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HIGH TEMPERATURE GEOTHERMAL DRILLING AND COMPLETION IN ICELAND

Tang Song-ran

UNU Geothermal Training Programme, Iceland
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Tang Song- ran*
UNU Geothermal Training Programme,
National Energy Authority,
Grensásvegur 9, 108 Reykjavík, Iceland

*Permanent address:
Institute of Exploration Techniques,
Ministry of Geology,
Bei Wan Chaung 26, Beijing,
People's Republic of China.

ABSTRACT

Geothermal drilling and completion practices in Iceland are described as observed by the author during drilling operations in the Krafla geothermal field, one of the high temperature fields in Iceland. A cable tool rig is used to start the geothermal wells due to the hard rock formation to save rig time of the big rotary rig. Due to the light weight on the drill bit (the short length of the drill string) the drilling progress of the rotary rig would be very slow in the hard surface formation.

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1 INTRODUCTION

1.1 Scope of work

The author was awarded a United Nations University Fellowship to attend the 1981 UNU Geothermal Training Programme at the National Energy Authority in Iceland. The training started with an introductory lecture course lasting for 4 weeks, on a wide range of topics related to geothermal energy, including geothermal energy around the world, geology, geophysics, geochemistry, borehole geology, borehole geophysics, drilling and completion, reservoir engineering and utilization of geothermal resources. The lectures provided a general background concerning most aspects of geothermal energy.

Following the lecture course the author did about 4 weeks literature survey and attended lectures on drilling and completion technology with special emphasis on casing, cementing and blowout prevention.

From June 29th to July 9th the author went on an excursion to the main geothermal fields in Iceland. In southern Iceland the State Horticultural College was visited as well as a wool washing factory, the high temperature areas of Geysir and Nesjavellir, and the Thingvellir rift zone. In western Iceland several low temperature areas were visited, and in northern Iceland the author was shown the diatomite factory which utilizes steam from the Námafjall high temperature area.

At the close of the excursion the author stayed at the drill site in the Krafla high temperature area for about 3 weeks to study drilling and the completion techniques used on site. Other drill rigs were also visited, such as a cable-tool, Failing 3000CF, Wabco 2000CF and Mayhew 1000. This report is the result of about 2 months work on the data mainly collected at the drill site in the Krafla high temperature area and a literature survey.

1.2. Geothermal drilling capacity in Iceland

Geothermal drilling has been carried out in Iceland for about 60 years and a wealth of experience has been gathered. The combined length of the wells drilled is about 400 km, and the annual production is about 54 million tons of geothermal water and 2 million tons of steam from various geothermal areas in the country (Ragnars and Benediktsson, 1981).

Five rotary drilling rigs are employed in Iceland with depth capacities ranging from 400-3600 meters. The five rigs are of the following types:

	Depth capacity
1. Jötunn (Gardner Denver 700 E)	3600 m
2. Dofri (Oilwell 52 T)	2000 m
3. Narfi (Failing 3000 CF)	1600 m
4. Glaumur (Wabco 2000 CF)	1000 m
5. Ýmir (Mayhew 1000)	400 m

Krafla is one of the high temperature fields in Iceland and drilling operations there are considered representative for the high temperature drilling in Iceland with respect to geology and the drilling and completion technology used. The author stayed at the drilling site for 3 weeks in order to learn about the drilling techniques used.

2 GEOTHERMAL DEVELOPMENT IN KRAFLA

Iceland lies astride the Mid-Atlantic Ridge. The surface expressions of the ridge are the so called neovolcanic zones where the structure is dominated by fissure swarms and central volcanoes. The Krafla central volcano is situated on one of the five distinct fissure swarms in the northeast volcanic zone in Iceland.

The Krafla central volcano developed a caldera during the last interglacial period, but since then the caldera has been almost filled with volcanic material. The caldera measures about 8 by 10 km. During a rifting episode that started in 1975 magma is believed to be stored in a magma chamber at about 3 km depth under the Krafla central volcano from where it is expelled along the fissure swarm to form dykes. The geothermal fields are located near areas where magma concentration is at shallow levels in the swarm (Stefansson, 1981; Björnsson et al., 1979).

The surface manifestations of the geothermal area cover approximately 30 km^2. This area is relatively large compared with some other known high temperature fields in Iceland. Therefore,it was initially concluded that the geothermal potential of the Krafla field was high and it was decided to build a 60 MW power station.

Production drilling started in the Krafla area in the summer of 1975 and at the same time the construction of a power station was started. The power station has two 30 MW turbine-generator units, but only one has been installed. Although 17 wells have been drilled today the power station is still operating at partial load and further drilling is needed for increased production of steam. Two rigs have been used for the drilling of the production wells which are mostly about 2000 m deep.

The subsurface rocks which predominantly are of basaltic composition can be divided into three main lithological units, the hyaloclastite formation, the lava formation and the intrusive formation. The hyaloclastite formation predominates in the uppermost 800-900 m. The underlying lava formation, which in general is highly altered, extends to a depth range of 1500-1600 below which less altered basaltic intrusives predominate. From the drilling point of view, the lithologic characters of these formations are hard but rather fragile, which means that the stability and drillability is good.

According to results of exploration, the geothermal system in Krafla consists of two separate geothermal zones (Stefansson, 1981). The shallower one, extending down to 1100 m depth, is a water-dominated system with a mean temperature of 205°C. The deeper zone ranges from about 1100-1300 m depth to at least 2200 m (which is the deepest well). This zone is boiling, i.e. the fluid in the formation is a mixture of steam, water and CO_2. The temperature in the lower zone ranges from 300°C to 350°C, and both temperature and pressure are found to be close to saturation (Stefansson, 1981). The two zones are connected by an upflow channel near the Hveragil gully east of which wells are presently being drilled, i.e. KJ-14, KJ-16 and KJ-18. Fig. 1 shows a simplified model of the Krafla geothermal field with the main flow pattern and the average temperature profile (Stefansson, 1981).

3 WELL DESIGN

3.1 Well design

The design of production wells depends on the expected flowrate, pressure and temperature of steam or water in the reservoir. For deep wells a major consideration should be given to the pressure drop from the bottom of the hole to the top. The pressure drop is inversely proportional to the diameter of the hole to the power of 3.75 and proportional to the square of the flow rate. For shallow wells a major consideration should be the surface area of the well in the producing zone, which is normally in proportion to the diameter of the well (Kunze et al, 1980). Table 1 gives the calculated relative cost of steam based on different well design and distance between wells, assuming that 50 percent of the wells are successful. In general, well design No. 2 is the most common in Iceland and the world today (Karlsson, 1981).

Fig. 2 shows a standard well design used in the Krafla geothermal field. Due to the relatively low temperature of the upper zone (Fig. 1) and to the inconvenience of the calcite depositions associated with the water from the upper zone in the field west of the Hveragil gully the upper zone is usually closed off by the production casing. Mixing steam and water from the two zones can cause deposition inside pipelines and machinery.

TABLE 1. CALCULATED COST OF STEAM BASED ON DIFFERENT WELL DESIGN

(from Karlsson, 1981).

Well design No	1		2		3		4		5	
Hole or Pipe	H	P	H	P	H	P	H	P	H	P
Surface Pipe 50-60 m	20"	16"	22"	18 5/8"	26"	22"	29"	24"	33"	28"
Protection pipe 200 m	14"	10 3/4"	17 1/2"	18 3/8"	20"	16"	22"	18 5/8"	25"	22"
Production pipe 1000 m	8 1/2"	7"	12 1/4"	9 5/8"	14 3/4"	11 3/4"	17 1/2"	13 3/8"	20"	16"
Slotted liner 2000 m	6 1/4"	5"	8 3/8"	7"	10 3/4"	8 5/8"	12 1/4"	9 5/8"	14 3/4"	11 3/4"
Distance Between Wells	190 m		250 m		285 m		295 m		315 m	
Relative steam cost	133.6%		100 %		91.1 %		94.7 %		96.0 %	

3.2 Basis of casing design

The diameters chosen for the casing design in Fig.2, depend on the well design relating to conditions of the geothermal reservoir.

The undisturbed temperature and pressure are very close to saturation in the lower production zone in Krafla. This means that bottom temperature and pressure in a well of 2000 m depth may be as high as 340°C and 145 bar respectively. At these conditions it may be difficult to design a string of casing based on the conventional requirements of keeping the casing material within the elastic limits.

Since API specifications furnish no minimum strength requirements at elevated temperatures, the ASME Boiler and Pressure Vessel Code has been used as a reference. This code defines the design stress intensity as the lowest of the following stress values (Karlsson, 1978):

a) One third of minimum tensile strength at working temperature.
b) Two thirds of minimum yield strength at working temperature.

In order to determine the stresses to which a string of casing in a steam well is subjected all the possible load combinations acting on the casing must be considered. The most critical effect seems to be caused by the combination of internal pressure and thermal expansion. Since at boiling conditions a given pressure is always accompanied by a given temperature, the maximum pressure that a pipe of a given thickness can withstand may as well be given by the corresponding temperature of the formation around the casing. This is done in Table 2 for the standard API casing (Karlsson, 1978).

TABLE 2 MAXIMUM ALLOWABLE TEMPERATURE FOR API CASING BASED ON INTERNAL PRESSURE (°C)

Casing size	Weight lbs/ft	H-40	J-55	C-75	N-80	P-110
9 - 5/8"	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
13 - 3/8"	48.0	261				
	54.5		288			
	61.0		298			
	68.0		306	322		
	72.0			327	331	>340

If the temperature through the pipe wall is assumed to be constant and expansion of the pipe in the axial direction is prevented altogether, the maximum allowable temperature as prescribed by the Code is given in Table 3. If the formation surrounding the casing in the well allows an axial expansion of 20 percent of stress free expansion the allowable maximum temperature is considerably higher as shown also in Table 3 (Karlsson, 1978).

TABLE 3 MAXIMUM ALLOWABLE TEMPERATURE FOR API CASING BASED ON AXIAL EXPANSION (°C)

Axial expansion	H-40	J-55	C-75	N-80	P-110
None	222	270	320	340	>340
20%	262	312	>340	>340	>340

According to the ASME Code the range of stress intensity allowed for screwed pipe joints is only one third to a half of that allowed for integral pipe. For this reason it could be expected that cyclic thermal loads may cause failure of screwed casing joints. It is therefore a good practice to use API Buttress type threaded coupling which have a higher strength than ordinary threads as shown in Table 4 (Cigni et al., 1981).

TABLE 4 SPECIFICATION AND PERFORMANCE PROPERTIES OF CASING

Casing size	Weight	Wall thickness	Joint strengths			Pipe yield strength	Axial therm. loading for T=200°C
			API Short	API Long	Buttress		
(Inch)	(lbs/ft)	(mm)	(tons)	(tons)	(tons)	(tons)	(tons)
$13^{3}/8$	48	8.38	220	-	377	320	436
J55API	54.5	9.65	247	-	504	387	500
	61	10.92	281	-	568	436	564
$9^{5}/8$	68	12.19	315	-	632	485	628
J55API	36	8.94	191	210	347	256	330
	40	10.03	216	236	388	286	370

To prevent caving in the hole during steam production a slotted liner is necessary. This liner is usually hung inside the lower end of the production casing and extends to the bottom. The total area of slots per m of the slotted liner in the geothermal well is at least equal to the cross sectional area of the pipe (Karlsson, 1981). For example the slotted liner used in KJ-17 in Krafla is 7 5/8 inches in diameter. The slots are cut with an acetylene/oxygen burner. They are 70 to 75 by

20 to 25 mm, spaced in circles of four slots. There are five such rows on each meter of pipe. The slots per meter add up to an area that is 1.2 to 1.5 times the cross section of the casing.

The casing must reach a depth where the formation (or pore) pressure below the casing is greater than the corresponding pressure in the well. The pressure variation in closed wells of various depths is shown in Fig. 3. The intersection between the formation pressure line and the well pressure curve represents the minimum casing depth. It is also seen from Fig. 3 that wellhead pressures estimated by this method are on the order of 60 percent of the well bottom pressure (Karlsson, 1978).

The results described above together with Table 2 are applied to determine casing grade and weight or wall thickness for different depths and the necessary pressure rating of the wellhead equipment. Table 5 gives casing and wellhead pressure rating as a function of total depth (Karlsson,1978).

TABLE 5 CASING AND WELL HEAD PRESSURE RATING AS A FUNCTION OF TOTAL WELL DEPTH

<table>
<tr><th></th><th></th><th colspan="10">Well depth (m)
0 800 1600 2400 3200</th></tr>
<tr><td rowspan="4">Casing</td><td rowspan="2">$9^5/8$"</td><td colspan="3">H-40</td><td colspan="3">J-55</td><td colspan="4">N-80</td></tr>
<tr><td colspan="2">32.3(lbs/ft) 7.92 mm</td><td colspan="3">36.0 8.94</td><td colspan="3">40.0 10.03</td><td colspan="2">43.5 11.05</td></tr>
<tr><td rowspan="2">$13^3/8$"</td><td colspan="10">H-40</td></tr>
<tr><td colspan="10">48.0 lbs/ft 8.38 mm</td></tr>
<tr><td rowspan="2">Well head</td><td>$9^5/8$"</td><td>ASA 300 (PSI)</td><td colspan="3">ASA 400</td><td colspan="3">ASA 600</td><td colspan="2">ASA 900</td><td>ASA 1500</td></tr>
<tr><td>$13^3/8$"</td><td colspan="10">ASA 300</td></tr>
</table>

4 DRILLING

4.1 Cable- tool drilling

It is a common practice in Iceland to use a cable-tool rig with a heavy percussion bit to drill through the surface formation to about 50 to 60 m depth when starting a new well.

The advantage of using the cable-tool drill rig is that it is comparatively inexpensive, easy to move and can be operated by two men. In addition, it does not use circulation water, and power is generated by a relatively small diesel engine. The cost is lower than by applying a rotary bit.

The preparation work of a drill site consists of installing and cementing the surface casing, levelling the drill site and preparing the foundation for the rig. The foundation is commonly on the order of 45 by 50 m, and it has a 3.5 m deep cellar of concrete around the hole at the center of the site. Fig. 4 gives the dimensions of the drill site and the concrete cellar of KJ-18. By using the percussion drilling to start a well, it is possible to save about a week or more time for the big rig, and the rotary rig can use 40-50 m of drill collars when starting to drill. This will supply enough bit weight to give acceptable penetration rate from the beginning.

By cable-tool drilling it is possible to drive the casing behind the drill tool to eliminate caving of the hole and loss of circulation as well as preventing serious problems for the rotary rig that can not drive the casing and drill at the same time. Other types of drill rigs such as the truck mounted rotary rigs could also be used instead of the percussion rigs by using hammer drill and air compressor to drill through the surface layers.

The percussion rig in Iceland is used to run and cement the surface casing. This is done before the cellar is built and the drill site is then made ready for the rotary rig to move in.

4.2 Rotary drilling

To explain the rotary drilling technique we can take as an example the rig Jötunn which is used in Krafla.

Specifications:

Type- Gardner Denver 700E.
Capacity- 12-14,000 ft with 5" drill pipes.
Diesel/Electric - SCR unit from Ross-Hiss Corp. Total output 1500 KW.
Derrick- Lee C. Moore 131 ft high, retractable mast.
Hook load capacity - 393,000 lbs with 8 lines on travelling block.
Drawworks-Gardner Denver 700E with 750 Hp electric motor.
Rotary table - Gardner Denver 22 1/2" with 750 Hp electric motor.
Swivel - Gardner Denver SW-30-300 tons.
Mud pumps - 2 Gardner Denver PZ-8. Triplex-pumps each with 750 Hp. motor.
Drill pipes - 12,000 ft 5"x19.50 lbs/ft grade E.
Drill collars - 10"(2), 7"-7 1/4" (20)
Blowout preventers:
  two Cameron 12" Type QRC series 900 with hydraulically operated rams.
  one Hydril Gk-12" ser. 900 Annular BOP.
  one Grant-12" ser. 900 Rotating drilling head.

The rig was made in U.S.A. 1972. It was purchased in 1976 and has until now drilled 18 wells in Iceland. The total depth is 32650 m. Fig. 5 shows the progress chart of three wells completed recently. The net drilling time, for most of the wells, is 26 - 35 % of total time. Penetration rate and life of rock bits is listed in Table 6, based on data from 12 bits that have drilled a total of 11.050 m.

TABLE 6 DATA ON BITS USED IN KRAFLA AREA

Bit size		Footage drilled by bit		Life	Drilling
	No.	Average	Highest	of bit	Rate
Inches	of bits	m	m	hours	m/h
$17^1/2$	3	406	483	96.3	4.22
$12^1/2$	4	1075	1195	137.8	7.80
$8^1/2$	5	1106	1392	145.6	7.60

The common weight on the bit at Jötunn is set at about 1 ton per inch of diameter, i.e. 10 to 12 tons are maintained on the 12 1/4" bit and 8 to 9 tons on the 8 1/2" bit. At the same time the flow rate of the mud pump is set to maintain an annular velocity in the hole of about 1 m/s and the próper speed selected for the rotary table (55 to 60 RPM). The penetration rate can be kept rather high (see Table 6), while the deviation of the well may also be monitored at closely spaced depth intervals. As an example it is only 0.2° from vertical from the surface to a depth of 1250 m in KJ-17.

The most common drilling procedure and well design is the following: A 17 1/2" bit is used from the base of the cable-tool hole (50-60 m) to a depth of about 200 to 300 m and then a 12 1/4" bit down to 700 to 1000 m. Correspondingly, a 13 3/8" and 9 5/8" casings are run and cemented. Finally, an 8 1/2" bit is employed for drilling down to a final depth around 2000 m. The depth of the well depends on the expected temperature and pressure, the casing program and drilling condition. The production part of the well is then cased with a 7" or 7 5/8" slotted liner which usually hangs inside the 9 5/8" casing using a liner hanger of suitable design and reaches to the bottom.

Following circulation stops, e.g. due to delays or cementing, temperature logs are frequently run, mainly because the lubricator sealing rings used in the sealed bearing drill bits cannot stand higher temperature than 120 to 130°C. If the well can not be cooled by cold water injections, the temperature log will show how deep into the well it is safe to sink the drill bit before it is necessary to break out drill stands and to start cold water circulation to protect the drill bit (Stefánsson and Steingrímsson, 1980).

Various logging techniques provide very useful information for drilling work such as locating zones of lost circulation or water entry, well diameter and direction, inspection of casing and estimating the quality of cement. Since BOP (Blowout Prevention) valves can not be applied for one or two days during the running of casing or liner into a well, there is a potential blowout risk. However, the logging can evaluate the risk of blowout. Some of the results which the logging provides will be quoted later (Stefánsson and Steingrímsson, 1980).

5 DRILLING FLUIDS

5.1 Flushing fluid

Fresh water is commonly used in drilling for geothermal water and steam in Iceland (Jónsson, 1975). The advantages of using water are considered to be the following:

1. Water is cheaper drilling fluid than other types such as mund, air or foam. There is no native clay in the country and imported bentonite is very expensive. Water sources are in most cases easily available in Iceland.
2. Most of the formations drilled are stable enough to allow fresh water flushing.
3. Water does not plug or seal off production zones as mud may do. Lost circulation will cool down the formation and increase the permeability. Cuttings that are washed into the formation can usually be flushed out.
4. Water can be used for flushing after drilling to increase the productivity of steam and water from the hole. This water injection technique can open up every part of the hole if there are some fissures existing in the formation, but this is not a real fracturing (Tómasson and Thorsteinsson, 1975).

Use of drilling mud may be necessary when drilling shallow layers where the hole diameter is large and the formation is loose with a tendency to cave in as well as when drilling into formation of high static pressure or temperature above the boiling point. This can happen when drilling in a deep valley with high water level. Sometimes, lost circulation materials such as fibrous, bulky and flaky materials are used to control the leakage of the hole.

After setting the production casing, i.e. during drilling into the production zone, use of drilling mud may affect the reservoir. In recent years considerable research has been done on how permeability near the wellbore is impaired in the matrix type hot water reservoirs due to drilling fluid filtrate and particle invasion. In a recent study of drilling fluid and formation interaction (Enniss et al., 1980) it was found that the permeability of the formation (sample) under simulated geothermal well conditions using a high temperature mud made with bentonite, sepiolite, brown coal and KCl polymer, is reduced to 25% of initial porosity at 100°C for 48 hours, and to 50% of initial at 200°C for the same time (see Fig.6). It is a possibility that calcium montmorrillonites can form a low grade cement in the 150°C temperature range. The montmorrilonitic particles which have invaded the rock matrix near the well will continue to consolidate with time (Enniss et al., 1980). This indicates that it is advisable to eliminate the influence of mud on the reservoir during penetration into the production zone.

5.2 Lost circulation and air-water system

Lost circulation during drilling and cementing in geothermal wells is a problem common to most geothermal areas, and the Krafla area is no exception.

The Krafla area lies within a fissure swarm which means that there are numerous dykes and fractures in the formation. The water level in wells is generally more than 100 m below surface, i.e. the pore pressure is sub-normal pressure with lower than normal pressure gradient ($<0,1\ kg/cm^2/m$). The result of this combination can cause difficulties in circulation of fresh water. Lost circulation in the upper zones tends to occur more frequently than in the lower zone. For example, lost circulation during the drilling of KJ-17 amounted to 40 l/s before the 13 3/8 inch casing was cemented but only about 12 to 15 l/s after cementing the casing. The water for circultation, about 30 l/s, had to be supplied to the drill site by two stages of pumps. The first stage was powered by 100 KW electric motor and the second stage by a 105 HP diesel engine. The two pumping stages were necessary because of the elevation difference between the water supply and the drill site.

The use of water instead of mud circulation to carry cuttings to the surface calls for higher annular velocity and more pump capacity. When the upward flow rate in the hole is decreased due to loss of circulation, the cuttings concentration in the hole tends to increase. This creates a hazard as the cuttings will sink down the hole and around the drill collars if the pump stops. This can easily result in a stuck drill string and a difficult fishing job.

By using air or aerated water drilling it is possible to reduce the circulation losses. Penetration rate can also be increased. The experience of a Mayhew 1000 drill rig fitted with an air compressor in Iceland proved to be highly effective.

A balanced air-water system has been used successfully in New Mexico and California, USA (Pye, 1981). In Krafla it might prove effective in eliminating lost circulation. This would, however, call for an effective blowout prevention because the very high temperature would build up high pressure at the wellhead.

The normal practice in air-water drilling is to use the full capacity of either one or two compressors, and then adjust the air-water ratio by increasing or decreasing the fluid pump rate. This is the easiest method of operation for the driller. In general, the compressor used has a rated capacity of about 31-34 m^3/min. Air-water volume ratios vary significantly, but 60:1 is probably a good starting guess. The driller must then adjust this ratio up or down based on how the well performs. If it is difficult to keep the well circulation steady the air-water ratio has to be increased (decrease the water pump rate), and if circulation becomes too violent, the ratio will be decreased (increased pump rate). Drilling deeper and encountering productive fractures, or if hot formation fluid enters the hole, a part of this fluid flashes to steam, which usually will increase the air-water ratio in the annulus. The inlet air-water ratio must then be decreased to counteract the increased flow that occurs in the annulus due to the produced fluid (Pye, 1981).

Jet subs have been used successfully in air-water drilling systems. The jet sub is a bit jet nozzle mounted in a drill pipe sub which allows part of the air and water to exit some distance above the bit to make it easier to establish circulation. They are usually placed about 150 m below the fluid level. The presence of the jet sub then helps to lift this 150 m column of water and establish circulation (Pye, 1981).

6 CEMENTING

The success of a production well depends to a large extent on whether the cementing of casing is a success or failure, which includes the selection of the proper composition of cement and cementing method.

6.1 Cementing materials

Selecting the cementing composition without regard to the conditions prevailing in the well often leads to failure. Some cementing compositions may show a satisfactory compressive strength when first set, but will begin rapidly to lose strength when continuously exposed to high well temperatures. As the compressive strength decreases cement permeability will increase until the cement column may no longer prevent communication or flow of thermal water between zones (Shryock and Smith, 1981).

Cements showing strength retrogression have been found to contain two hydration products, calcium hydroxide and di-calcium silicate alpha-hydrate. These products appear together and sometimes singularly, depending on temperature and time. This begins at temperature of 110°C and accelerates as temperature increases. The process of using silica flour in concentration of 30 to 80 percent by weight of the cement has provided means of overcoming this. When silica flour is added to the cement, a portion of it reacts with the calcium hydroxide to form di-calcium silicate alpha-hydrate. The remaining silica reacts with the alpha-hydrates to form tobermorite. Tobermorite has a better cementing phase than alpha-hydrated di-calcium silicate and therefore brings about the desired improvement for resistance in high temperature wells (Shyrock and Smith, 1981) .

The mixing of various cementing compositions based on desired conditions may be done with the equipment at the drill site. The mixing method is to employ a compressor which blows the proportioning cementing materials from one storage tank to another, and then they are blown between the tanks until full mixing is achieved. It is not uncommon that blowing back and forth three times is necessary.

The proportion between cement materials varies with different well conditions. The following list gives the range of the compositions used in Iceland.

APi Class G Cement	100 kg
Silica Flour	35-40 kg
Perlite	4-5 kg
Bentonite	2 kg
Retarder	0.4-0.5 kg

6.2 Cementing method - Stab-in

The socalled Stab-in cementing is done through the drilling string that stabs into duplex shoes and collar sizes 7 5/8 to 30 inch that are furnished with heavy duty connections, to provide greater liner carrying capacity. Fig. 7 shows four different types of the method which suits various conditions (Composite Catalog, 1978).

The advantages of the STAB-IN method compared with conventional cementing are that the cement is pumped down through the drill pipe, no plug is required which results in even less contamination and greater displacement accuracy. A minimal drill-out is required. In addition, cement mixing can be terminated at any time, and cementing pressures are confined to the drill pipe to protect the casing.

Fig. 8 shows the heavy duty duplex connections which have 4 inch OD left hand square threads and 3 1/2 inch ID seal bores, and are capable of carrying 45 tons with a minimum safety factor of 2. Tubing seal nipple or STAB-IN sub has field-proven chevron seals for positive sealing of the nipple in the seal bore. It also features an expandable left hand latch mechanism which allows the nipple to be "stabbed" into the duplex connection. The nipple is released by rotating to the right unscrewing the latch mechanism from the duplex connection (Composite Catalog, 1978).

The method was orginally used to cement a large diameter well. It seems now that it is employed extensively for cementing in deep geothermal wells such as in Italy and Iceland (Cigni et al., 1981).

6.3 Stab-in cementing example and problems

Although this method of cementing is widely utilized, problems may be encountered when all factors in the hole system to be cemented are not properly accounted for. There were some problems for example during cementing of the 9 5/8 inch casing in wells KJ-15, KJ-16 and KJ-17. After the first cementing in well KJ-17 the position of the cement level in the annulus was established by logging. The casing was then perforated and cemented again to compensate. Obviously, the second or subsequent cementing jobs can no longer be carried out by the Stab-in cementing method. Undoubtedly, this procedure will consume large amounts of cement and time. Fig. 9 shows that the 9 5/8" casing needed three separate cementing jobs before the annulus was properly cemented.

According to the cementing programme calculation 47 tons of API class G cement mix were needed. The reason for the first failure was early set of the cement. The surface line suddenly broke when the pressure of the pump increased rapidly. The second cementing job was a failure because the cement slurry failed to return to surface when the slurry was pumped down. The position of the top of the cement bond had been found by logging. It can be seen from Fig. 9 that the total length of the three drillouts are 177 M not counting the necessary section below the Stab-in sub. In other words, the volume of the setting cement in the pipe is 6,9 m^3 and assuming a specific gravity of the cement set of 1.82 g/cm^3, the cement mix in the pipe is nearly 14 tons in addition to the waste in the drill pipe and the amount lost due to the burst surface line during the first cement job.

It is of importance to find out the reason for these failures. The first failure may be due to flash setting. There will be a rapid initial set of the cement slurry when it is contaminated by $CaCl_2$. There may have been water loss in the cement mix due to wrong type of perlite in the blend (milled perlite). The most likely reason for the failure is that 4.000 litres of a 10 percent $CaCl_2$ solution was used as a preflushing fluid. If there is any water and water glass isolated between the solution and the slurry, the partial mixing of the slurry and the solution somewhere in the annulus is unavoidable. A $CaCl_2$ content of 1 to 3 percent or even less in the slurry under high temperature conditions will lead to flash setting of the slurry. This well lead to the annulus becoming blocked, the pressure of the pump is increased which in turn leads to the bursting of the line and the cementing has to be stopped.

It appears that the predetermined excess volume factor of 2 in the hole was correct. The results obtained with the caliper log indicated that the diameter of the upper section of the well was somewhat larger than that of the lower section curves of D.H. in Fig. 9. What may then be the reason for the second cementing failure? The quantity of the cement set inside the pipe and in the annulus corresponds to a quantity of cement put into the hole. Indications are that there was not an excessive leakage in this section of the hole, and the slurry had already entered into the annular space between the two casings. The slurry must have run back into the casing due to the higher hydrostatic head in the annulus than in the pipe with the result that the length of the drill-out was close to 100 m. If the cement had been increased by a few tons, and the cement head had been sealed securely the cementing job would have been a success.

To avoid the flash setting of the cement it is important to change from $CaCl_2$ solution to another type or to employ only water glass (sodium silicate) with some lost circulation materials for the preflushing fluid. This should be sufficient since the aim of this preflushing is to reduce lost circulation. A simulated test in the laboratory should be conducted.

7 BLOWOUT PREVENTION

The aquifers or reservoirs in the Krafla area are usually below 700 m and the water level is always below 100 m so it might seem that a blowout is not very likely. However, it should be born in mind that the lower zone below 1100 m is boiling. The temperature in this lower zone ranges from 300°C to 350°C and both temperature and pressure is close to saturation. Under these conditions blowout may occur when drilling is delayed or stopped for a long time. In addition the tectonic activities consisting of volcanic eruptions, earthquakes and cyclic rise and subsidence of the ground has caused serious trouble and damaged some of the wells to the extent that they are unusable. The most serious case occurred in well KJ-4 in 1975, the wellhead of which consisted of a Regan annular preventer, two 12" rams (blind and pipe), and a gate valve rated at ASA series 300. The depth of hole was 1978 m and the 9 5/8 inch casing had been set to a depth of 593 m before any trouble was encoutered. A lost circulation zone was encountered at about 700 m depth. When the well head pressure had increased to 34-38 kg/cm^2 60 m^3 of weighted mud with specific gravity of 2.4 was prepared and used to kill the well for about 20 minutes. In less than half a minute after the pump was stopped a violent blowout occurred which the wellhead equipment was not capable of controlling fully. The equipment was removed from the well and preparations started to gain control over the well. Before anything could be done, however, the well blew off the gate valve. The flow rate of the hole was 150-200 l/s with a pH of the hot water of 2-4 and soon the upper portion of the casing was corroded and disintegrated forming a crater of 60-70 m in diameter and a depth of 10 - 15 m. Within a year the blowout had run its course and stopped by itself, probably because of calcite precipitation in the collapsed well.

This example points out the necessity of quality wellhead equipment. Fig.10 shows the prevention equipment used in the Krafla area today. The equipment consists of two 12" gate valves rated at 900 psi pressure a set of blowout preventers (see section 4.2 Rotary drilling) with a total height of about 7 m.

It is very important to have enough cold water near the drill site to make it possible to cool the rubber in the blowout preventers, because the rubber is normally not guaranteed to withstand more than 120-130°C.

Every effort should therefore be made to prevent accidental blowouts such as by a correct selection of drill site and by sufficient cooling during the drilling operation.

Types of Blowout preventers:

a) Ram type blowout preventers

The most common type of blowout preventer is the ram type.
It has two rams closing against each other not unlike two gate walve plates.
There are different sets of rams used to close around different diameters of drill pipes and collars, and a set of blind rams to close the hole completely if there is no drill string in the hole. Previously blowout preventers were manually or mechanically operated but most new models are hydraulically operated. The new models are also designed to make it possible to change the rams without removing the blowout preventer from the wellhead.

b) Annular blowout preventers

The annular blowout preventer is hydraulically operated. It has a rubber ring of special design molded around steel segments. The ring is pressed inwards by a conical sleeve actuated by a hydraulic piston. This rubber ring can close around any diameter of drill pipe, drill collar or around the kelly, both a hexagonal and a square kelly. This blowout preventer can also be used to strip the drill string out of the hole under pressure.
If the temperature gets too high, more than 120-130°C, it may be necessary to cool the rubber because it is not designed for temperature over 130°C.
The annular type blowout preventer is well suited for drilling in low temperature areas where steam blowout is not expected to occur.

c) Rotating blowout preventer

The rotating blowout preventer is designed to seal around the kelly during the drilling operation. It can be used for drilling in areas susceptible to kicks or blowouts, drilling under pressure, drilling with reverse circulation and circulating with air or gas. The upper part rotates with the kelly. The cylindrical rubber is mounted in the rotating part and rotates with the kelly.

The rotating blowout preventer is also used as a stripper to pull out the drill string from the hole under pressure or from a blowing steam well. The rubber can not withstand very high temperature and must therefore be cooled with water when pulling out of blowing steam wells. The hydraulically operated blowout preventer is normally controlled from the driller control panel at the rig floor as well as from the ground.

8 CONCLUSIONS

The author has found that there is much to be learned from Icelandic experience in high temperature geothermal drilling and well completion. Among the points to which he would especially like to call attention are the following:

1. A cable-tool rig is used to start new holes. It is well equipped to penetrate through hard basaltic caprock which is a common formation in geothermal fields. The cable tool drilling also saves cost and time.

2. The maintenance work of the rotary rigs is of great importance to guarantee smooth and successful operation. For example, lost time due to repair work caused by mechanical failures of Jötunn is very little and the repair time has been on the order of about 1-2% of total operation time since 1976.

3. Cooling of the bit during delays in drilling through the reservoir will protect the bit and extend bit life.

4. The mixing of cementing composition at the drill site is of great importance and the use of Stab-in cementing is worthy of consideration for similar types of geothermal fields.

5. The use of water as drilling fluid is characteristic for Icelandic geothermal drilling, resulting in considerable savings in drilling costs.

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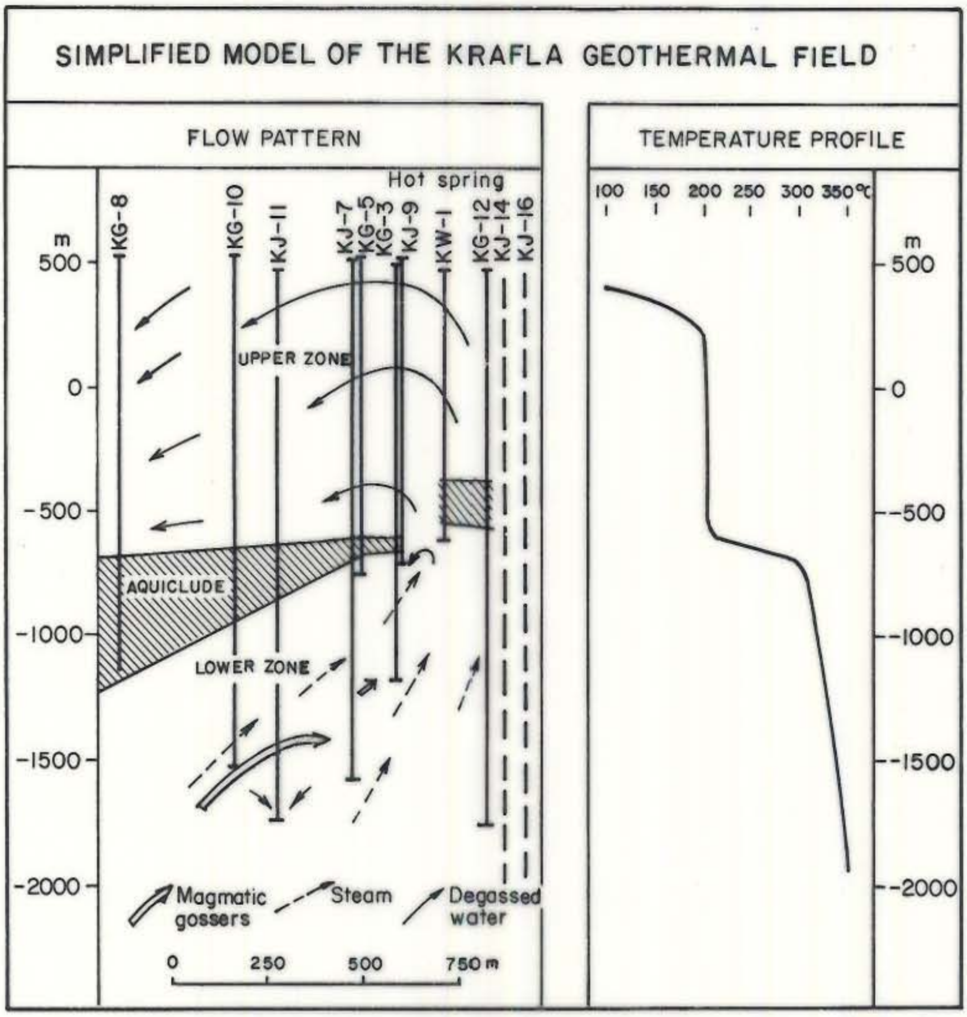

Fig. 1 Simplified model of the Krafla geothermal field showing the main flow pattern and the average temperature profile of the field.
(Stefánsson 1981)

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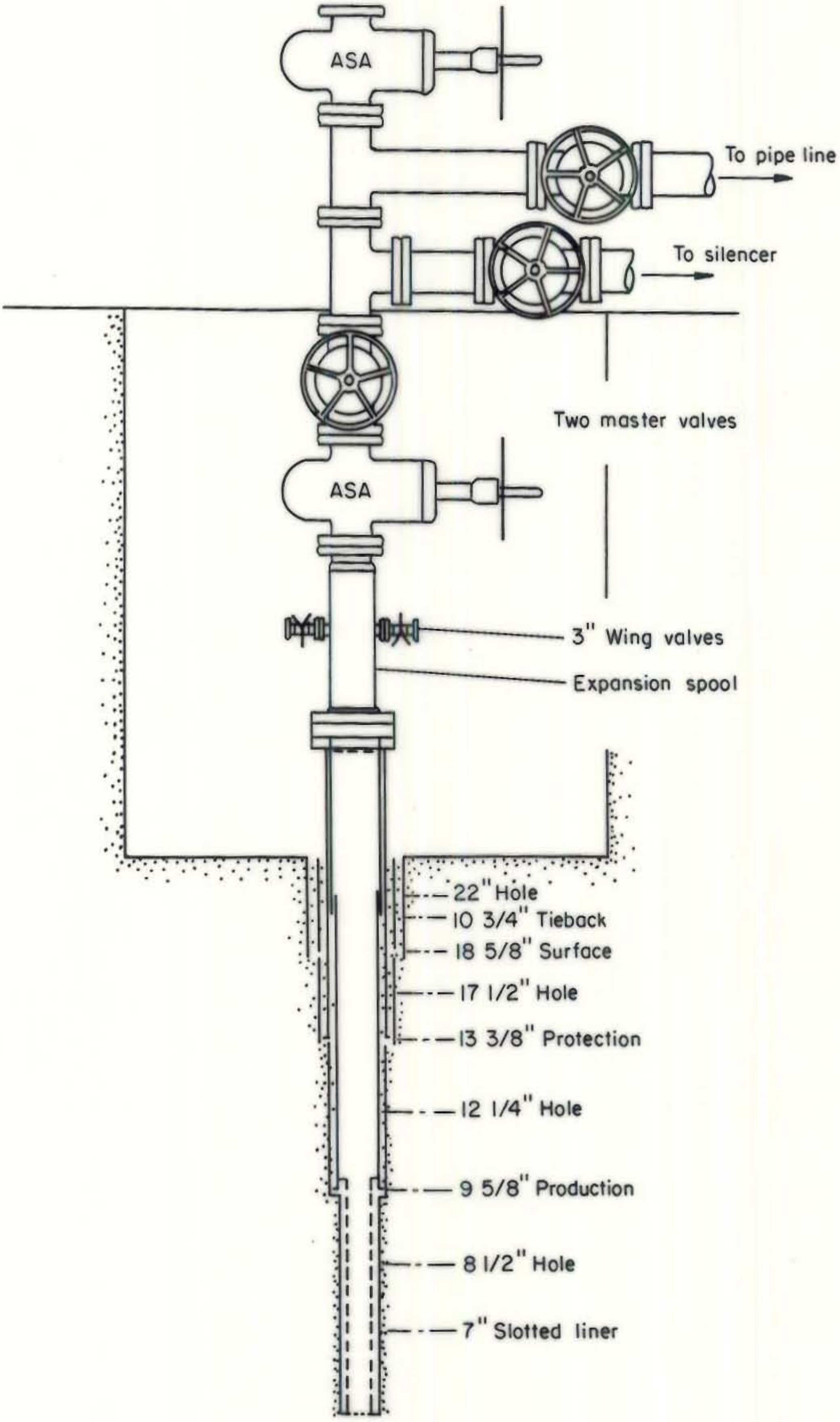
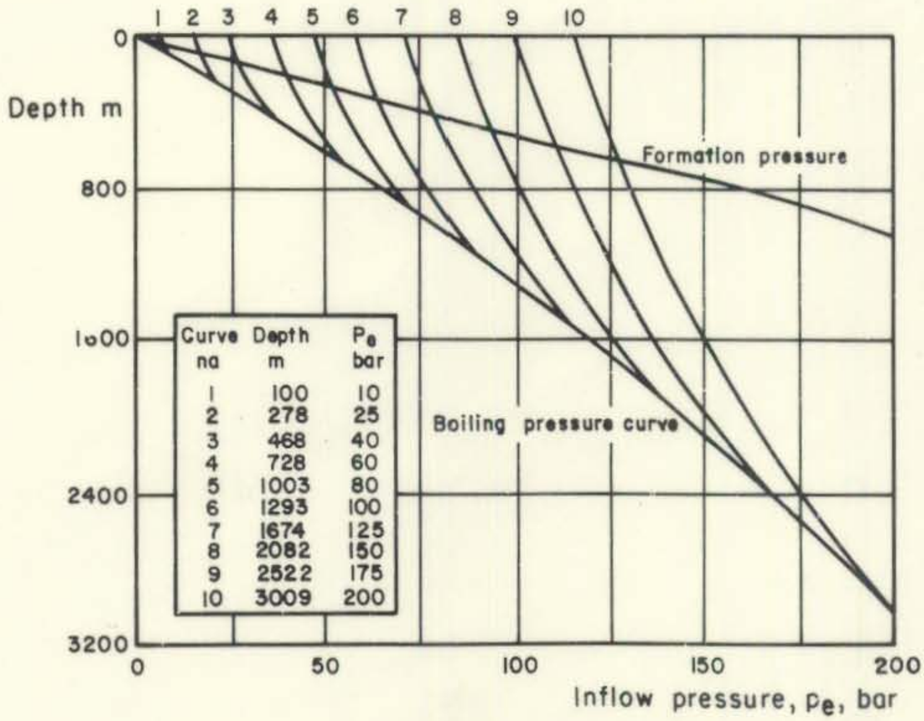


Fig. 2 SCHEMATIC DIAGRAM OF KRAFLA COMPLETION



Curve no	Depth m	P_e bar
1	100	10
2	278	25
3	468	40
4	728	60
5	1003	80
6	1293	100
7	1674	125
8	2082	150
9	2522	175
10	3009	200

Fig. 3 Pressure variation in shut-in wells (from Karlsson, 1978).

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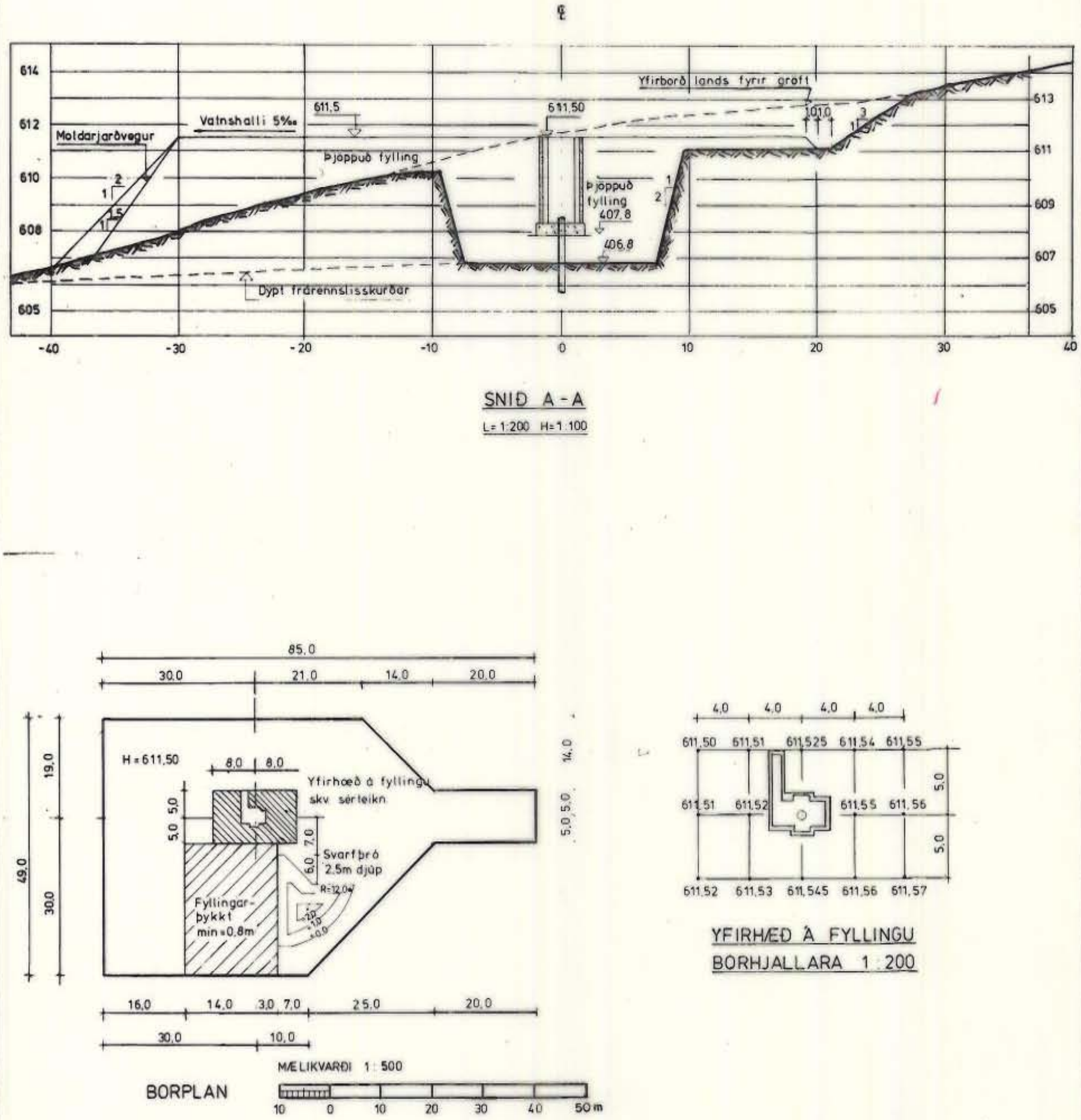

SNIÐ A-A
L=1:200 H=1:100

BORPLAN

YFIRHÆÐ Á FYLLINGU
BORHJALLARA 1:200

Section A-A
L=1:200 H=1:100

Fig. 4 Drill site and cellar of concrete (KJ-18)

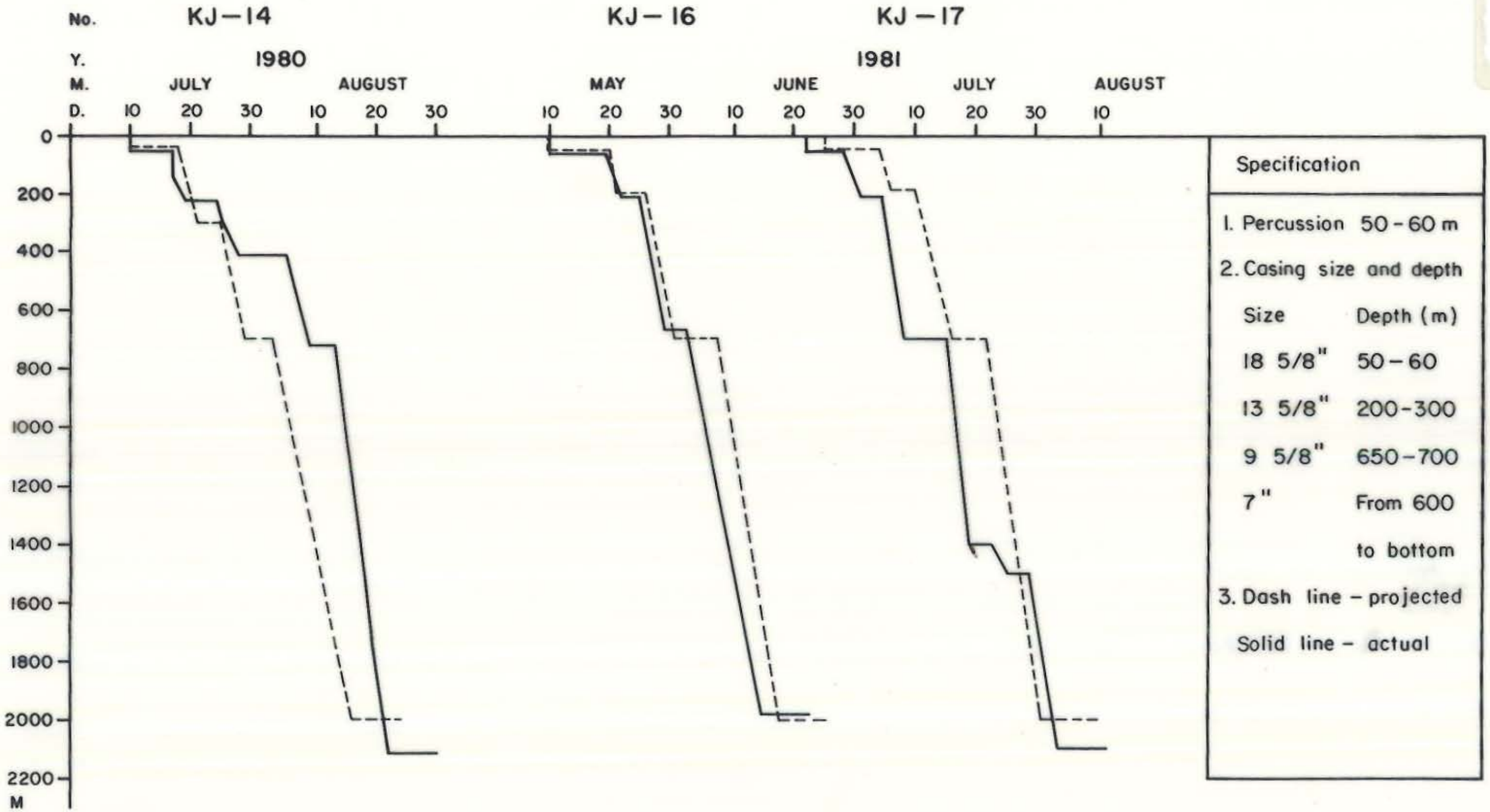

Fig. 5 PROGRESS CHART OF PRODUCTION WELL DRILLING

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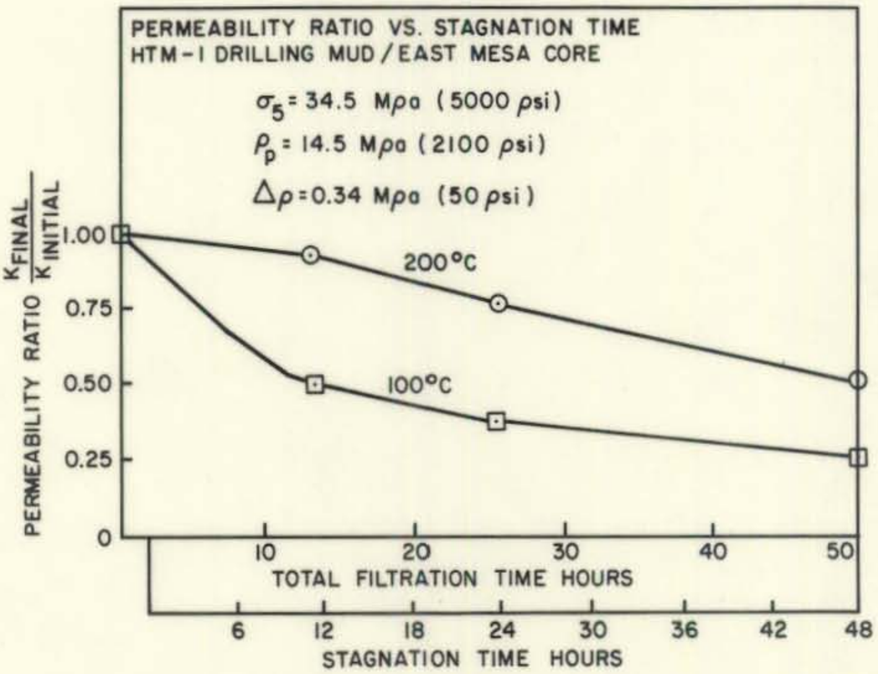

Fig. 6 Permeability ratio versus stagnation time (from Enniss et al., 1980).

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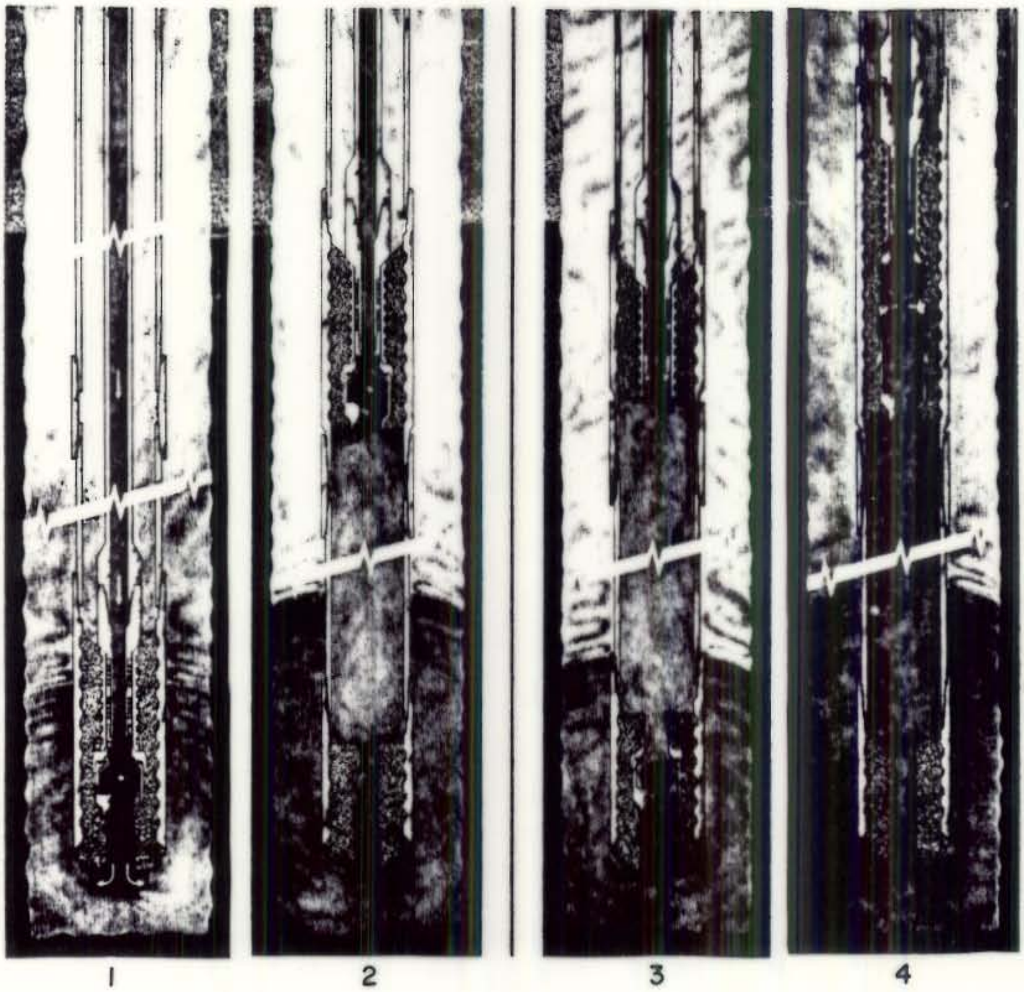

1. FLOAT SHOE--Recommended for shallow to medium depth conductor and surface casing cementing jobs where displacement volumes can be accurately controlled.
2. FLOAT COLLAR AND GUIDE SHOE--Recommended for large diameter casing cementing from shallow to deep applications where a shoe joint is needed to prevent over displacement of cement.
3. COLLAR AND FLOAT SHOE--Recommended for large diameter casing cementing from shallow to deep applications.
4. NON-CIRCULATING FLEXIFLOW FILL-UP COLLAR AND GUIDE SHOE--Recommended for applications where it is desired to provide an automatic fill feature as casing is run in the hole.

Fig. 7 Stab-in cementing (Baker)

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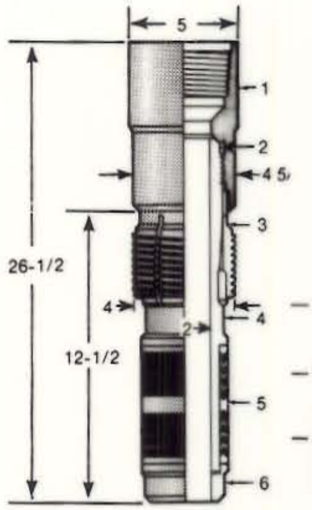
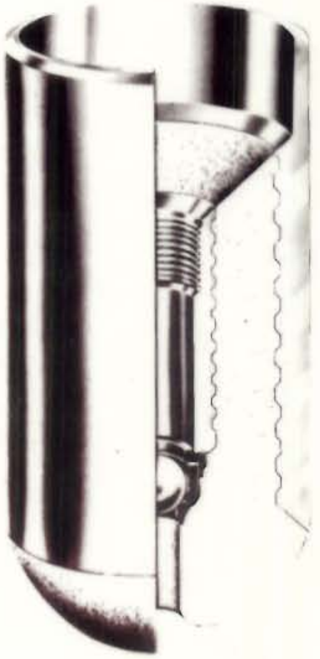
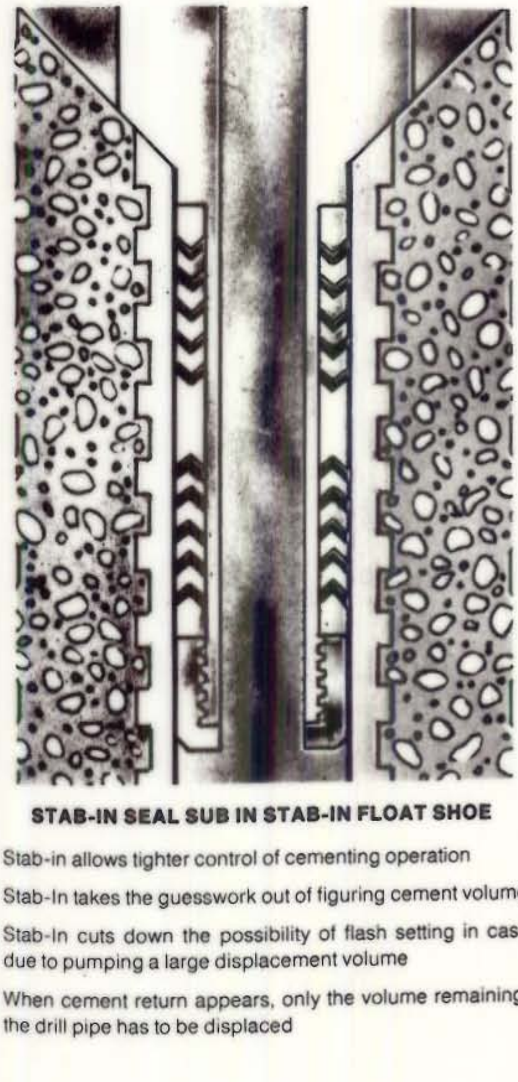


Bakerline Model "E" Duplex Tubing Seal Nipple



Duplex Cement Float Shoe, Product No. 250-03



STAB-IN SEAL SUB IN STAB-IN FLOAT SHOE

- Stab-in allows tighter control of cementing operation
- Stab-In takes the guesswork out of figuring cement volumes
- Stab-In cuts down the possibility of flash setting in casing due to pumping a large displacement volume
- When cement return appears, only the volume remaining in the drill pipe has to be displaced

Fig. 8 Heavy duty connection (Baker)

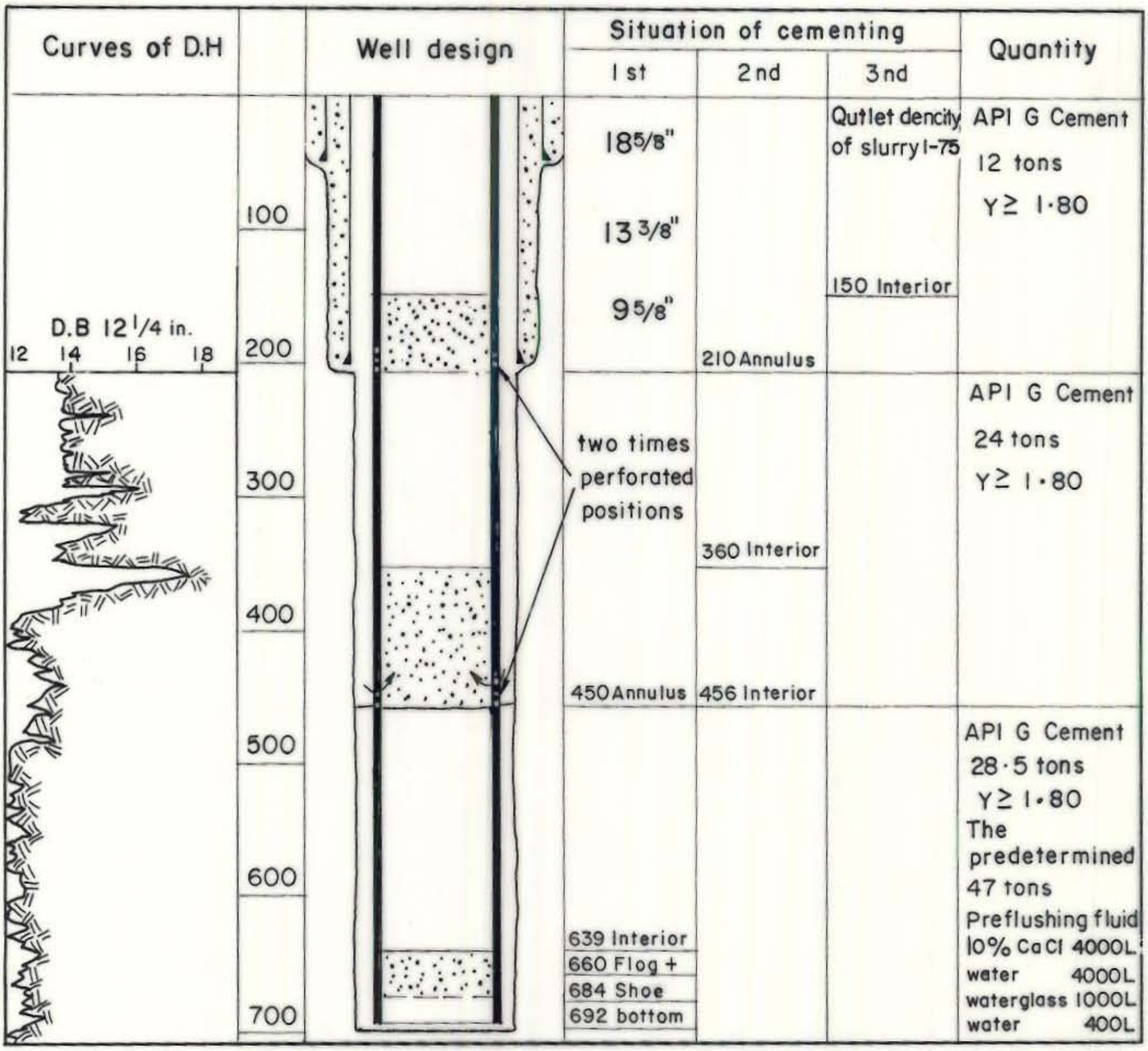


Fig. 9 Cementing situation in KJ-17 (from Jötunn)

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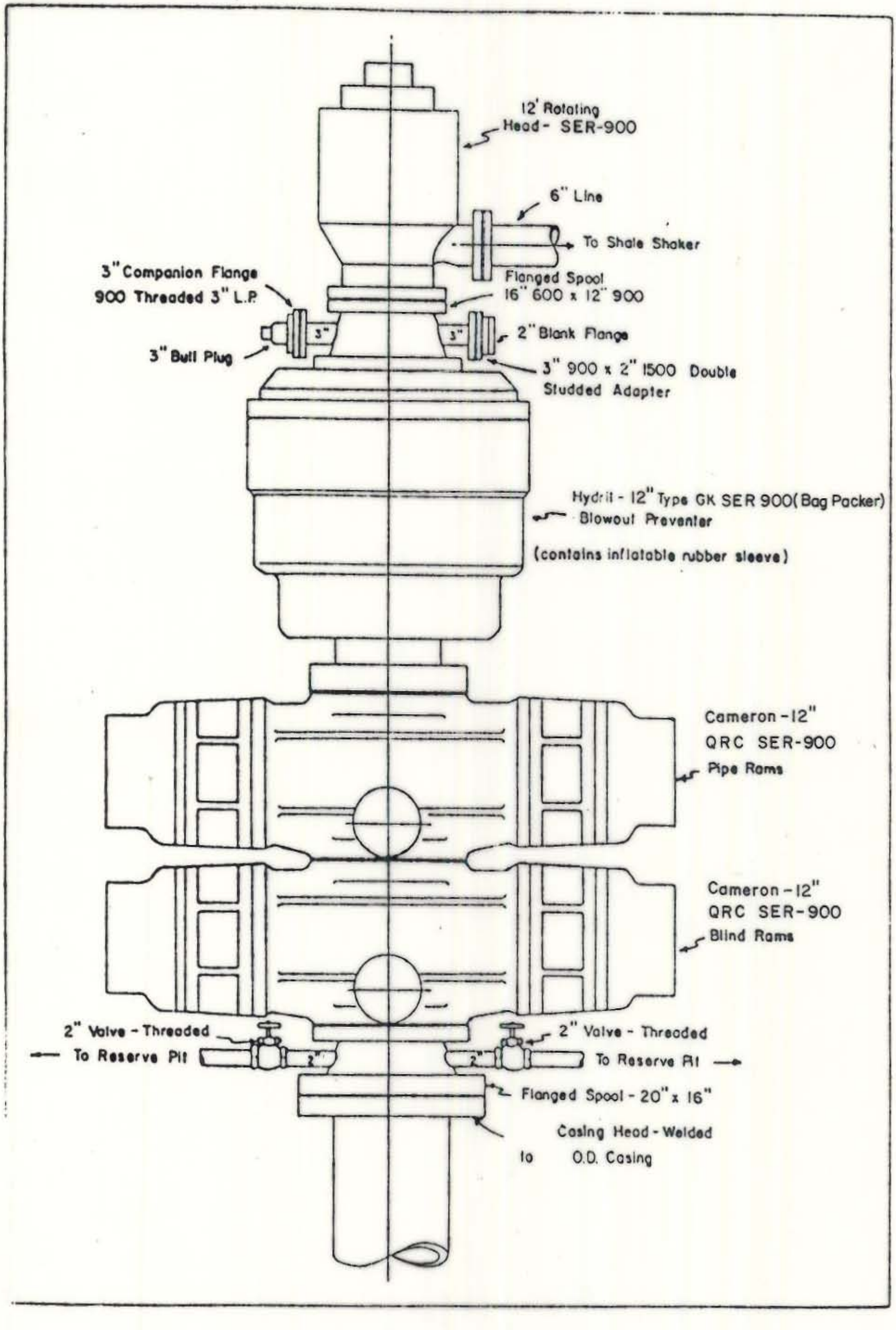

Fig. 10 Blowout preventers used in Krafla