9-10 pp.

Nicholson, R. Robert, 1985: Unique aspects of geothermal casing design, Course paper on high temperature geothermal wells, 23-24 August 1985, Kailua-Kona Hawaii.

Reed rock bit company: A paper on rock bit design, dull grading, selection and application, April 2, 1982, section B5.

Steingrimsson, Benedikt, Stefansson V., 1981: Geothermal logging 1, an introduction to techniques and interpretation, second edition, Orkustofnun report OS80017/JHD09, 23 pp.

Thórhallsson, S. 1986: UNU Geothermal training programme lecture notes.

Table 1 Cable tool rig drilling progress (well NJ-17)

Working day	Drilled depth,m	Working hours	Working day	Drilled depth,m	Working hours
1	4.7	8.8	11	43.4	9.8
2	12.0	13.6	12	48.2	14.2
3	16.1	13.9	13	52.0	14.4
4	20.0	13.6	14	55.0	9.8
5	24.0	11.8	15	57.5	13.5
6	28.5	12.0	16	62.5	14.5
7	31.5	12.5	17	62.5	14.5
8	32.5	13.5	18	65.0	10.0
9	36.5	9.5	19	65.0	11.0
10	39.0	12.5	20	65.0	10.7

Table 2 Slurry specific gravity variation recorded during cementing of a) 13-3/8" casing b) 9-5/8" casing.

TIME (Mins.)	PUMP PRESSURE (bars)	SP.GR.	TIME (Mins.)	PUMP PRESSURE (bars)	SP.GR.
2	8	1.75	1	5	1.62
4	6	1.58	3	9	1.74
6	5	1.58	5	6	1.68
8	4	1.50	7	8	1.69
10	5	1.62	9	8	1.69
12	8	1.67	11	9	1.68
14	6	1.59	13	8	1.61
16	8	1.63	15	9	1.68
18	8	1.66	17	9	1.71
20	7	1.65	19	8	1.69
22	7	1.66	21	10	1.78
24	8	1.68	23	10	1.75
26	7	1.66	25	8	1.65
28	9	1.77	27	6	1.62
30	6	1.65	29	8	1.70
32	7	1.67	31	6	1.55
34	9	1.72	33	6	1.72
36	6	1.64	35	5	1.53
38	5	1.62	37	6	1.58
40	8	1.66	39	6	1.53
42	6	1.64R	41	7	1.54
44	5	1.62R	43	7	1.60R
45	5	1.63R	45	6	1.61R
47	6	1.63R	47	6	1.63

a) R = sp. gr. for returns b)

Table 3 Bit record and cost analysis for well NJ-17.

BIT RECORD AND COST ANALYSIS

Geothermal Field: Nesjavellir
Well number: NJ-17
Rig name: Jötunn
Date: June-August 1986
Rig cost: 373 $/hr

		DRILL BIT				DEPTH			PEN-RATE	TRIP			
RUN	SIZE	TYPE	CODE	COST $	IN	OUT	m	h	m/h	h	% Bit usage	Run cost	$/m
1	17.50	S-53	5.3.5	20000	65	271	206	66	3	2	33	31842	155
2	12.25	FP-62	6.2.7	10000	271	773	502	89	6	3	50	39349	78
3	8.50	J-44	6.2.7	6600	773	876	103	23	4	4	25	11832	115
4	8.50	T.C.B*	-	6000	876	880	4	3	1	5	50	5802	1450
5	8.50	J-44	6.2.7	6600	880	1003	123	21	6	5	25	11261	92
6	8-7/16	D.C.B*	-	20000	1003	1010	7	5	1	5	75	18740	2677
7	8.50	H.P.S.M	5.4.7	6445	1010	1447	437	79	6	6	50	34895	80
8	8.50	T.C.B*	-	6000	1447	1457	7	5	1	7	50	7402	1057
9	8.50	RZBK	-	22000	1457	1674	220	67	3	7	100	49697	226
10	8.50	HPSM	5.4.7	6445	1674	2100	426	119	4	9	50	50798	119

T.C.B* = Tungsten carbide coring bit
D.C.B* = Diamond coring bit
RZBK = Razorback 3 bit (from Reed Bit Company)

Table 4 Core No.1 data

CORE BARREL: Smith Dowdco 6-7/8"(o.d.) 25 ft long
CORE BIT: Tungsten Carbide.
BIT SIZE: 8-1/2"(o.d.) and 4-3/8"(i.d.)
PUMPRATE: 17 l/s (API Bentonite Mud).

TIME mins.	RPM	PUMPRATE spm	PUMP-PRESSURE psi	CORE LENGTH cm	WOB 000 lbs
	0	95	120		
	35	95	155		
	40	95	155		
0	37	95	160		
5	38	96	156	4	2
10	38	95	154	10	3
15	39	95	154	12	3
20	39	96	154	17	3
25	50	96	154	20	3
30	51	96	154	27	6
35	49	95	154	33	6
40	48	96	162	41	8
45	49	95	162	51	8
50	52	95	162	60	10
55	51	96	166	71	10
60	50	96	168	80	10
70	50	96	165	97	10
80	50	96	160	115	10
90	49	95	162	132	10
102	53	95	168	164	10
115	53	95	166	192	10
125	53	95	156	250	10
140	53	95	156	288	10
150	53	95	152	312	10
160	53	96	151	340	10
170	53	95	135	367	10
180	53	96	140	396	10
190	53	95	138	419	10

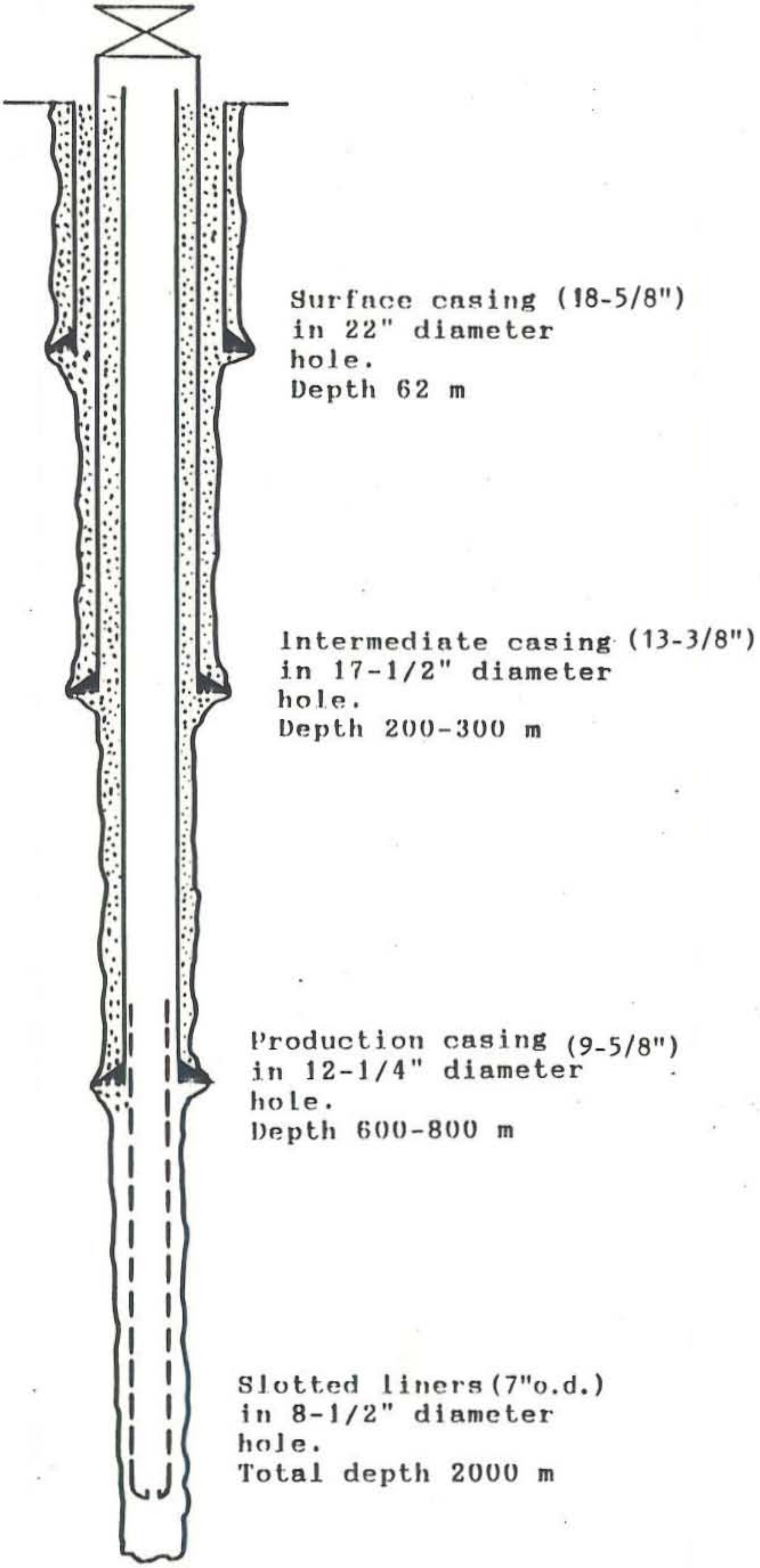
Table 5 Tensile strength requirements of casing manufactured according to API specification 5A, (Karlsson, T. 1978).

Casing grade	Yield min N/mm^2	Strength max N/mm^2	Min. tensile strength N/mm^2	Min.elongation, % in 2"
H-40	276	-	414	29.5
J-55	380	551	517	24.0
K-55	380	551	655	19.5
C-75	517	621	655	19.5
N-80	551	758	690	18.5
P-110	758	965	862	15.5

Table 6 Rig time breakdown for some wells in Nesjavellir (Data from Jarðboranir hf.).

YEAR:	I985		I985		I985		I985		I986	
HOLE NO.	NJ-I3		NJ-I4		NJ-I5		NJ-I6		NJ-I7	
HRS & %	HRS	%	HRS	%	HRS	%	HRS	%	HRS	%
I.I Drilling	230.0	25.9	I83.5	30.58	I72.5	30.69	35I.0	4I.79	476.5	42.24
I.2 H. Opening										
I.3 Tripping	6I.0	6.87	64.5	I0.75	67.5	7.50	59.05	7.08	160.5	14.23
I.4 Pumping	20.0	2.25	22.5	3,75	I6.5	I.68	34.00	4.08	56.5	5.01
I.5 Ráthole	0.5	0.06	4.0	0.67	I.0	0.II	3.00	0.36	0.5	0.04
2.I Reaming										
2.2 Casing	I47.0	I6.56	I26.5	2I.08	I68.5	I8.98	I64.50	I9.58	121.5	10.77
2.3 Caving Probs.	I9.5	2.20	2.5	0.42	83.5	9.40			0.5	0.04
2.4 Trspt.&Erect	II4.0	I2.84	I35.0	22.50	I39.0	I5.65	I48.0	I7.62	213.0	18.89
2.5 Logging	49.5	5.57	57.5	9.58	77.0	8.67	60.00	7.20	65.5	5.81
2.6 Delays					I5.5	I.75				
2.7 Fishing	29.0	3.27			26.5	2.98				
2.8 Repairs			I.0	0.I7	2.0	0.23	I.0	0.I2	5.5	0.49
2.9 Others	2I7.5	24.48	3.0	0.50	I8.5	2.08	I8.5	2.20	28.0	2.48
Total work hrs	888.0		600.0		888.0		840.0		1128	
Total work days	37.0		25.0		37.0		35.0		47	
Hole depth(Perc.)	I,609	(70)	I,304	(70)	I,748	(I00)	2,025	(74)	2100(65)	
Pentr. m/day	4I.59		49.36		44.54		55.74		46.62	
Pentr. m/hr	6.73		6.72		6.05		5.56		4.27	
" m/work hr	I.73		2.06		I.86		2.32		1.80	
Acc. m Vol m^3	54,I88	3,I84.I	55,422	3,275.I	57,070	3,377.6	59,02I	3,493.I	61,121	3,611.

NOTE: Acc=Accumulated m & Cuttings volume in m^3



Surface casing (18-5/8")
in 22" diameter
hole.
Depth 62 m

Intermediate casing (13-3/8")
in 17-1/2" diameter
hole.
Depth 200-300 m

Production casing (9-5/8")
in 12-1/4" diameter
hole.
Depth 600-800 m

Slotted liners (7"o.d.)
in 8-1/2" diameter
hole.
Total depth 2000 m

Figure 1 Design profile for well NJ-17.

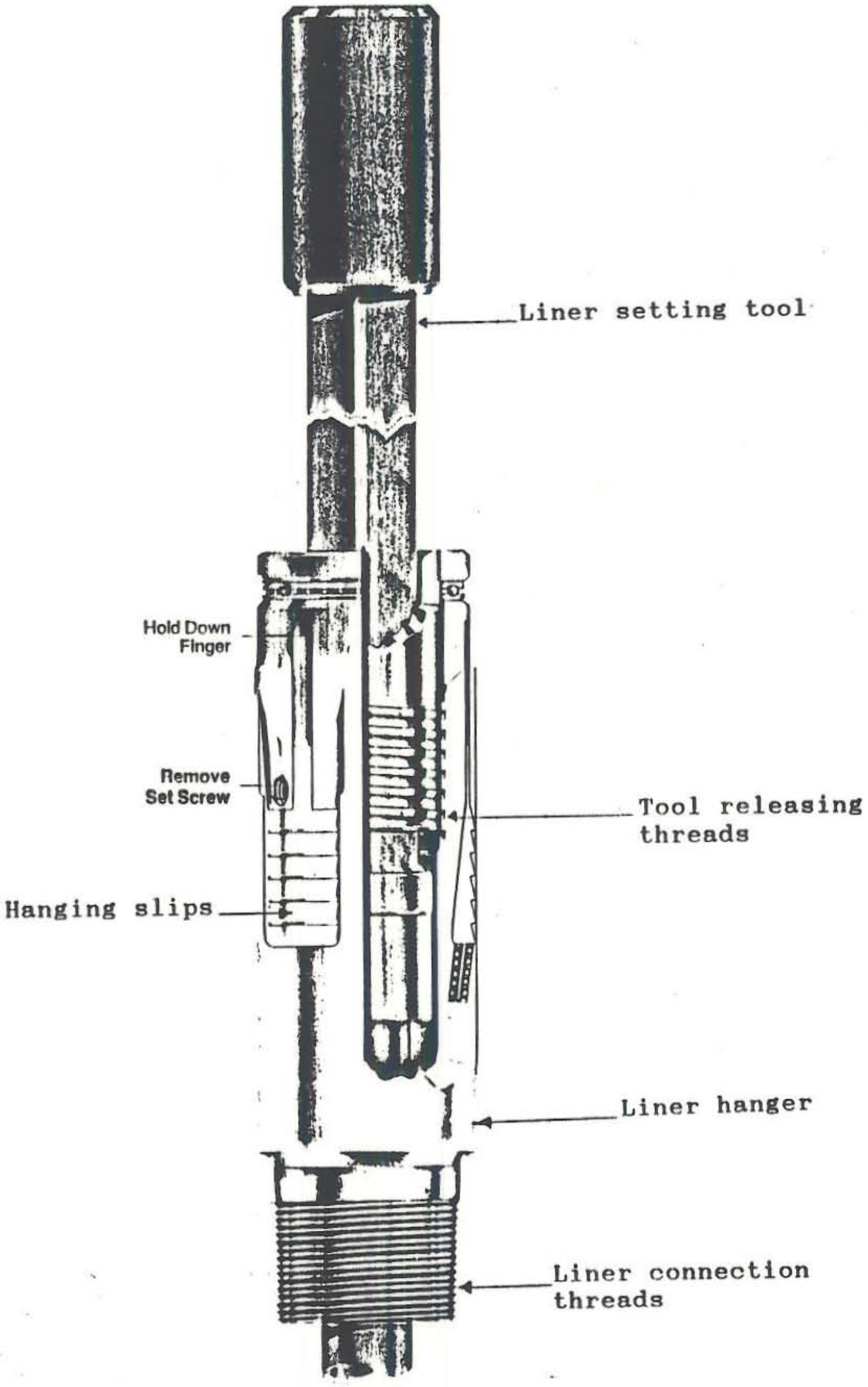


Figure 2 Slotted liner Hanger and Setting tool assembly (from Lynes catalog 1978-79).

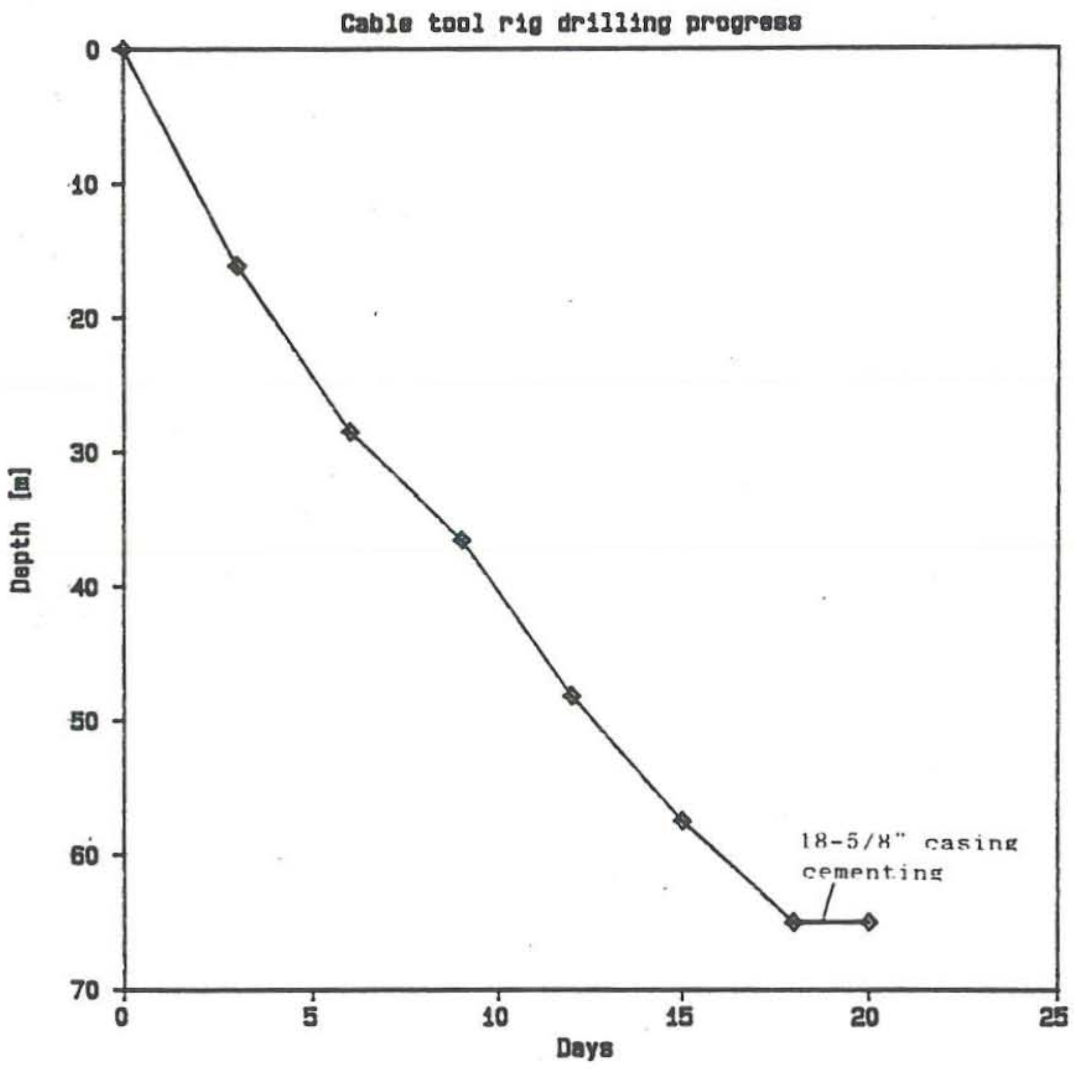


Figure 3 Cable tool rig drilling progress for well NJ-17.

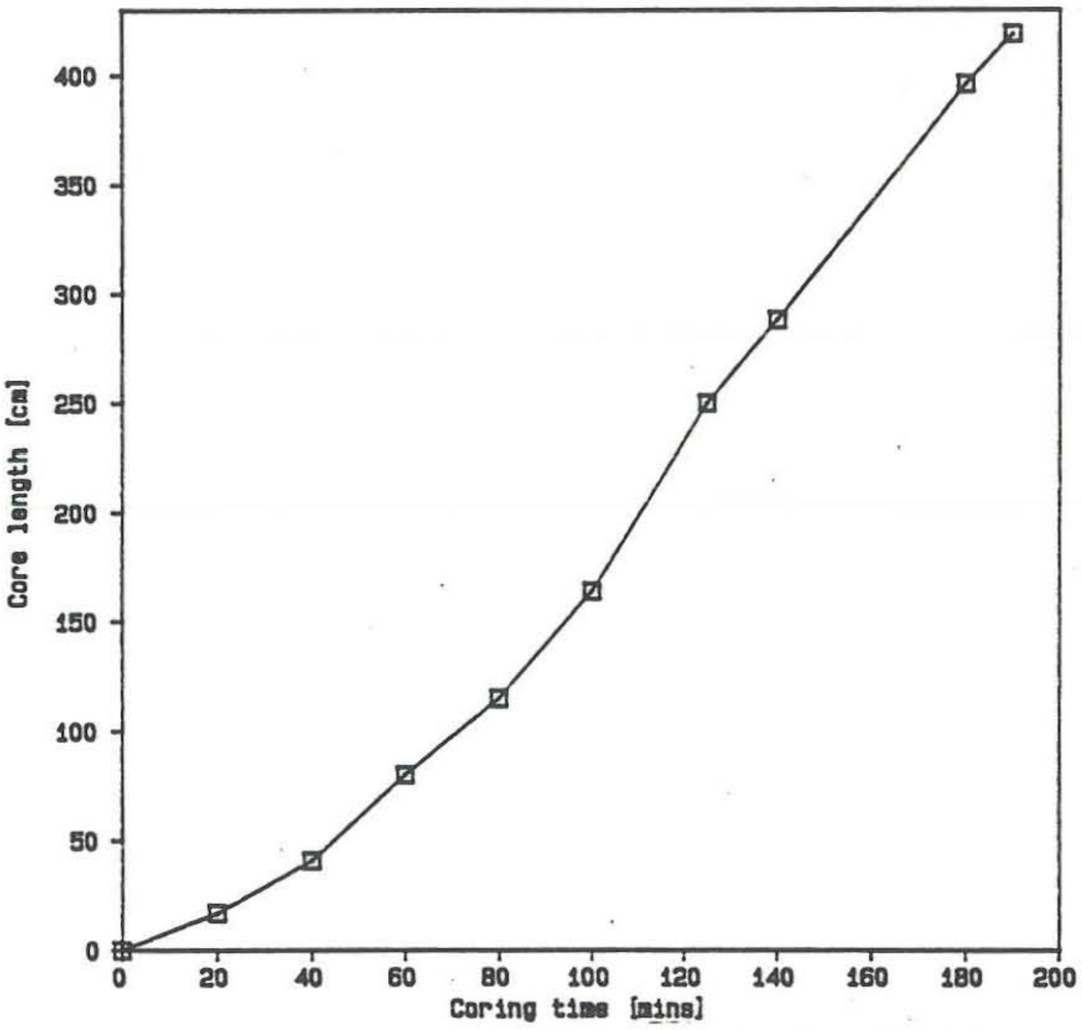
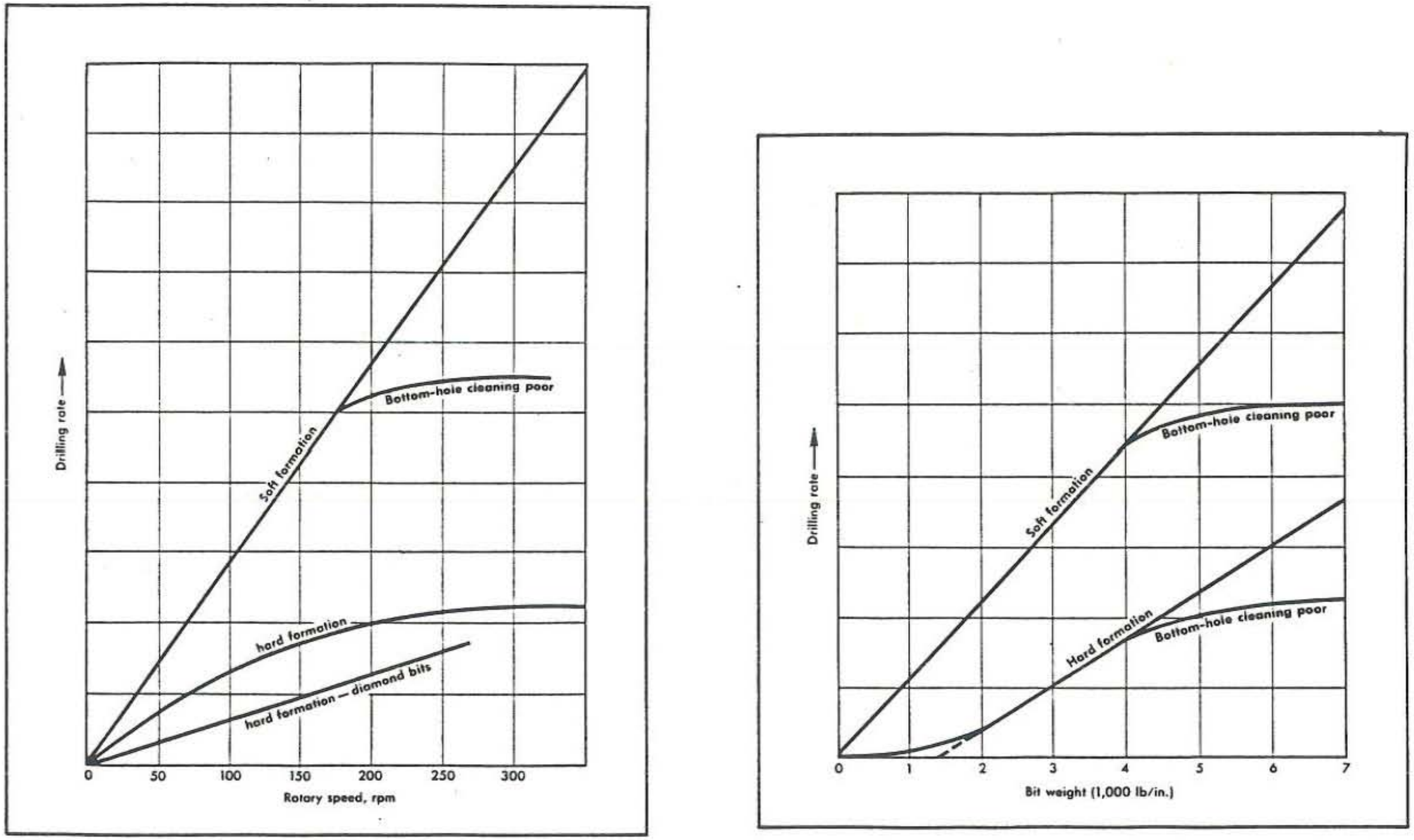


Figure 4 Core length versus coring time (Core No.1).



Drilling rate vs. rotary speed

Drilling rate vs. bit weight

Figure 5 Dependence of penetration rate on (a) Rotary speed and (b) Weight on bit.

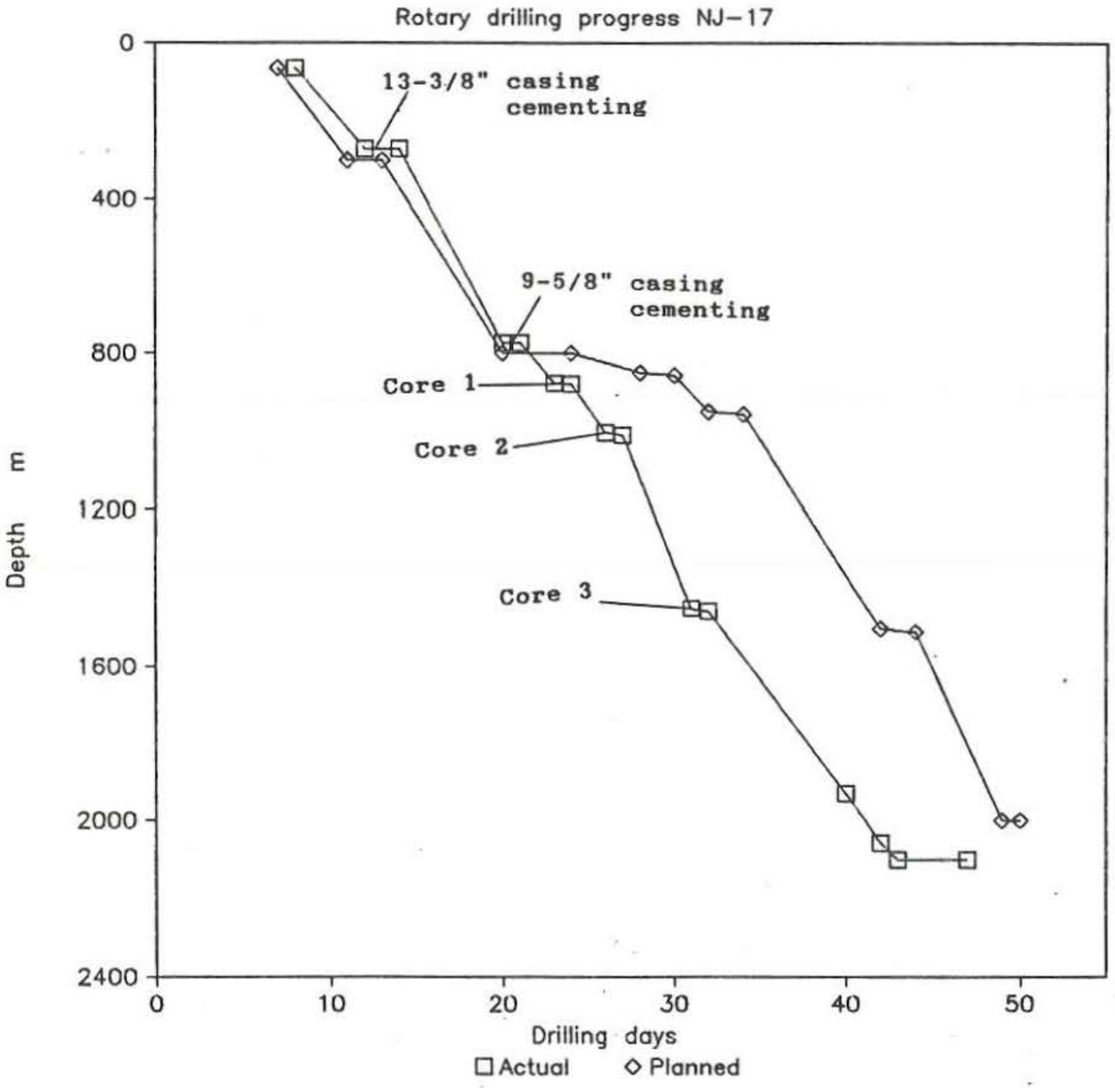


Figure 6 Rotary drilling progress for well NJ-17.

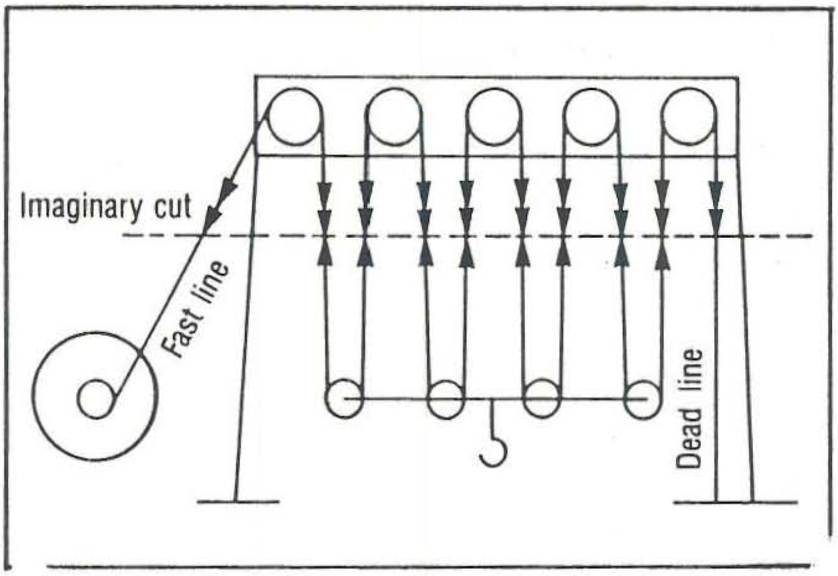


Figure 7 Rotary drilling line string-up on the crown and travelling blocks.

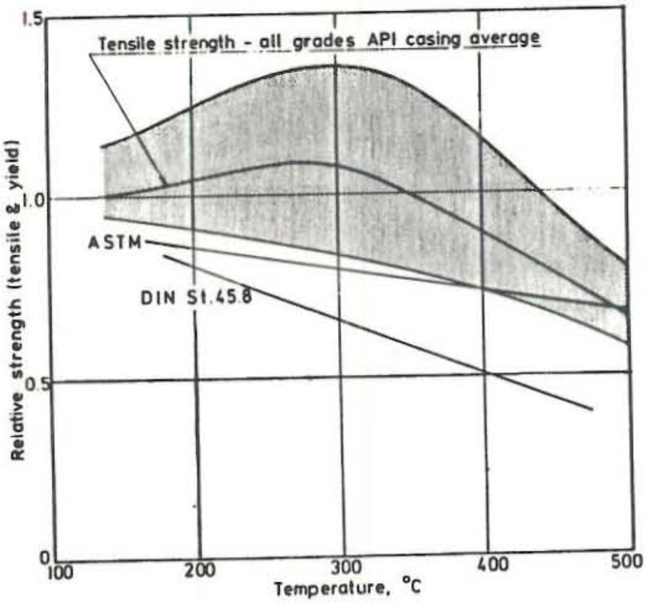


Figure 8 Variation in relative strength limits (Tensile or Yield) for API casing. The shaded area denotes the range of yield strength obtained for various grades of casing (Karlsson, T. 1978).

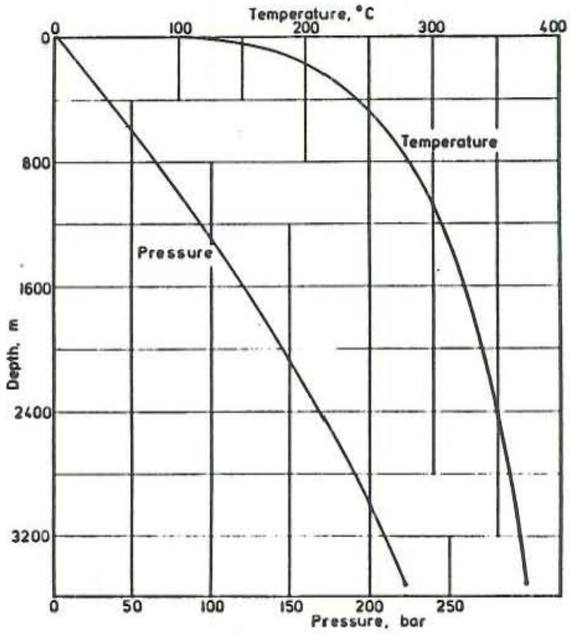


Figure 9 Boiling curve - Temperature and Pressure versus depth.

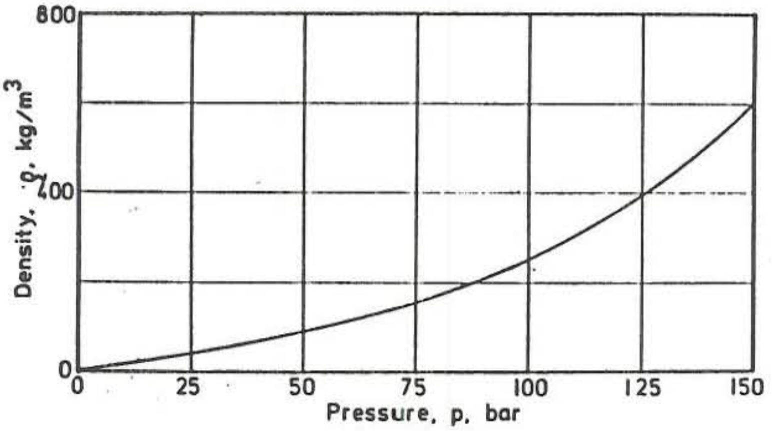


Figure 10 Density of steam/water mixture in a well with inflow pressure of 150 bars.

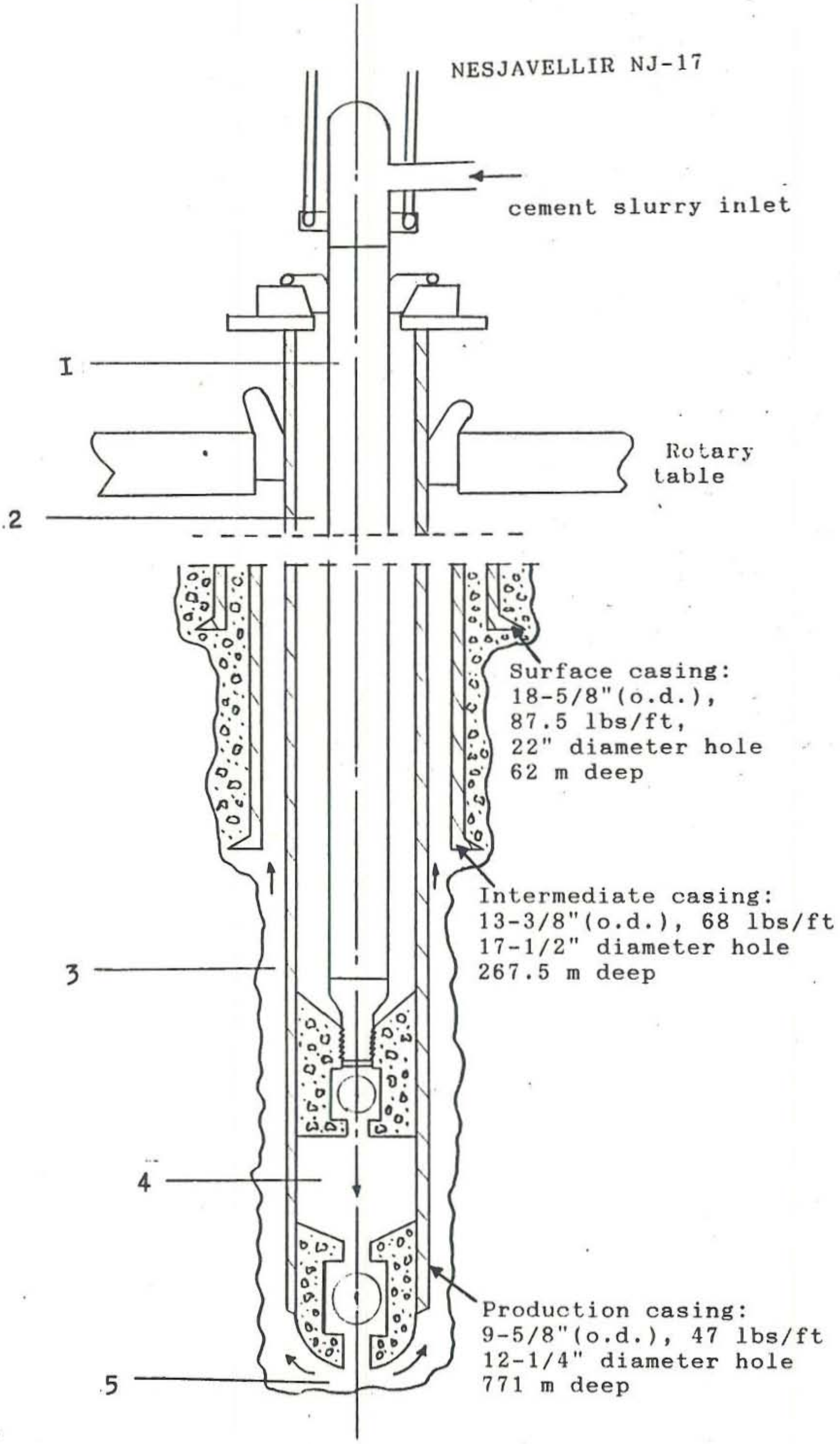


Figure 11 Actual cased depth and stab-in cementing method in well NJ-17.

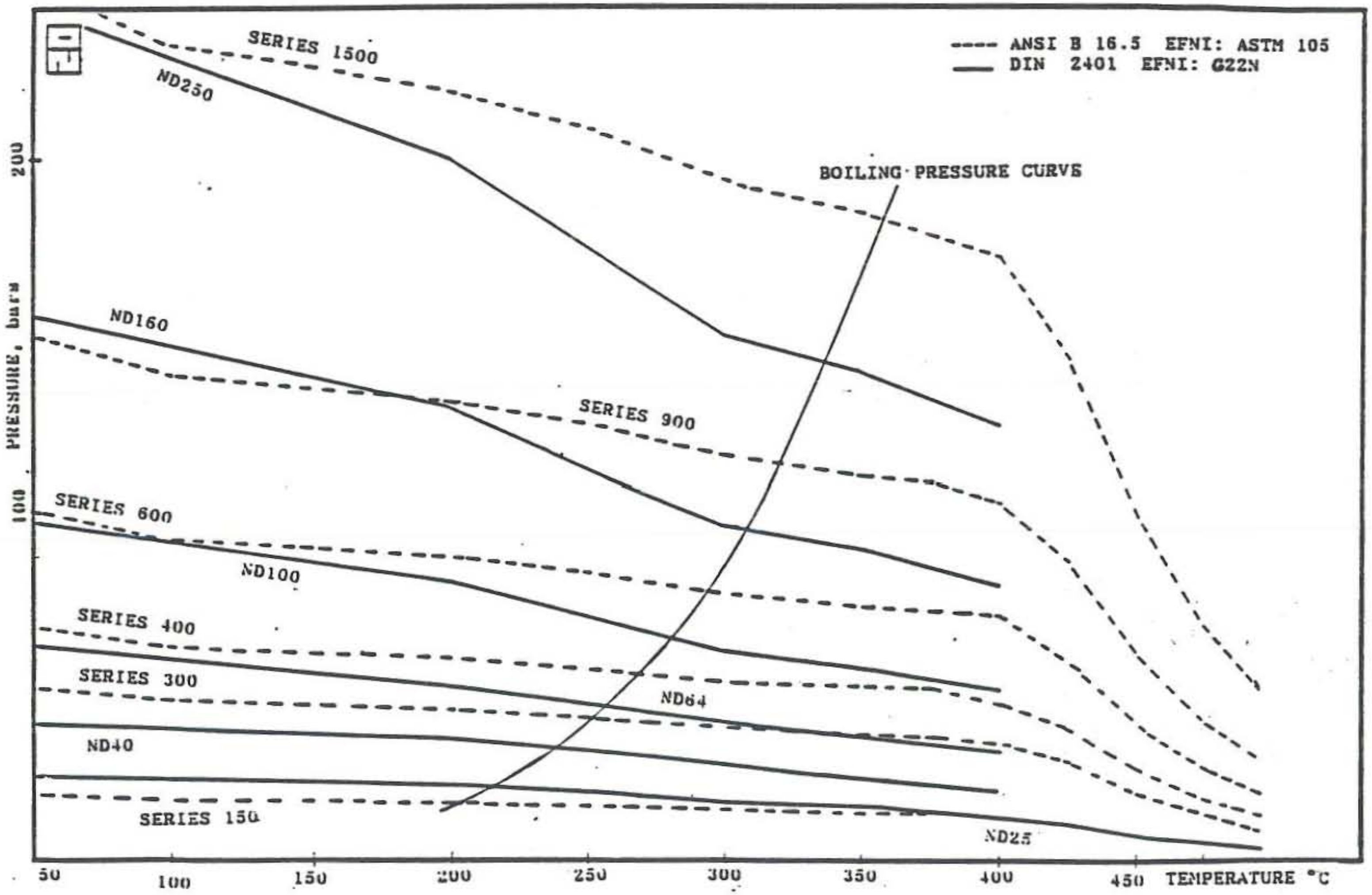
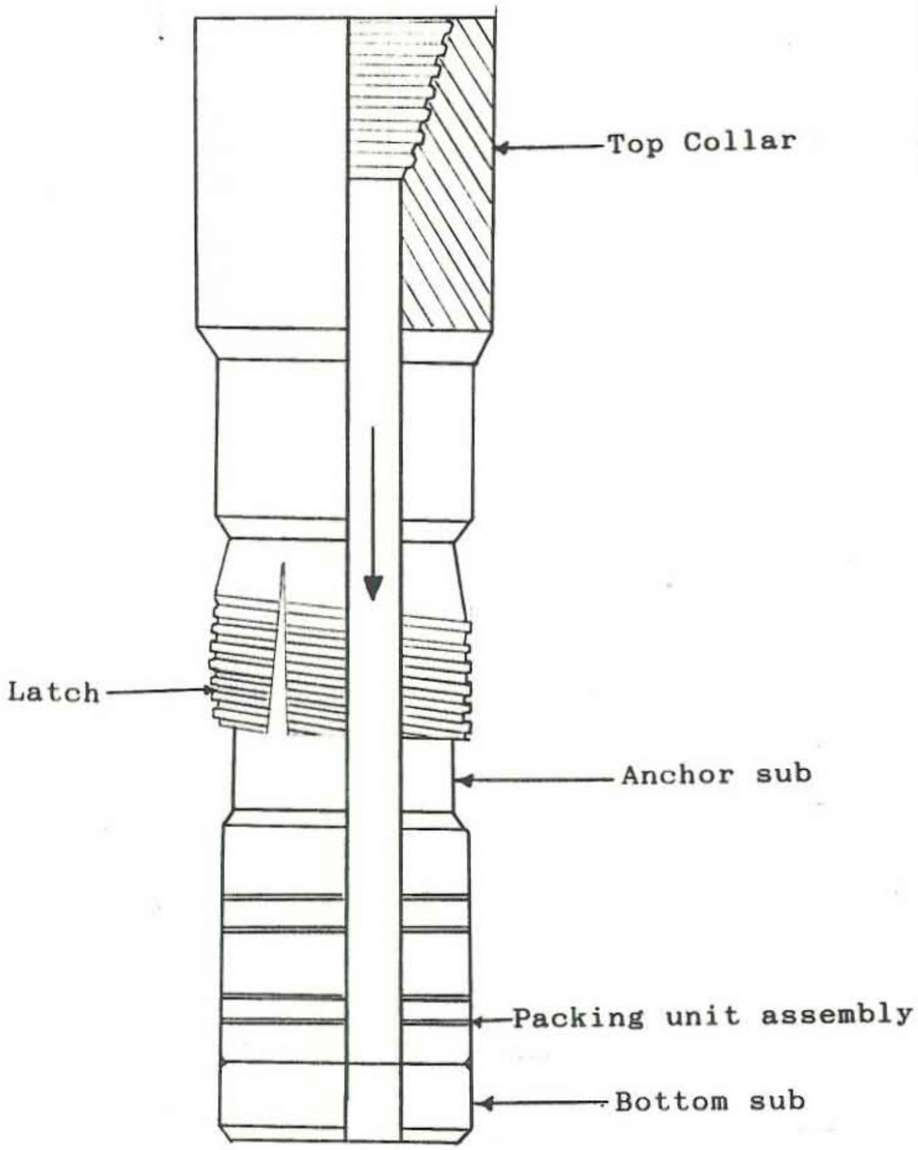
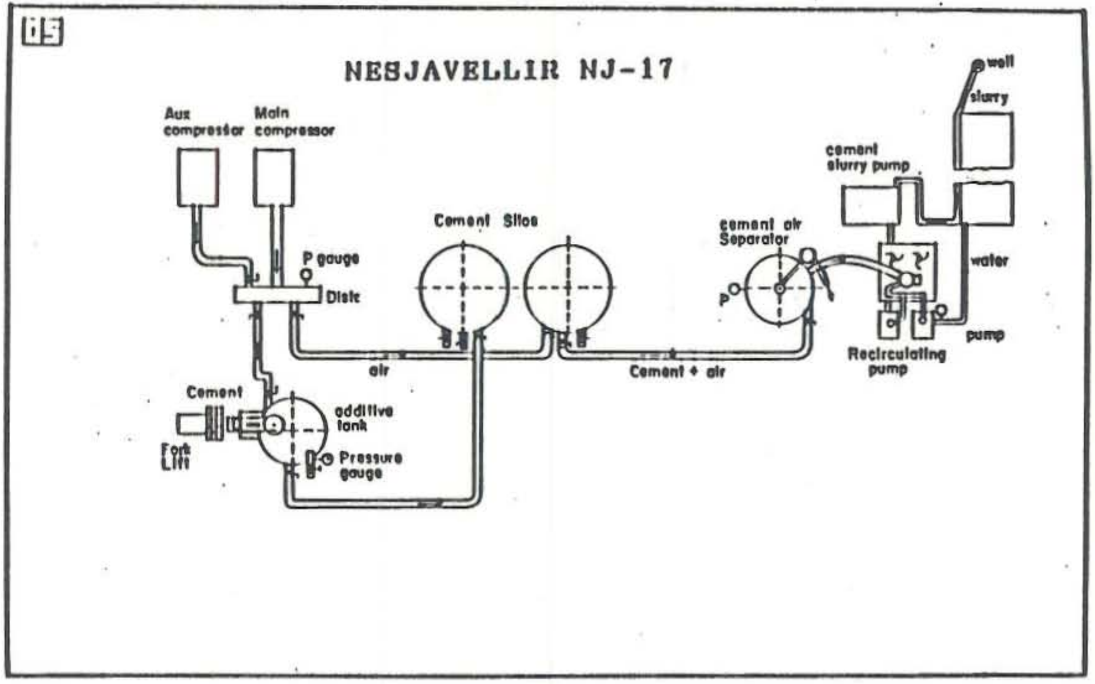


Figure 12 Pressure versus Temperature curves for the ANSI and DIN standards gate valves (from Karlsson, T., personal communication, 1986).

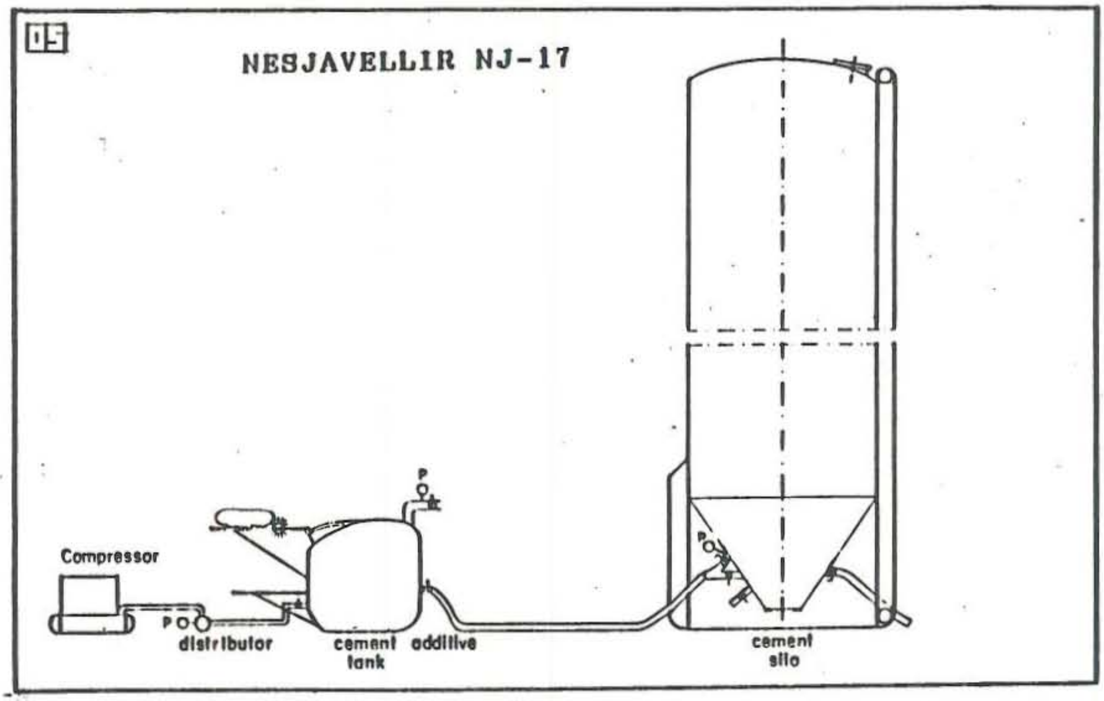


Bakerline Model "E"
Duplex Tubing Seal Nipple
Product No.443-13

Figure 13 Stab-in cementing method seal nipple.

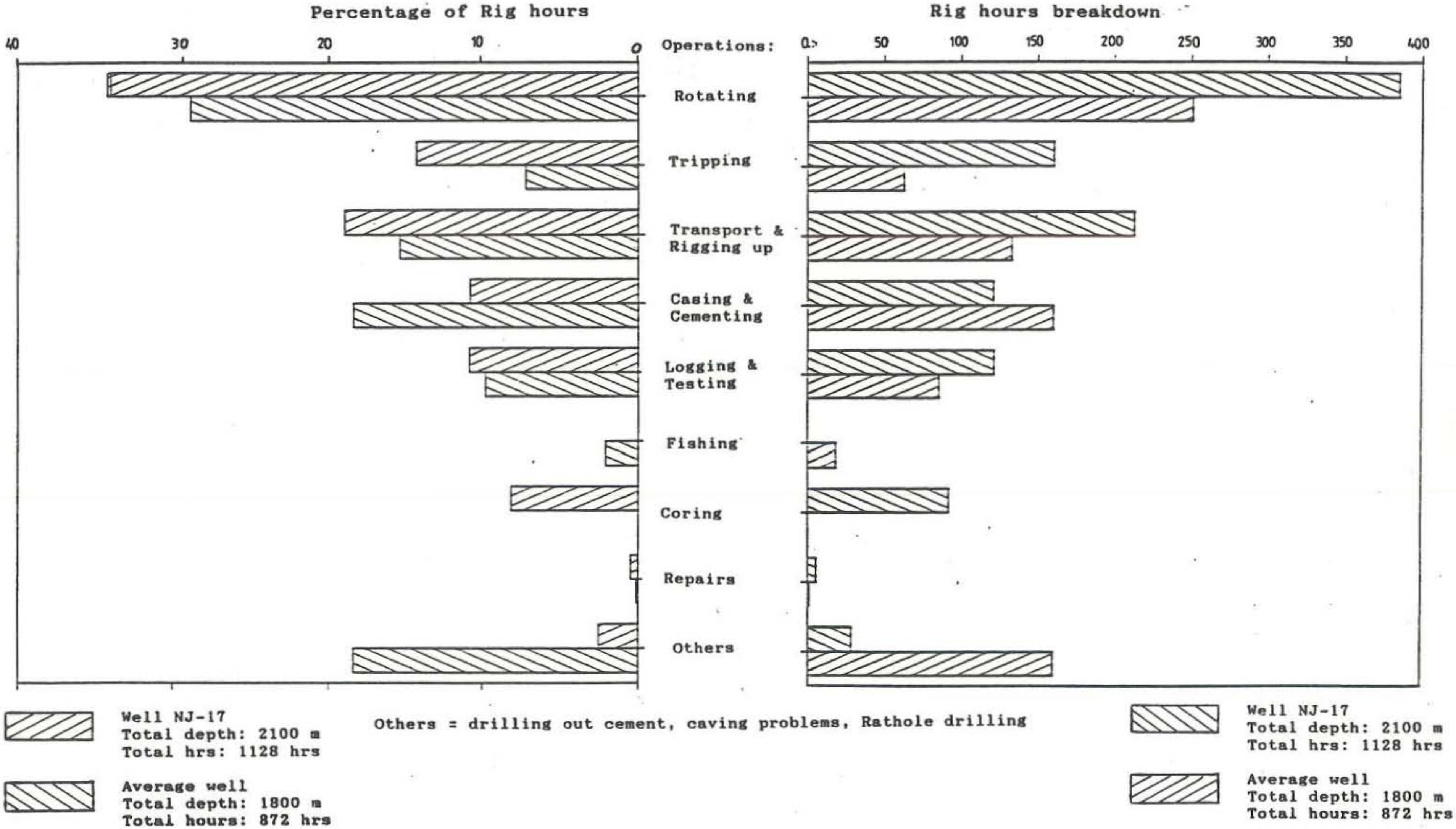


a) Slurry mixing process.



b) Bulk silo and additives tank.

Figure 14 Cementing equipment used at well NJ-17 (Teshome, 1983)



Others = drilling out cement, caving problems, Rathole drilling

Figure 15 Comparison of Rig time distribution between an average well (1800 m) in Nesjavellir and well NJ-17 (2100 m).

Appendix A: Some specifications for rig Jötunn.

RIG IDENTIFICATION: Gardener Denver

1 MAST

NOMINAL CAPACITY = 491,000 lbs
WIND RESISTANCE WITH 12,960 ft OF DRILL PIPE SET BACK = 112 mph
RACKING CAPACITY OF 5" DRILL PIPE = 12,960 ft
STATIC HOOK-LOAD CAPACITY (WITH 8 LINES STRUNG TO TRAVELLING BLOCK = 393,000 lbs.

2 CROWN BLOCK

MAKE: Lee C. Moore TD99
WEIGHT: 7,480 lbs
NO. OF SHEAVES: 5

3 TRAVELLING BLOCK

RATING: 660,000 lbs
MAKE: Gardner Denver TBJ-30
WEIGHT: 9,000 lbs
No. OF SHEAVES: 5

4) HOOK RATING: 550,000 lbs

5) SWIVEL RATING: 660,000 lbs

6)ELEVATOR LINKS RATING: 770,000 lbs

7) DRILL PIPE ELEVATORS RATING: 770,000 lbs

8) CASING ELEVATORS CAPACITY: 330,000 lbs

9) ROTARY DRILLING LINE:

Classification - IWRC
Size - 1-1/4"
Grade - Right regular lay
Center - IWRC
API breaking strength - 156,400 lbs
Safety factor - 3.18
No. of lines - 8