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GEOTHERMAL DRILLING TECHNIQUES

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ABSTRACT

This report is a general description of three geothermal drilling methods which were selected by the author for consideration during the training programme. They are important for their potential applications in geothermal drilling in El Salvador.

First, the directional drilling method is described including a study of all the implied characteristics and special equipment required. In addition, the question of where to drill a geothermal well using either a neglected well platform or an unused platform needs to be considered. Directional drilling means increased drilling costs but these costs can be offset by lowering the cost of platform preparation and time. This method also allows drilling in inaccessible mountainous areas where geothermal reservoirs are frequently found.

Air drilling with its use of a percussive and rotative tool is the second method described in this report. This results in a high rate of penetration and consequently substantial savings in drilling operations.

Cable tool drilling is the third and last method described in this report. Although it is an outdated method, the author considered its use important for efficient use of time during initial penetration of geothermal wells. In El Salvador, all drilling stages are made with big rigs, but it is possible to drill the first hole with a cable tool rig used for fresh water wells.

TABLE OF CONTENTS

	Page
ABSTRACT	3
TABLE OF CONTENTS	4
LIST OF FIGURES	5
LIST OF TABLES	5
1. INTRODUCTION	6
2. TOPICS ON DIRECTIONAL DRILLING	7
2.1 Definition of controlled directional drilling	7
2.2 History	7
2.3 Applications of controlled directional drilling	7
2.4 Well design and directional program	8
2.5 Tools	10
2.6 Surveys	14
2.7 String make-up	18
3. DIRECTIONAL DRILLING PROGRAM	19
3.1 Results of directional drilling of well KJ-22 at the Krafla geothermal field	19
3.2 Comparison of drilling directional wells and straight wells	22
4. DRILLING GEOTHERMAL WELLS WITH AN AIR HAMMER	23
4.1 Definition	23
4.2 History	23
4.3 Advantages and limitations of air hammer drilling	23
4.4 Description of an air hammer and bits	24
4.5 Air compressor requirements	24
4.6 Drill strings	26
4.7 The Odex method	29
4.8 Maintenance	31
5. RESULTS OF AIR HAMMER DRILLING AT LAUGALAND IN THELAMORK	32
5.1 Rig and equipment description	32
5.2 Drilling procedures and well design	32
5.3 Rate of penetration for wells LÞN-10 and LÞN-11	36
5.4 Reservoir analysis for Laugaland	36
6. CABLE TOOL DRILLING	38
6.1 Definition	38
6.2 History	38
6.3 Applications of the cable tool	38
7. CONCLUSIONS	40
ACKNOWLEDGEMENTS	41

Page

REFERENCES 42

APPENDIX I: Information about directional drilling 43

APPENDIX II: Tables and diagrams for air hammer drilling 46

LIST OF FIGURES

1. The three basic hole patterns for directional drilling 8
2. Different types of whipstocks 10
3. Positive displacement downhole motor 12
4. Downhole turbine motor 13
5. Downhole motor types 14
6. Downhole motors with bent sub 15
7. Gyroscopic systems 16
8. Basic steps for building up angle 18
9. The platform location for well KJ-22 19
10. The well profile for KJ-22 20
11. KJ-22, planned and actual rate of penetration 22
12. Downhole drill cycle for an air hammer 24
13. A schematic diagram for air hammer drilling 25
14. Downhole drill string for air hammer 27
15. Flatbottom percussion bits 28
16. Odex string make up 29
17. Details of an Odex drill bit 30
18. The progress and final design of well LÞN-11 33
19. Comparison for rate of penetration for wells LÞN 10 and LÞN 11 36
20. Variation in water level in Thelamork wells during airlifting in LÞN-11 37
21. Diagram for a cable tool drilling rig 39

LIST OF TABLES

1. Krafla field, deviation results for well KJ-22 21
2. Cost estimate for a straight well and a directional well 22
3. Air consumption / penetration rate 26
4. The Odex method, recommendations for rpm, torque and depth 30
5. Activities during the drilling of well LÞN-11 34

1. INTRODUCTION

Advances in drilling technology are constantly changing the methods used to optimize use of available resources. Initially, drilling methods were a hit or miss affair, where chance was the predominant factor. However, with increased studies and experience, geothermal drilling techniques have been perfected and knowledge of events taking place in the ground has improved.

In this report, the author tries to describe, in a general way, three geothermal drilling methods utilized in Iceland. First, the directional drilling method is described in detail, along with methods for drilling nonvertical wells, tools used and the way to control inclination and orientation. Next, a very effective method for increasing the rate of penetration is shown. This is the air hammer drilling method which uses a tool called an air hammer. This novel tool works with rotation and reciprocating movements. Finally, an outdated but still viable drilling method is shown which is very useful and economical for drilling the first part of the geothermal wells. Iceland utilizes this method for pre-drilling all high temperature geothermal wells. This cable tool drilling method uses a heavy chisel as the bit. The tool breaks the rock with reciprocating movements transmitted from the surface by support cables, with slow rotative movements transmitted from the surface by the equipment operator.

Applications of the two first methods can be found in the text, and some calculations are made.

2. TOPICS ON DIRECTIONAL DRILLING

2.1 Definition of controlled directional drilling

Controlled directional drilling is the science of deviating a wellbore along a planned course to a subterranean target located a given distance horizontally from a point directly under the center of the rotary table of a drilling rig (IADC).

In short, a deviated hole is always longer than a vertical hole drilled to the same depth, and this accounts for some of the increased expense incurred in directional drilling.

2.2 History

The technique of deviating the borehole of a well was iniated in the late 1920s on the Pacific coast of the United States. Previously, oil wells in this area were drilled from piers built out into the ocean, but eventually piers were banned in the harbors because they began to impede ship traffic. An ingenous California contractor believed he could locate his drilling rig on shore and deviate the hole so that it would bottom out under the harbor. Without asking permission of the harbor authorities-or anyone else for that matter-he proceeded to do so. His idea worked well and later, the directional drilling technique was utilized as a way to overcome uncontrolled wells (IADC).

2.3 Applications of controlled directional drilling

Inaccessible locations
It is sometimes impossible to locate the drilling rig over the exact spot where a well is to be bottomed out. To solve this problem, the rig can be set to one side and the hole deviated to reach a point under the obstruction. These obstructions could be hills, mountains, rivers or even cities.

Fault drilling
Directional drilling is also used for drilling into reservoirs with near-vertical fractures so that the well will intersect more fractures than if drilled straight.

Sidetracking and straightening
Directional drilling can be used to bypass some of the problems that occur downhole. For instance, if the well is supposed to be vertical but instead goes beyond the allowable deviation, the crooked portion can be plugged with cement and deflection tools set to guide the bit around the plug and into a vertical path. If a portion of the drill string is lost in the hole and cannot be fished out, cement can be placed on top of the fish, and the hole then deviated around it in an operation called sidetracking (IADC).

Relief wells
Directional drilling isapplied to the drilling of relief wells so that water, mud and special chemical solutions may be pumped into the reservoir of an uncontrolled well. This is normally referred to as "killing" a well.

Multiple wells from single platform
Using directional drilling, several wells can be started from a single platform and then deviated so that the wells bottom out in the production zone in accordance with the required well spacing.

Basic hole patterns

A carefully conceived directional drilling programme based on geological information, knowledge of mud and casing program, target area, etc., is used to select a hole pattern suitable for the operation. However, experience has shown that most deflected holes will fit one of the following types (Figure 1) (Eastman Whipstock):

Type I is planned so that the initial deflection is obtained at a shallow depth and the angle is maintained as a "locked in" straight angle approach to the Target. This pattern is mainly used for moderate depth drilling, in areas where the producing formation is located in a single zone and where no intermediate casing is required; but it is also used to drill deeper wells requiring a large lateral displacement. This is the most common type used in geothermal drilling.

Type II also called "S" curve pattern, is also deflected near the surface. The drift is maintained, as with Type I until most of the desired lateral displacement is obtained. The hole angle is then reduced and/or returned to vertical in order to reach the Target. This pattern, which can present some problems, is mainly used for wells in multiple production zones or with lease or target limitations.

Type III is so planned that the initial deflection is started well below the surface and the hole angle is maintained to the bottom hole target. This pattern is particularly suited to special situations such as a fault or any situation requiring redrilling or repositioning of the bottom part of the hole.

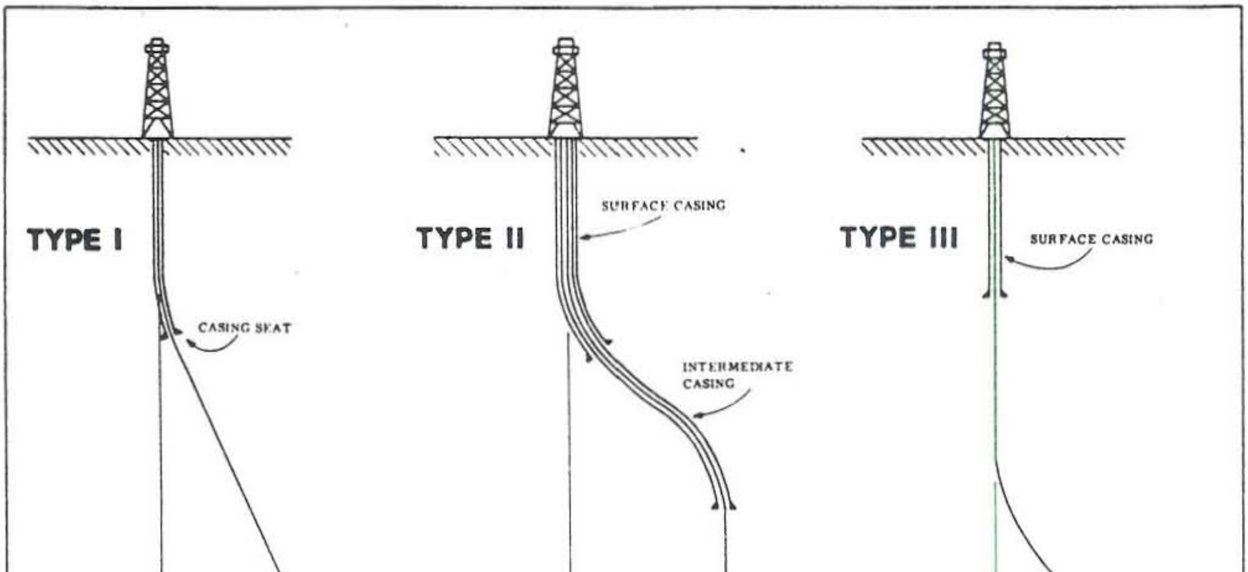


FIGURE 1: The three basic hole patterns for directional drilling

2.4 Well design and directional program

The first step in designing a directional well is to define the objectives. The casing diameters have to be fixed and also their respective depths. The equipment capacity must be selected to overcome unforeseen events

Surface casing is placed and cemented in the first hole which is drilled with a cable tool rig (percussion drilling). Second and third stages of drilling the hole are drilled with rotary rigs. Usually in the third stage the deviation of the hole starts. The depth where the deflection occurs is called the kick off point. The final stage is drilled with water to the bottom.

Part of the directional programme is to determine the kick-off point, selecting an adequate tool for making the deflection and an adequate drill string make-up to increase or decrease the inclination angle. Survey instruments for measuring inclination and orientation must be considered in the directional well programme, as well. In Appendix I-A, a typical directional programme is presented.

Well planning

Deflecting a well bore involves many complex factors which must be considered individually. Therefore, expert planning is the key to minimizing the overall costs of directional drilling, since the correct choice of tools and procedures may significantly improve operating efficiency and economics. The services of a directional drilling superintendent specialist are often employed.

Factors involved in planning directional programs

The target

The first step in directional planning is to specify the target (the area to be penetrated by the well at a stated depth). Its size and shape usually depends on geological structures and the location of the producing zones. The target must be discussed by all concerned so that the well plan can be drawn up accordingly.

Selection of optimum surface location for drilling rig

It is essential to select an optimum surface location for the rig, taking advantage of natural formation deviation tendencies. These formation attitudes have a marked effect on the drift of the hole. For example, drilling through alternately hard and soft formations with a well stabilized bit usually results in a course perpendicular to the bedding plane. However, when a laminated formation dips in excess of 45°, the bit will tend to drill parallel to the bedding. Likewise, the formation attitudes also have an effect on directional tendencies; if the proposed direction is due up-dip, it follows the natural bit tendencies, and drift angle can be readily built. But if the proposed direction is left of up-dip, the bit will tend to turn to the right, and if the direction is right of up-dip, the bit will deviate to the left. Therefore, selection of an optimum location should be based on all subsurface information to take advantage of the formation attitudes, and to minimize undesired hole deviation (Eastman Whipstock).

Hole size

Larger diameter holes are easier to control directionally than smaller diameter holes, since slim hole drilling calls for smaller, more flexible drill collars and pipes. Such collars also limit the range of weight available. Consequently, in slim hole drilling, formation characteristics will have more effect in drawing the hole off course. But, fortunately, such problems are not insurmountable and can be overcome by competent drilling personnel.

Casing and mud programs

Most directional projects can follow the same casing programs used in straight hole drilling. The only exception to this rule is for deep holes, or holes of high inclination, where it becomes necessary to install rubber protectors on the drill pipe to reduce wear on the casing and drill pipe. Mud control is also extremely important in decreasing the drag in a directional hole. However, most geothermals wells are drilled with water.

Effect of drill string magnetism and adjacent well bores on survey instruments
Experience has shown that a drill string worked in a bore hole usually becomes magnetized (Eastman Whipstock). However, these known effects can be compensated for by using non-magnetic drill collars which will prevent inconsistencies in survey readings. Also, some surveys taken in adjacent holes may be affected by residual magnetism in the casing of previous holes. This magnetism is usually small in magnitude but should, nevertheless, be taken into consideration during the initial planning.

2.5 Tools

A prime requirement for directional drilling is suitable deflection tools, along with special bits and other auxiliary tools. A deflection tool is a mechanical device that is placed in the hole to cause a drilling bit to be deviated from the present course of the hole. There are numerous deflection tools available for use in the deflection of a hole or to correct direction. The selection of a deflection tool depends upon several factors but principally upon the type of formation at the point where the hole deviation is to start (IADC).

Whipstocks
The standard removable whipstock (Figure 2a) is used to initiate the deflection and direction of the well, to sidetrack cement plugs or straighten crooked holes. It consists of a long inverted steel wedge that is concave on one side to hold and guide a whipstock drilling assembly. It is also provided with a chisel point at the bottom, to prevent the tool from turning, and a heavy collar at the top, to withdraw the tool from the hole.

FIGURE 2: a) Standard removable whipstock; b) Circulating whipstock; c) Permanent casing whipstock (Eastman Whipstock)

The circulating whipstock (Figure 2b) is run, set and drilled like the standard one. But in this case, the drilling fluids flow through a passage to the bottom of the whipstock and circulate the cuttings out of the hole, insuring a clean seat for the tool.

Both whipstocks are used with a drilling assembly consisting of a proper size whipstock drill bit, a spiral stabilizer and an orienting sub rigidly attached to the whipstock by means of a shear pin.

The permanent casing whipstock (Figure 2c) is designed to remain permanently in the well. It is mainly used to bypass collapsed casing or junk in the hole, or to re-enter and drill out old wells. It is set, by means of a setting trigger, to an assembly consisting of a starting mill, an orienting sub and the standard drill string (Eastman Whipstock).

The whipstock method is rarely used nowadays in geothermal drilling.

Downhole hydraulic motors

Today, the most common tools used to deviate a hole are downhole hydraulic motors and turbine motors. Both types of downhole motors have several advantages over the older types of deflection tools. Among other things, downhole motors drill a full gauge hole so that no follow up run is required to open the deviated hole to full gauge.

Positive displacement motors

The positive displacement downhole motor (Figure 3) consists of a motor assembly (comprised of a rotor and stator), a connecting rod assembly, a bearing and drive shaft assembly, a rotating bit sub to which a conventional roller cone bit is made up and a dump valve. It will operate on either air or mud (IADC).

The dump valve operates hydraulically, opening when there is no fluid pressure in the drill string and closing when pressure builds up. Its main purpose is to allow drilling fluid to fill the drill pipe when tripping in and to allow drainage when tripping out.

The motor assembly is approximately half the total length of the tool and consists of only two parts, a rotor and a stator. The stator tube forms the outer body of the motor assembly. This tube is lined with a rubber-like Buna N compound specially formulated to resist abrasion. In the manufacturing process of the stator, a spiral-shaped core is centered within the tube. Then the Buna N is injected into the tube and allowed to cure. The core is then removed, leaving a spiral-shaped cavity that is elliptical in cross-section. The rotor is machined from a solid alloy steel bar and is plated with a special hard chrome to reduce abrasive wear. Its final shape is a single helix or spiral with a round cross-section (Jurgens and Marx, 1979).

When the motor is assembled, there is a continuous seal along its length between the rubber stator and the matching contact points on the spiral rotor shaft. As drilling fluid is pumped through the cavities between the rotor and stator, the hydraulic pressure causes the shaft to rotate within the stator.

The connecting rod assembly has a three-lobe universal joint located at each end. The universal joints are surrounded by a clamped rubber sleeve to insure pressurized lubrication. The drive shaft below the connecting rod assembly is hollow. The hollow drive shaft receives drilling fluid from the motor and sends it to the bit. The thrust bearings in the drive shaft assembly carry the drilling weight. An additional thrust bearing at the top of the tool provides for the "no load" weight when the tool is operated off bottom.

After the tool has been run into the hole, the motor is started by circulation of drilling fluid. Then the bit is set on bottom. Since the tool is a positive displacement motor, drilling torque is proportional to the pressure loss through the tool; that is, the higher the pressure loss, the higher the torque. Furthermore, the rotation is proportional to the fluid pumping rate. A typical motor will turn once for every gallon of fluid. Thus, 300 gallons per minute pumping rate results in 300 rpm of the bit (IADC).

In addition, surface pressure increases as more weight is applied to the bit. Excessive weight will stall the motor; therefore, drilling with this tool is a matter of coordinating the available pump pressure and weight on bit.

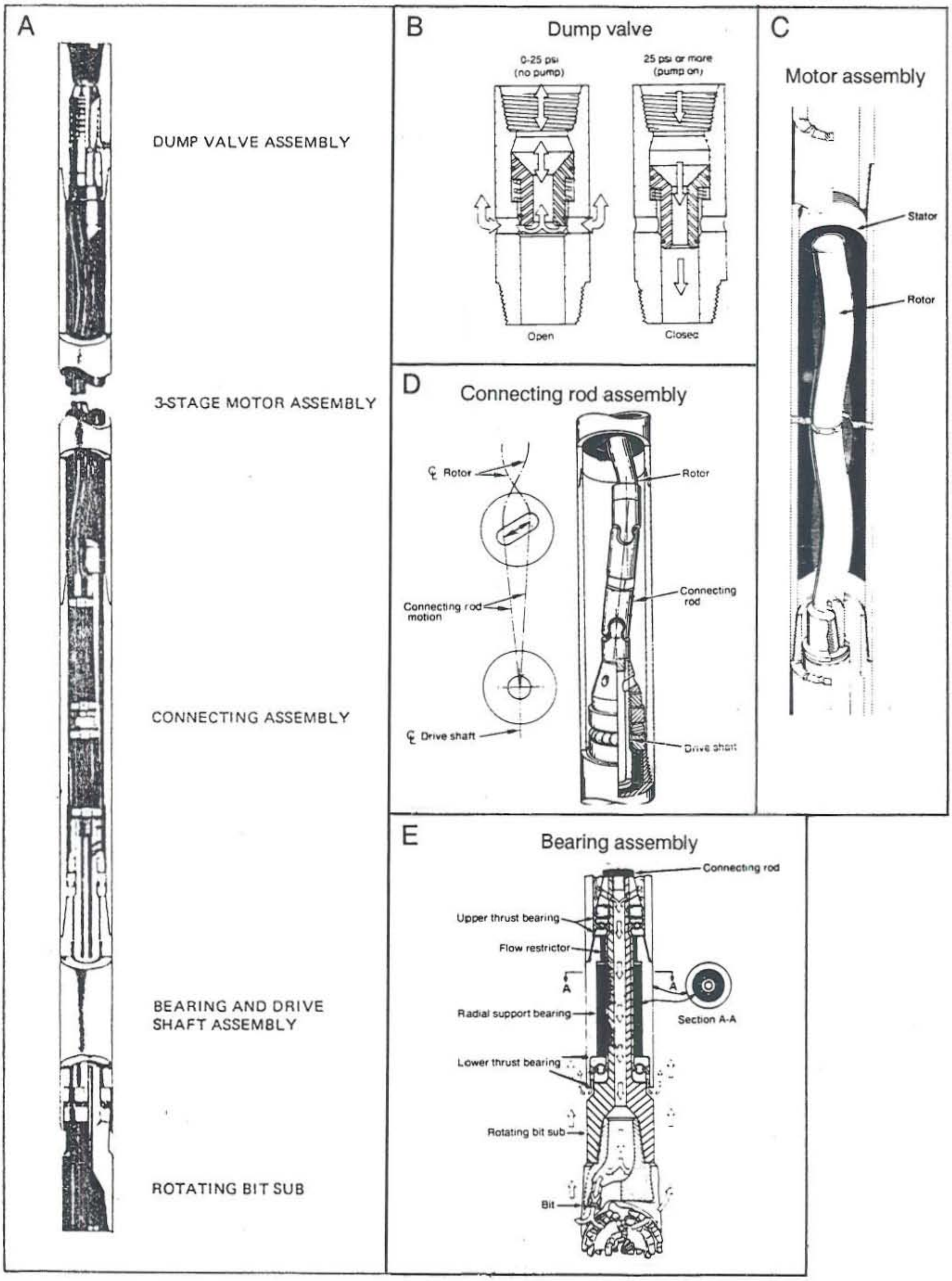


FIGURE 3: Positive displacement downhole motor; a) The whole unit; b) Dump valve; c) Motor assembly; d) Connect. rod assembly; e) Bearing assembly (Jurgens and Marx, 1979)

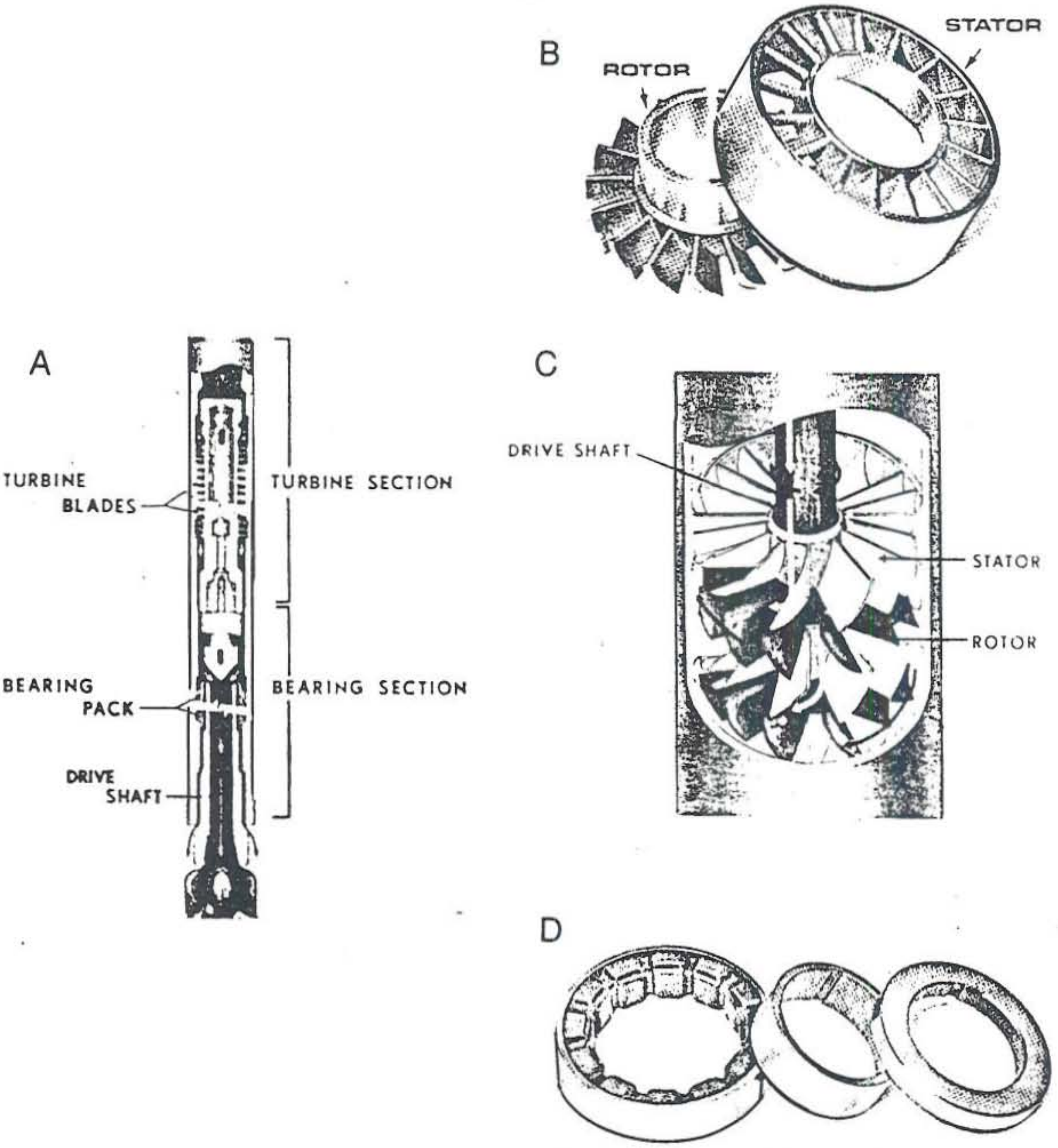


FIGURE 4: Downhole turbine motor; a) The whole unit; b) Rotor and stator stage; c) Schematic cross-section of turbine motor; d) Rubber bearing body and thrust disc (IADC)

Downhole turbine motors:

Downhole turbine motors (Figure 4) consist of a turbine section, a replaceable bearing section, and a rotating bit sub on which a conventional bit is made up. Turbines operate only with mud or water as the circulating medium.

The turbine section contains bladelike rotors and stators. The stator is attached to the outer case of the tool and is held stationary by it. The rotor is attached to the drive shaft. Each rotor and stator are termed a stage, and several stages make up the turbine section. In operation, drilling mud is pumped down the drill string and into the tool. The blades in each of the stationary stators guide the mud onto the rotor blades at an angle. Mud flow forces the rotors-and thus the drive shaft-to rotate to the right. Since the bit sub and bit are attached to the drive shaft, the bit turns.

In the replaceable bearing section are a number of thrust bearings. Each bearing is comprised of a rubber bearing body, sleeve, and thrust disc. After about 150 hours of operation (depending on the severity of use), these bearings become worn and must be replaced (IADC).

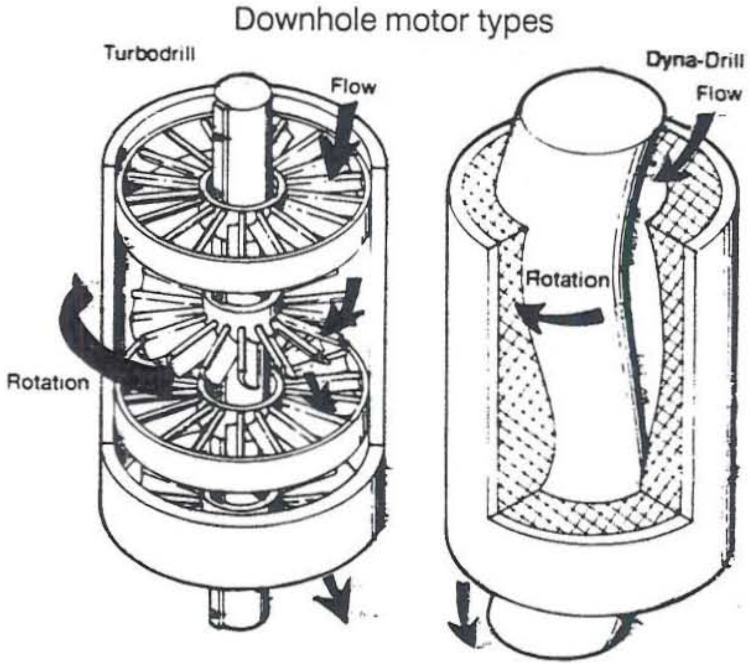


FIGURE 5: Downhole motor types (Jurgens and Marx, 1979)

Bit walk
Downhole motors (Figure 5) have one characteristic that other types of deflection tools do not have - a tendency to create a reverse torque. Reverse torque is the result of drilling fluid flowing against the stator, trying to rotate the drill string to the left while the rotor and bit rotate to the right. This phenomenon must be taken into account when orienting downhole motors because the direction in which the tool faces upon being run to bottom is not necessarily the direction in which it will go when drilling commences. One rule of thumb often used is to allow 10° per 1000 ft of depth when drilling soft formations and 5° per 1000 ft when drilling hard formations (IADC).

Deflection of downhole motors
None of the downhole motors just described can, by themselves, deviate the hole off vertical. Indeed, both tools are sometimes used in drilling straight holes. However, a number of things can be done to deflect downhole motors (Figure 6). In the case of positive displacement motors, the manufacturer can supply a motor with the housing bent 1° or 2° off vertical at the point where the connecting rod and rotor are attached with universal joints. The face of the tool, in this case, is the direction in which the case is bent.

Both the positive displacement motor and the turbine motor can be deflected with a 1° to 3° bent sub. Again, the face of the tool is the direction in which the sub is bent. A bent sub is a short sub that has its upper thread cut concentric with the axis of the sub body and its lower thread cut concentric with an axis inclined 1°, 2°, or 3° in relation to the axis of the upper thread. Thus, the downhole motor is deviated from the axis of the drill string by the number of degrees incorporated into the sub. Usually, a nonmagnetic collar is used above the bent sub to facilitate accurate orientation. When the bent sub is used with either type of downhole motor, or when a bent housing is used with a positive displacement motor, the assembly must be run into the hole with care because the bit will tend to dig into the wall of the hole owing to the bend put into the bottom-hole assembly (IADC).

2.6 Surveys

Directional surveys are used to accurately locate the well bore trajectory. It permits the determination of the bottom hole location relative to the surface location at a given vertical depth, location of possible doglegs or excessive hole curvatures, the monitoring of the course direction and drift during the drilling process, and orientation of the deflecting tools.

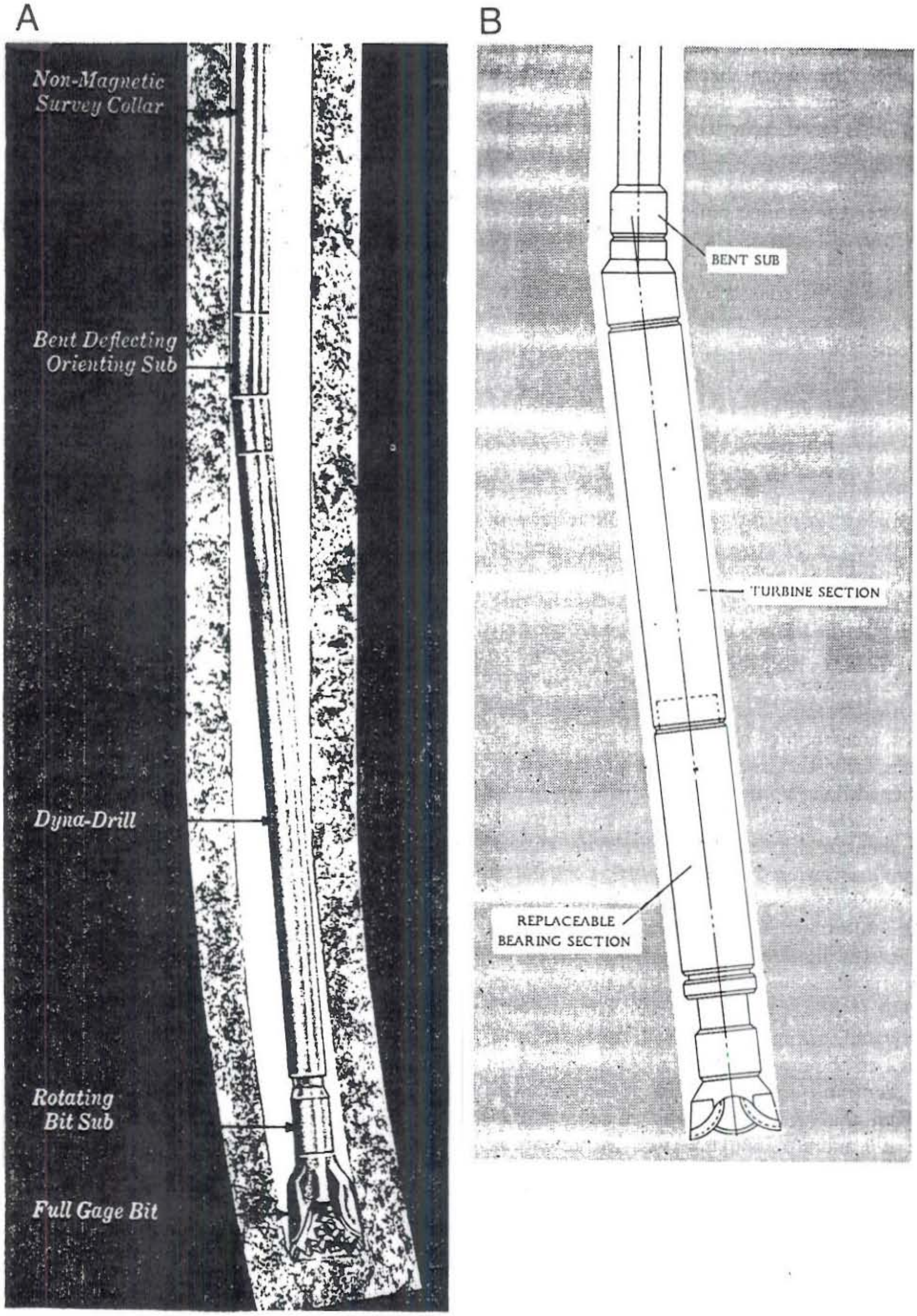


FIGURE 6: a) Positive displacement motor deflected with bent sub;
b) Turbine motor deflected with bent sub (IADC)

Today's survey instruments and methods provide a fast, accurate, and economical way of monitoring the well bore. The drift and course direction of the well bore at specific depths is determined by one type of survey called the "Single Shot Survey", while "Multiple Shot" surveys are used to record several individual readings at required depth intervals (Eastman Whipstock).

Magnetic surveys requiring a non-magnetic collar

Magnetic is a generic term covering several methods of surveying all with a common denominator. The instruments must be run inside a non-magnetic drill collar made of a special nickel alloy to nullify the magnetic influence of the drill string (Eastman Whipstock).

Magnetic single shot

The first type of magnetic survey is the "magnetic single shot", which is used to record simultaneously the magnetic direction of the course of an uncased well bore, and its inclination from the vertical. The instrument consists of three basic units: a timing device or a motion sensor unit, an angle indicating unit, and a recording device. The record is either an aluminum plate which is punched to mark the direction and angle, or a camera.

Magnetic drop-type survey

The "drop survey" is the most economical method yet developed to determine the drift and course direction of an uncased well bore. It is also run after the well has been drilled and utilizes a film strip to take several recordings at predetermined depths.

Open hole survey

Another type of magnetic survey, the "open hole multiple shot", is used to determine the drift and direction of an uncased well bore once the well has been drilled. A battery-powered instrument is run into the well and operates mechanically to photograph the angle and direction of a compass at a predetermined depth.

Other types of surveys run without non-magnetic collars

Drift indicator

The drift indicator is a mechanically operated device used primarily in obtaining drift readings in straight holes; however, it is also used to compute the total displacement or deviation of a well bore within a given radius at a total vertical depth. The instrument is protected from shock and pressure by a snap lock barrel. The unit, which is preset at the surface, is run on wire line or dropped on a dull bit. After a given elapsed time, the instrument punches a printed paper disc once, which then rotates automatically 180°. About 45 seconds later a second punch record is made allowing a positive check on the accuracy of the reading. This type of instrument is not affected by magnetism and can therefore be run without a non-magnetic collar.

Drop multishot inclination survey

The "drop multishot inclination" instrument is used to record multiple surveys after the well has been drilled. Since the instrument is encased in a steel outer barrel, the inclination capabilities of the angle unit are not affected by magnetic influences. The instrument is simply dropped through the string to the baffle plate, and surveying is accomplished as the drill string is retrieved from the well.

Gyroscopic surveys

The "gyro" instrument (Figure 7) can also be run without non-magnetic collars since the magnetic compass is replaced by a "gyro" compass disc controlled by a high R.P.M. electric rotor (Eastman Whipstock). The "gyro single shot's" primary purpose is to orient deflection tools in areas of magnetic influence and also to determine the drift and direction of the well bore. The instrument consists of a timing device, a camera section, and the very sensitive gyro compass section.

The gyro unit is first oriented to a known direction, and the timing device is set. The instrument is encased in a protective outer barrel and lowered to the survey station where the survey is recorded. The instrument is then retrieved from the well and the film is unloaded and developed.

The "gyro multiple shot" instrument is used to record the drift and direction of a cased or uncased well bore. The battery-powered instrument and camera section have the same characteristics as the standard "drop" multishot instrument. The gyro unit is again oriented to a known direction, and the timing device is synchronized with a surface watch. Once the instrument is assembled it is run on wire line through the well bore.

Gyro systems are very sensitive and should therefore be handled with extreme care. Their compasses should also be checked for drift when the assembly is retrieved. To insure complete accuracy of the downhole data, all survey instruments must be aligned parallel to the axis of the well bore.

The most popular method, the "centralized" method, is accomplished by equipping the instrument barrel with rubber fingers or, for gyro surveys, with metal belly springs called centralizers. As the instrument is lowered to and centered on the baffle plate, its upper section is centered by the centralizers which align the instrument to the well bore axis.

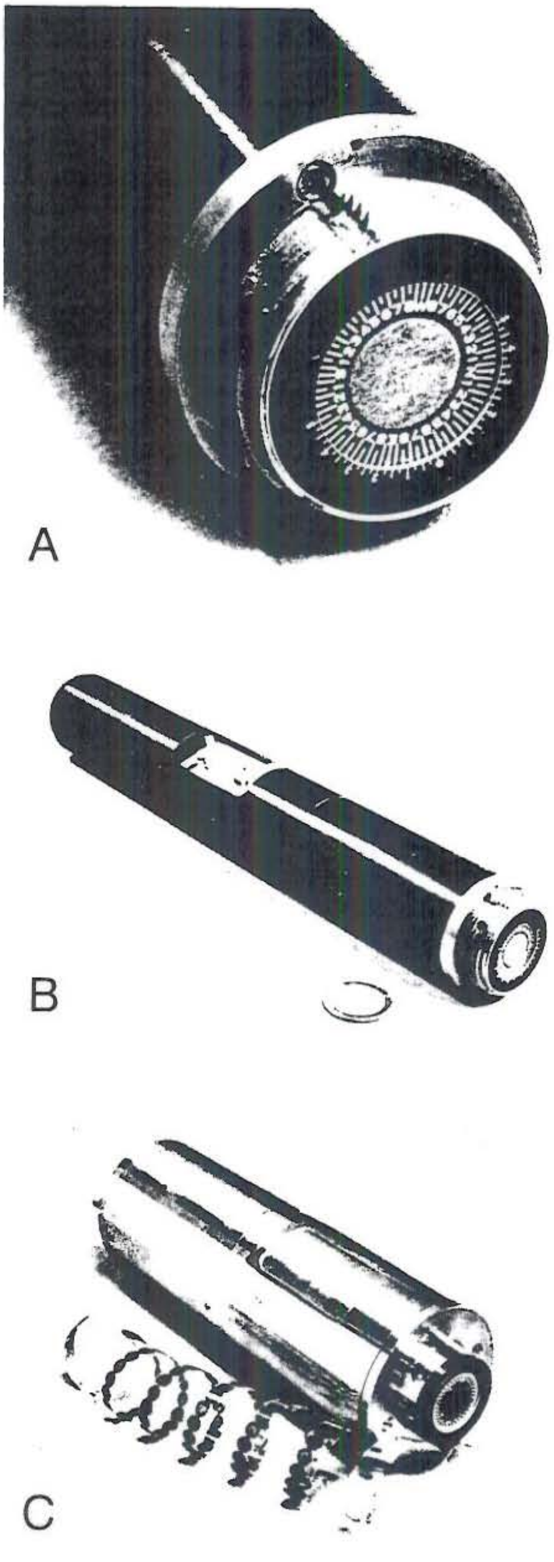


FIGURE 7: a) Gyroscopic system; b) Gyro single shot; c) Gyro multiple shot (Eastman Whipstock)

2.7 String make-up

In order to design a good directional drilling programme it is necessary to obtain information from several sources. That information is the target, actual depth, type of formations, casing programme and drilling fluid program. The selection of the kick-off point becomes one of the most important factors as well as drill string make-up to create correct angles, and to stay on course. The directional drill string patterns are described so (Figure 8):

A. Kick off point assembly

This type of drill string is used for starting the deflection of the well. Figure 8 shows an assembly for 0° to 8° angle building of 1.5° build / 10 m. Surveying every 10 m with single shot magnetic or gyro instruments is recommended.

B. Build up angle assembly

For 8° to 18° angle building of 1° build / 10 m. Surveying every 10 to 30 m with single shot magnetic or gyro instrument is recommended.

C. Directional drilling assembly

For 18° to 30° angle. Surveying every 30 to 100 m with single shot magnetic or gyro instruments is recommended.

D. Locked in drilling assembly

For keeping the inclination angle. Surveying every 100 m with single shot magnetic or gyro instrument is recommended.

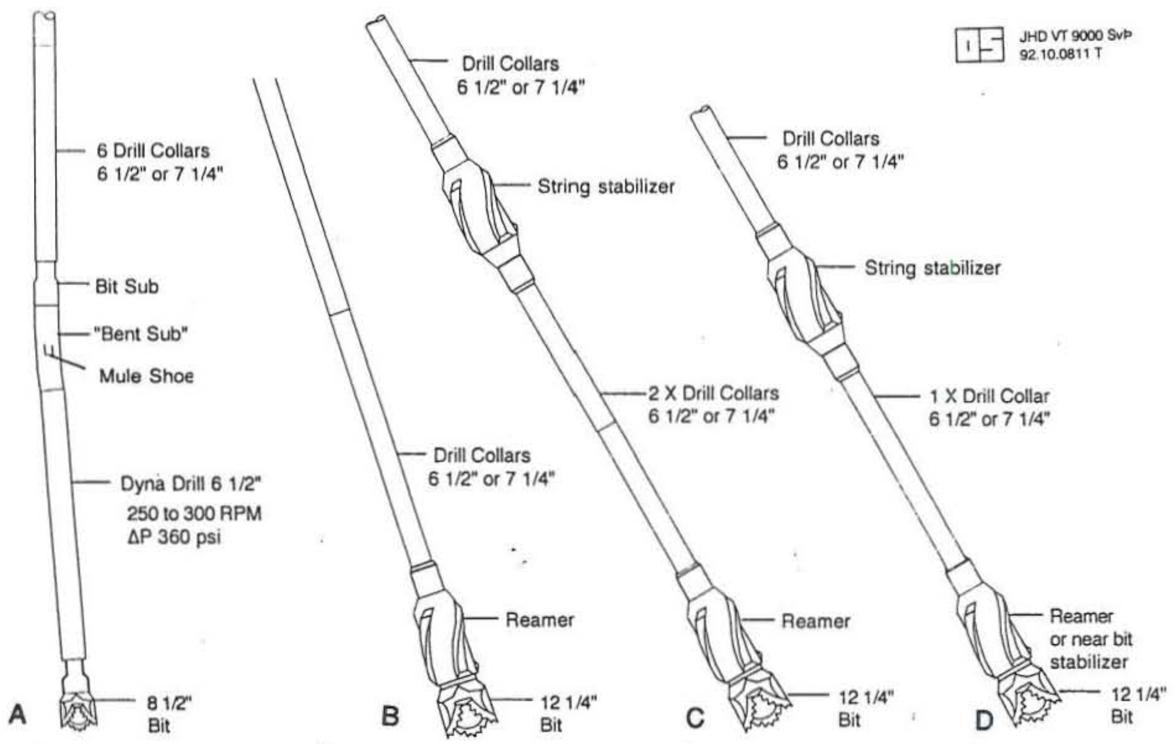


FIGURE 8: Basics steps for building up angle: a) Kick-off; b) Build up angle; c) Directional drilling; d) Locked-in drilling (Thorhallsson, 1992)

3. DIRECTIONAL DRILLING PROGRAM

3.1 Results of directional drilling of well KJ-22 at the Krafla geothermal field

There are three directional wells in Iceland, located in the Krafla geothermal field. This is a high enthalpy geothermal field in the northeast part of Iceland. A 30 MW_e Power Plant was installed which started in February, 1978. These directional operations were effected between July, 1982 and August, 1983. The wells mentioned are KJ-13, KJ-20 and KJ-22.

The purpose in drilling well KJ-22 directionally was to intercept a series of nearly parallel fractures located at 670 m on the west north west part of the platform allotted to the borehole (Figure 9) to 2000 m depth (measured depth).

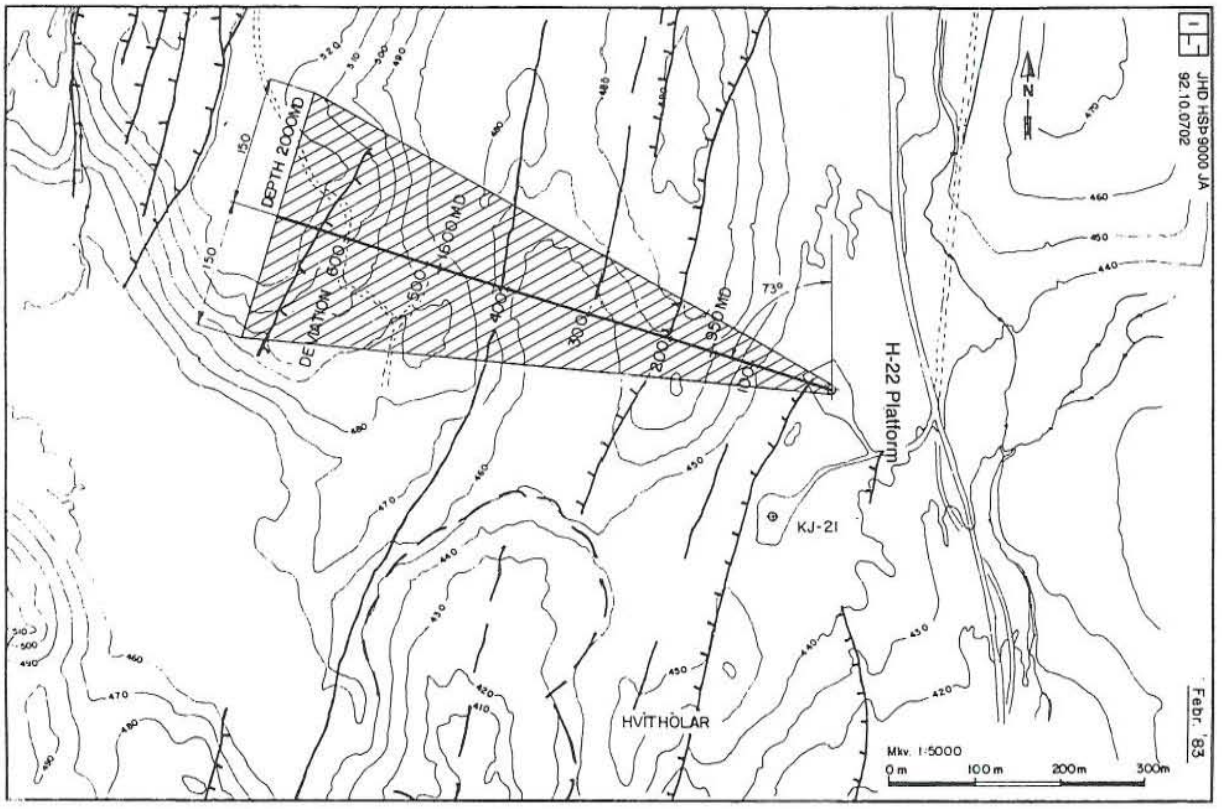


FIGURE 9: The platform location for well KJ-22 (Gudmundsson, pers. com.)

Casing programme (Gudmundsson, pers. com.)

Surface casing:	18 5/8" OD, 116 kg/m, cemented to 0-50 m depth, 22" ϕ bit;
Anchor casing:	13 3/8" OD, 101.2 kg/m, buttress threaded, cemented to 0-200 m depth, 17 ½" ϕ bit;
Production casing:	9 5/8" OD, 64.7 kg/m, buttress threaded, cemented to 0-550 m depth, 12 ¼" ϕ bit;
Slotted liner:	7" OD, 38.7 kg/m, buttress threaded, hung from production casing 500-2000 m, 8 ½" ϕ bit.

Directional programme (Gudmundsson, pers. com.)

a) To drill vertically down to 350 m;

b) Kick-off point at 350 m using a P.D. motor (Dynadrill 6 ½ " ϕ) with a 12 ¼ " ϕ bit;

c) Maximum angle in the 12 ¼ " hole 11° (MAB 1 ½°/30 m) (partially build up using mud motor and partially with angle building string arrangement;
d) Maximum angle build up in the 8 ½" ϕ hole 30°(950 MD) using an angle building string assembly;
e) Locked-in drilling down to bottom (2000 m MD).

This design was based on a target having approximately north south direction and inclined 5-10° from the vertical away from the well.

Directional surveying (Gudmundsson, pers. com.):
a) For the vertical part 0-350 m MD and 560 m MD to bottom use a drop shot inclinometer (Totco);
b) For the angle build up, i.e. the deviated part of the well (350-560 MD) use a gyro-single-shot survey;
c) Multishot gyro survey of the hole after total depth (TD).

In Appendix I-B the equipment required is presented.

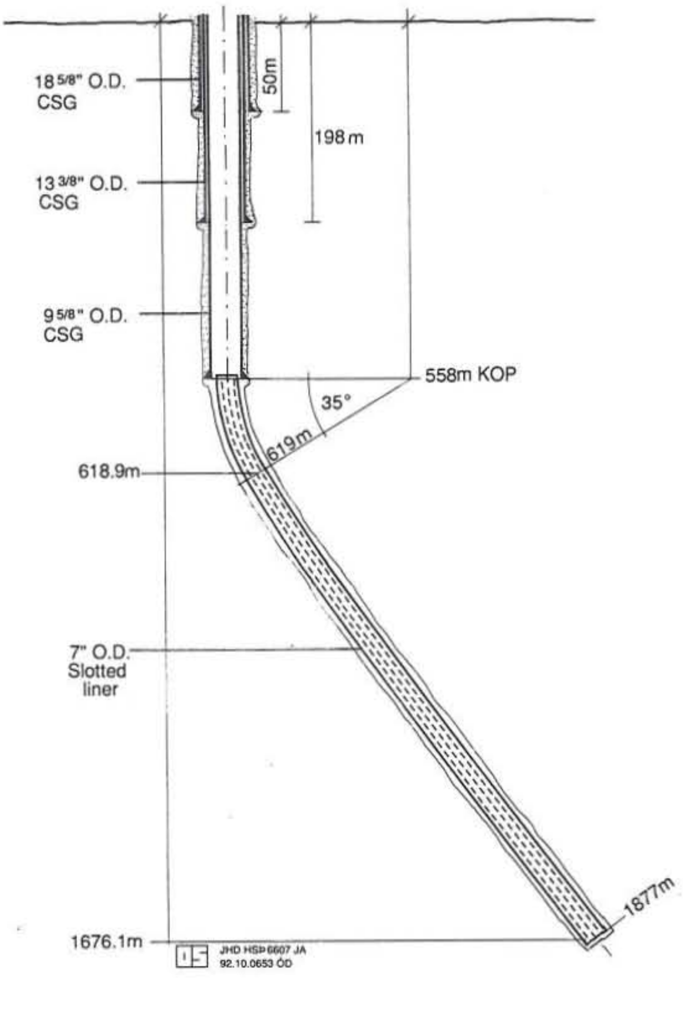


FIGURE 10: The well profile for KJ-22

Procedure

Figure 10 shows the well profile for KJ-22. The drilling started in May, 1983 and a 18 5/8" bit was used to 50 m. An 18 5/8" OD casing was placed to 47 m using special high temperature cement (Gudmundsson et al., 1983a). The second stage was drilled with a 17 1/2" bit to 198 m and 13 3/8" OD casing was placed to 160 m depth using high temperature cement. There was a collapse slightly above 198 m depth. A 12 1/4" bit was used during the third stage to 567 m (Gudmundsson et al., 1983b). This was different as the initial programme because solid and a safe formation was not found at 350 m. A 9 5/8" OD casing was placed and cemented to 558 m. The fourth stage was drilled with an 8 1/2" bit and the kick-off point was at 567 m. The drill string make-up was with 6 1/2" OD drill collars (2 1/4" ID), "bent sub" mule shoe (1.5 °), 6 1/2" ϕ Dyna drill and 8 1/2" rock bit. Gyro surveys were done to measure the face of the bit with a gyro single shot instrument. From 576 m depth the well was drilled with the Dynadrill to 627 m MD. Inclination and orientation measurements were made several times. When a 9.3° angle was created, an angle build up string was used to drill from 627 m MD to 1225 m, making an inclination angle of 27.8°. This string consisted of a 6 1/2" ϕ drill collars, a stabilizer near to the bit and rock bit. Inclination measurements were effected with drop shot inclinometer (Totco). After that a locked drill string was used to the 1800 m final MD, consisting of an 8 1/2" ϕ stabilizer, three 6 1/2" ϕ drill collars, an 8 1/2" ϕ stabilizer, two 6 1/2" ϕ drill collars and an 8 1/2" ϕ stabilizer near the bit. Nevertheless inclination angle continued to increase perhaps due to worn out diameter stabilizers. Inclination measurements were also done here and finally inclination and orientation measurements were effected with a gyro multiple-shot instrument from kick-off point depth to the bottom. (Gudmundsson et al., 1983c).

Table 1 shows the results of the deviation of well KJ-22 and Figure 11 the planned rate of penetration compared with the actual rate. In Appendix I-C and I-D drilling parameters and geological characteristics are shown and also deviation planned and actual, respectively.

TABLE 1: Krafla field, deviation results for well KJ-22 (Gudmundsson et al., 1983c)

Measured depth (m)	True vertical depth (m)	Inclination (degr.)	Dog leg severity /30 m (degr.)	Vertival section (m)	Azimuth	North	West
550	550	0					
560	560	0.97	2.91	0.08	268		
579	579	1.16	2.08	0.34	343.7	0.18	0.3
598	597.98	4.10	5.59	1.12	283	0.59	0.99
619	618.86	7.6	5.01	3.25	281	0.95	3.11
647	646.56	9.3	1.87	7.36	283.6	1.83	7.13
685	684	10.2	0.12	13.85	288	3.61	13.38
741	738.91	12.14	1.08	24.69	~287	6.66	23.78
798	794.46	14	1.01	37.58	"	10.23	36.17
851	845.69	15.7	0.96	51.16	"	14.2	49.16
912	904.06	18	1.13	68.64	"	19.37	66.06
968	957.17	19	0.54	86.61	"	28.57	83.06
1020	1006.03	21	1.15	104.39	"	29.77	100.06
1072	1054.21	23.2	1.27	123.95	"	35.49	118.77
1120	1097.97	25.2	1.17	143.68	"	41.26	137.63
1170	1142.8	27.2	1.12	165.8	287	47.7	158.8
1225	1191.6	27.8	0.3	191.2	"	55.2	183.1
1300	1257.7	28.6	0.3	226.9	"	65.6	216.9
1400	1344.7	30.5	0.6	275.9	"	80	264.1
1500	1430.3	31.8	0.4	327.7	"	95.2	313.6
1600	1514.4	33.8	0.6	381.8	"	111.1	365.3
1700	1596.3	36.2	0.7	439.2	"	127.9	420.2
1800	1676.1	37.9	0.5	499.2	"	145.6	477.8

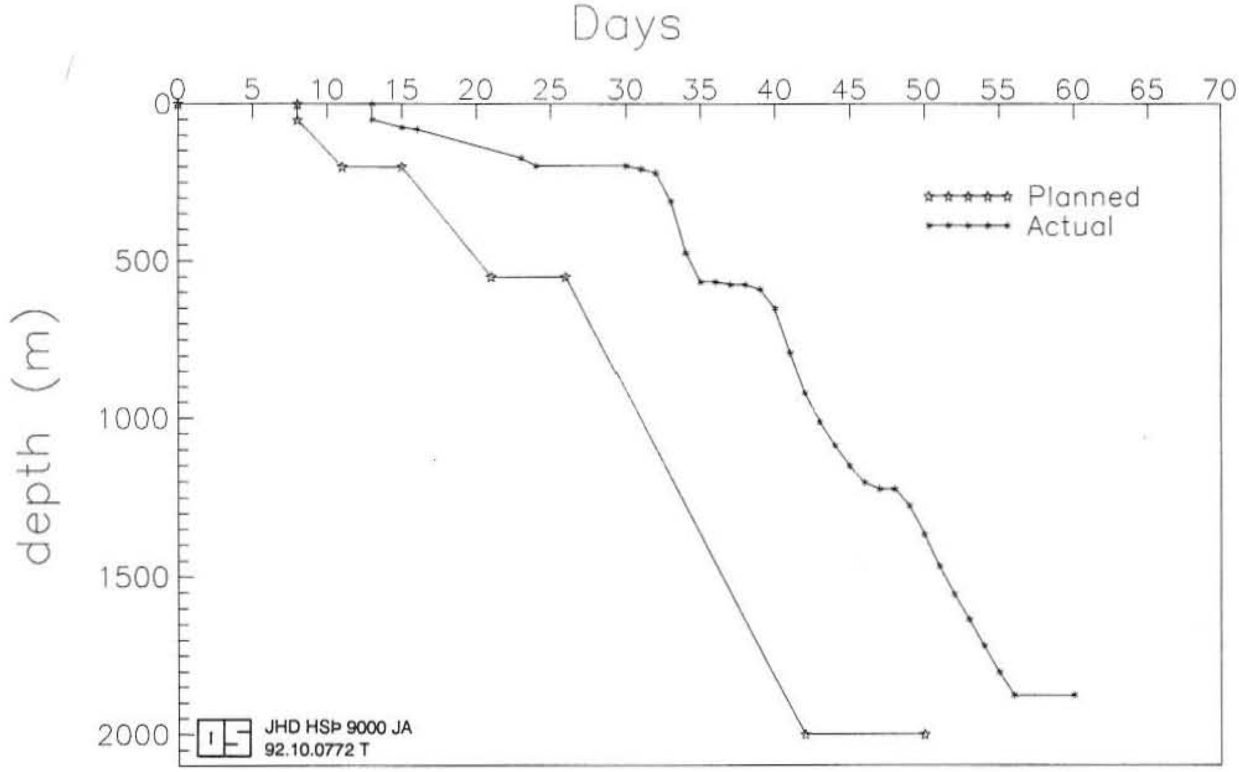


FIGURE 11: KJ-22, planned and actual rate of penetration

3.2 Comparison of drilling directional wells and straight wells

Table 2 shows the difference in cost estimate for a straight well and a directional well using the method of Thorhallsson (1992).

TABLE 2: Cost estimate for a straight well and a directional well

	Straight well		Directional well	
	USD	%	USD	%
1. Rig Rental	479,283	25.16	599,103	26.72
2. Rig Crew	308,301	16.18	385,376	17.19
3. Bits, Reamers, tools	82,590	4.34	99,108	4.42
4. Casing and tools	271,141	14.23	311,141	13.88
5. Wellhead and valves	51,443	2.7	51,443	2.29
6. Cement, high temperature	40,985	2.15	40,985	1.83
7. Mud materials	13,638	0.72	13,638	0.61
8. Rig transport	124,219	6.52	124,219	5.54
9. Pre drilling (Cable tool)	82,476	4.33	82,476	3.68
10. Consulting, supervising, logging services, etc.	137,789	7.23	177,788	7.93
11. Site preparation and roads	58,490	3.07	58,490	2.6
12. Cellar	6,157	0.32	6,157	0.27
13. Contingency (15%)	248,477	13.04	292,489	13.04
Total	1,904,989	100.0	2,242,413	100.0

4. DRILLING GEOTHERMAL WELLS WITH AN AIR HAMMER

4.1 Definition

Air drilling is a method which uses compressed air to transmit impact power to the bit, the compressed air acting as the drilling fluid. This method is cheaper and quicker than mud drilling and avoids possible plugging of fractures from cuttings or damage to the production zone from circulating mud which may enter the zone when drilling. Nevertheless, this method cannot be used in formations which tend to slough.

4.2 History

The first well using air as the drilling fluid was completed at Peters Point, Utah in 1953 by the El Paso Natural Gas Company (Lyons, Air and Gas Drilling Manual). Air drilling techniques have recently been used in some operations to drill through potential loss of circulation formations, such as fractured formations.

Air drilling techniques are used mostly in the drilling of offset wells (production wells) where the geology is well known and the potential producing formations are of rather low pressure.

4.3 Advantages and limitations of air hammer drilling

The following lists some of the advantages and limitations of air drilling (Lyons):

<u>Advantages</u>

a) Formation damage to potential producing formations is minimized;
b) Loss of circulation problems are virtually eliminated;
c) Greater analysis capability of potential producing zones is attained;
d) The penetration rate is higher (the deeper the hole, the better the relative rate);
e) Bits last longer;
f) The ability to deal with hard formations is much greater;
g) Under normal drilling conditions, holes are drilled straighter due to less weight on the bit;
h) Operating conditions are cleaner;
i) Overall costs for drilling operation are lower since such an operation takes less time than rotary drilling.;
j) The need for a heavy string of drill collars to add weight to the bit is eliminated. It is possible to drill deeper holes with a smaller rig;
k) Drill string torque loads are much lower than with straight rotary drilling. Rotation speeds are also much lower than with rotary drilling.

<u>Limitations</u>

a) Formation pressure control is minimal and, therefore, drilling is limited to geological regions where reservoir pressures are low;
b) Drilling is limited to geological regions where the rock formations are mature and competent because there is little or no fluid pressure to support the borehole wall and prevent sloughing;
c) There is a limited ability to cope with significant volumes of water entering the annulus from water producing formations;
d) The bit gauge can be appreciably reduced during drilling;
e) The drill pipe can experience rather high wear due to sand blasting characteristics of annular stream flow.

4.4 Description of an air hammer and bits

Drilling contractors in Iceland use downhole drills (DHD) for drilling gradient wells and for low temperature geothermal wells. Originally, DHD percussion drills were used primarily for improved penetration where formations were medium hard to very hard rock. More recently, numerous other advantages of DHD drilling are expanding its popularity throughout the range of consolidated formations. Drill exhaust air passes through the bit to clean the bit face and carry cuttings to the surface up the annular space around the drill pipe. Figure 12 shows a downhole drill cycle for an air hammer.

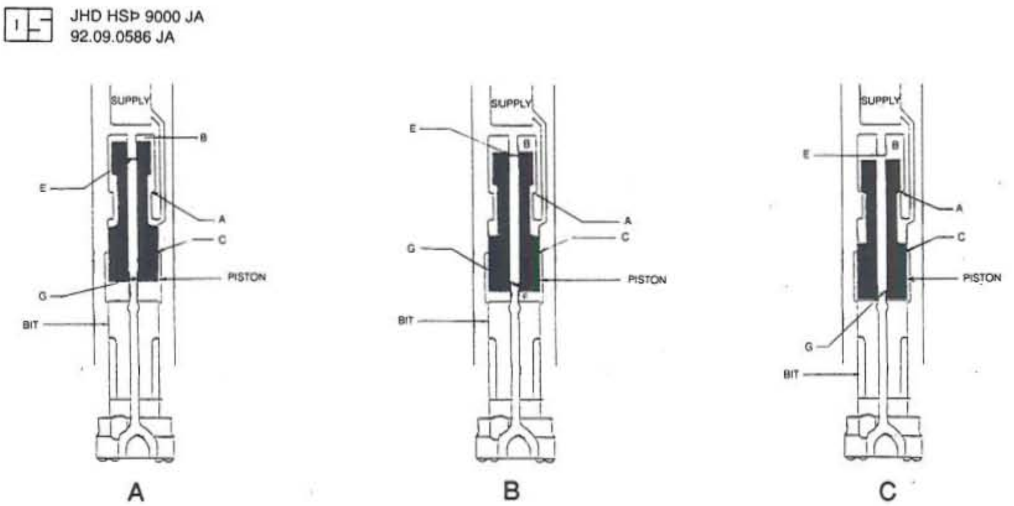


FIGURE 12: Downhole drill cycle for an air hammer (Ingersoll-Rand Construction Equipment)

Valveless drills are activated by surfaces or lands on the piston. The piston shown in Figure 12 is cycled by live air alternately passing the lands at A and C. As the piston covers each port, supply air is shut off, and the piston is then being driven by the expansion of air in chambers B and F. Exhaust is directed out the drill past lands E and G to complete the cycle. Because valveless drills utilize the expansion of air to drive the piston, they are very economical in air consumption (Ingersoll-Rand Construction Equipment).

Current bits used with downhole drills are all solid head, one piece construction with splines for transmitting rotation, and carbide inserts for cutting the rock. The original downhole drill bits were of the conventional chisel edge or "Carset" type. The major problem with this style of bits is that they will not tolerate much abuse from overrunning, allowing the carbide edges to become excessively dull. When this happens, the carbide pinches the hole, causing them to fracture.

Button bits can tolerate a larger flat than can the chisel-edge inserts in Carset bits. In addition, the support of the buttons allows harder grades of tungsten carbide to be used, thus reducing the wear rate. Field experience has shown that although button bits do require resharpening, they require it less often or with more footage drilled between regrinds. The improvement is on the order of 2 to 3 times footage drilled.

4.5 Air compressor requirements

Figure 13 shows the drilling scheme for air hammer drilling. While higher air pressure will

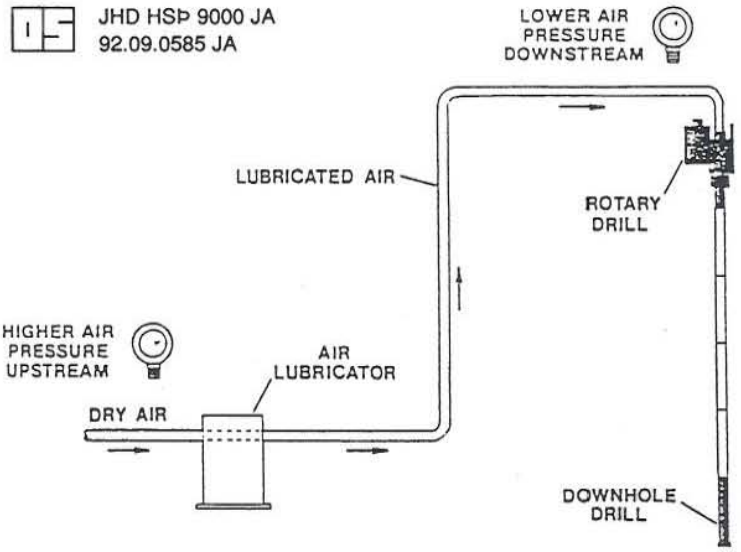


FIGURE 13: A schematic diagram for air hammer drilling (Ingersoll-Rand Construction Equipment)

increase hammer performance, one must be careful that the high air pressure being read at the compressor is not being dissipated in the connecting hoses and piping between the compressor discharge and the drill string.

It is a general rule of pneumatics that air pressure will never be the same at any two points in the system when air is flowing through the system. Air pressure will always be lower "downstream" because part of the pressure energy is used to move the air through the system (Ingersoll Rand Construction Equipment).

Small diameter hoses and fittings are the greatest cause of pressure drops in the system. To check the actual air pressure, use a needle gauge installed in the air hose at the swivel. Check the pressure with the hammer running or blowing. If the pressure at the swivel is considerably lower than pressure at the compressor, work backward through the system to find out where the biggest pressure drops are occurring.

In extreme cases, total system backpressure or pressure drop may exceed the regulation setting on the compressor and the compressor will start to unload reducing the air flowrate being delivered to the system.

If there is doubt as to whether the compressor is running full load, check the regulator to see if the control arm is in the maximum load position. Appendix II-A shows the drill air pressure vs. penetration rate.

The volume or CFM of air powering the DHD is important because it cleans the hole. As air is exhausted and rushes back up the drill pipe annulus, it carries the drill cuttings back to the surface.

Bailing velocity is determined by the following formula with a recommended bailing velocity for good chip removal at 15.3-35.6 m/s (Ingersoll-Rand Construction Equipment):

$$\textit{Bailing velocity} = \frac{Q \times 1.27}{(\textit{Bit dia})^2 - (\textit{Rod dia})^2} \tag{1}$$

where

Bailing velocity is in m/s;
Q is the air flowrate, m^3/s;
Bit dia is the bit diameter, m;
Rod dia is average drill string outer diameter, m.

Water and foam injection may be safely used with a DHD. Care must be taken to assure that the water is injected downstream of the lubricating oil. At the end of each shaft, the hammer and piping must be blown clean with dry lubricated air. Also, the water must be periodically tested to assure a neutral pH, otherwise corrosion-initiated stress cracks may form in the drill.

Foam is used to spread the air drilling application range. In large diameter holes, foam will clean the hole efficiently with bailing velocities as low as 0.77 m/s. In semi-stable holes, foam allows a lower bailing velocity to reduce borehole wall erosion. Foam also helps in situations of heavy water intrusion. The use of foam in wet holes can greatly reduce air capacity requirements.

TABLE 3: Air consumption / penetration rate, in cfm/fph
(Ingersoll-Rand Construction Equipment)

Bit size:	4 ½ "	5 1/8 "	6 "	6 "	8 "	12 1/4 "
Air pressure (psi)	DHD340 A	DHD350 R	DHD160	DHD360	DHD380	DHD112
80	80/20	119/20	180/26	-	290/28	399/14.4
100	110/28	159/32.5	239/39	-	380/36	569/23
125	140/39	208/48	279/52	-	500/48	808/37.5
150	167/50	239/52	359/62	290/55	620/58	998/43
200	220/68	347/85	510/91	435/83	860/87	1380/59
250	290/93	450/118	668/117	580/110	1060/111	-
300	400/112	605/142	880/134	770/133	-	-
350	469/130	760/165	1117/152	940/155	-	-

Table 3 shows air consumption vs. penetration rate for various hole diameters. Penetration rates for other hole diameters may be calculated by the following formula (Ingersoll-Rand Construction Equipment):

$$\left(\sqrt{\frac{dia\ A}{dia\ B}}\right)^3 \times \textit{Penetration rate A} = \textit{Penetration rate B} \tag{2}$$

For example: A DHD 360 drills 47.24 m/hr (155 ft/hr) with a 6" bit. The *penetration rate* for a 6½" bit is found in the following way:

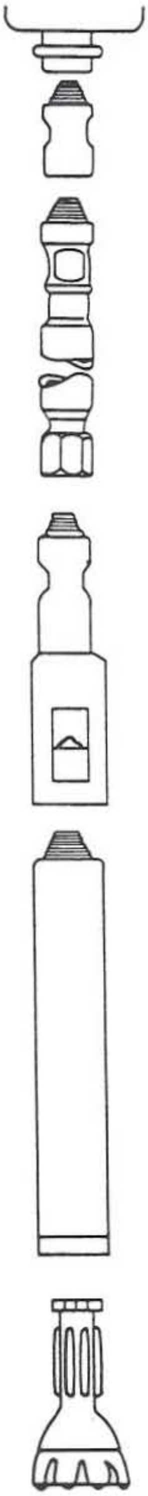
$$(\sqrt{6/6.5})^3 \times 47.24 = \textit{Penetration rate for } 6\tfrac{1}{2}''\ \textit{bit} = 41.9\ m/h\ (137\ fph)$$

4.6 Drill strings

Figure 14 shows a downhole drill string for air hammer drilling and Figure 15 flatbottom percussion bits. Since the DHD drill string is not subject to extreme torque loads and high RPM as with rotary drilling, components experience a much longer life. The absence of a heavy string of drill collars provides a much lighter drill string, which allows more hole depth for a given pullback capacity.

Stabilizers are used to control deviation and add stiffness to the drill string. The decision on whether to stabilize a drill string is largely a matter of operator preference. Stabilizers are rarely found in small diameter waterwell work (Ingersoll-Rand Construction Equipment).

JHD HSP 9000 JA
92.09.0575 JA



DECSRIPTION	SPECIFICATIONS	4½" DRILLPIPE SYSTEM	
Spindle	Box Down Thread	4" FH	
Spindle	Pin Up Thread	4" FH	
Sub	Box Down Thread	2⅞ IF	
Drill	Pin Up Thread	2⅞ IF	
Pipe	Size of Flat	3½"	
	Total Length	25'	
	O.D. Maximum	4.50"	
	Wall Thickness	337"	.674"
	Weight/Foot	17.2#	28.1#
	Box Down Thread	2⅞ IF	
Down Hole Drill	Model No.		DHD360
Sub	Pin Up Thread Flats Box Down Thread		
DHD	Pin Up Thread		2⅞ IF**
	Diameter		5⅜"
	Length		51"
	Weight		215 lbs.
	Air Pressure		150-350 PSI
DHD	Size		6B36
Button	and		6⅛B36
Bits	Model		6 3/16B36
	Number		6¼B36
			6½B36
			6½B36CF
			*8B36
			*8½B36DCBR

FIGURE 14: Downhole drill string for airhammer
(Ingersoll-Rand Construction Equipment)

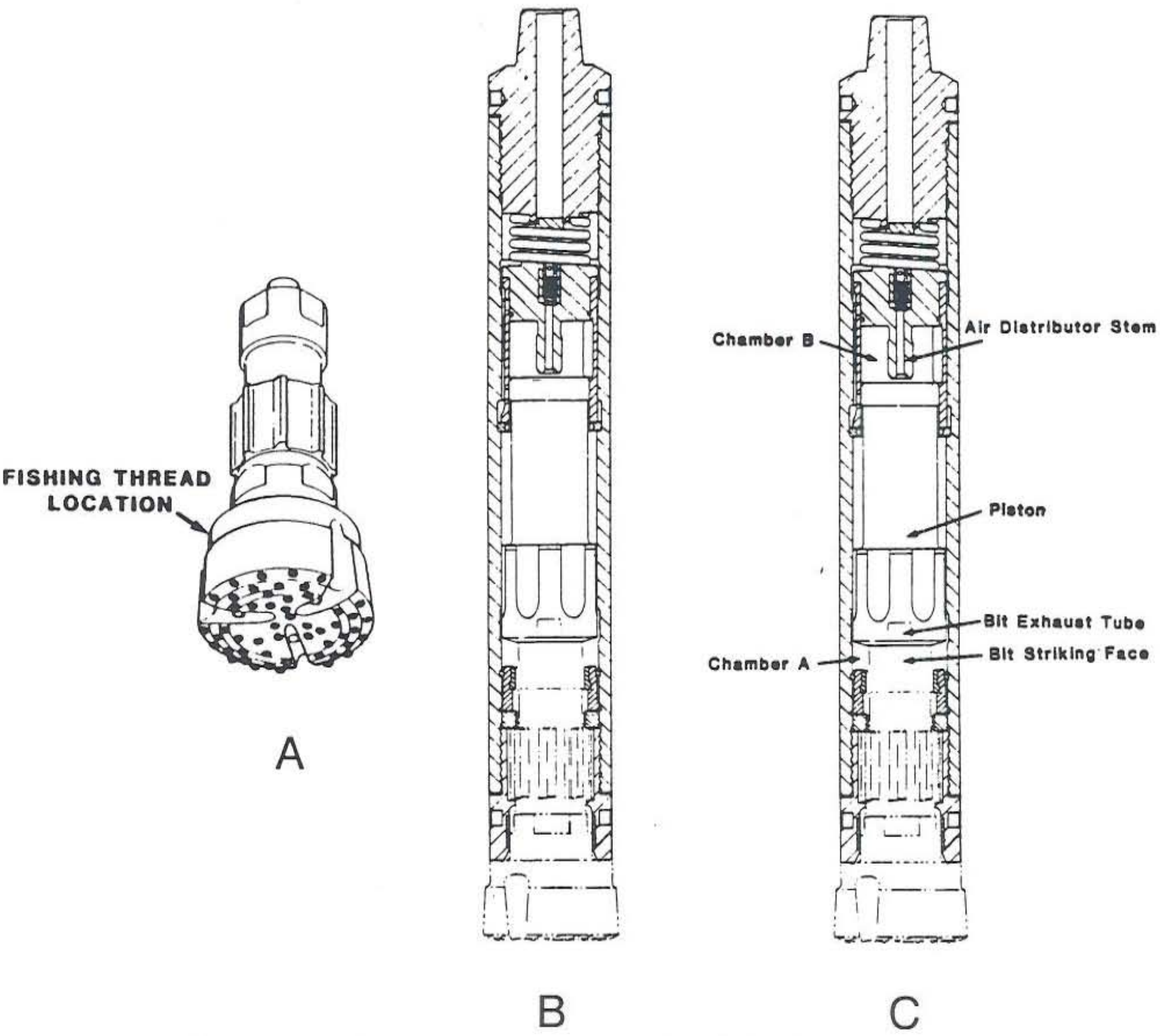


FIGURE 15: a) A typical flatbottom percussion bit; b) Model DHD 112; c) Model DHD 112 operating diagram (Whiteley and England, 1985)

Pressure loss

Pressure loss in the drill string can be calculated with the following formula (McCray and Cole, 1959):

$$F = \frac{fU^2 dL}{1024.2\, gD} \tag{3}$$

where

F is the flow friction pressure loss, kg/cm^2;
f is Fanning friction factor, dimensionless;
U is the air velocity, mt/s;
d is the air density, kg/m^3;
L is the length of the well, m;
g is the acceleration of gravity, 9.81 m/s^2;
D is the inner diameter of the drillpipe, m;

Air velocity can be considered from the following expression (McCray and Cole, 1959):

$$U = \frac{QTP_o Z}{AT_o P} \tag{4}$$

where

U is the air velocity, m/s;
Q is the air flow referred to standard conditions, m^3/min.;
T is the average air flow temperature, °K;
P_o is the standard pressure for air volume measurement, bar abs;
A is the cross-sectional flow area, m^2;
T_o is the standard temperature for air volume measurement, °K;
P is the average air flow pressure, bar abs;
Z is the average air compressibility factor, dimensionless (see Table Appendix II-B).

The Fanning friction factor can be read from the diagram in Appendix II-B and C after calculation of the Reynolds number by the formula (Verein Deutscher Ingenieure, 1963):

$$Re = \frac{D_i U}{\nu} \tag{5}$$

where

Re is the Reynolds number, dimensionless;
D_i is the inner diameter of drillpipe, m;
U is the air velocity, m/s;
ν is the kinematic viscosity, m^2/s.

4.7 The "Odex" method

Air drilling is difficult in poorly consolidated formations. The Odex method can be used to drill through loose overburden with casing at the same time (Sandvik Rock tools). It is considered a good advantage in unstable or poorly consolidated formations and also in drilling exploratory wells. The Odex string make-up with air consists of (Figures 16 and 17):

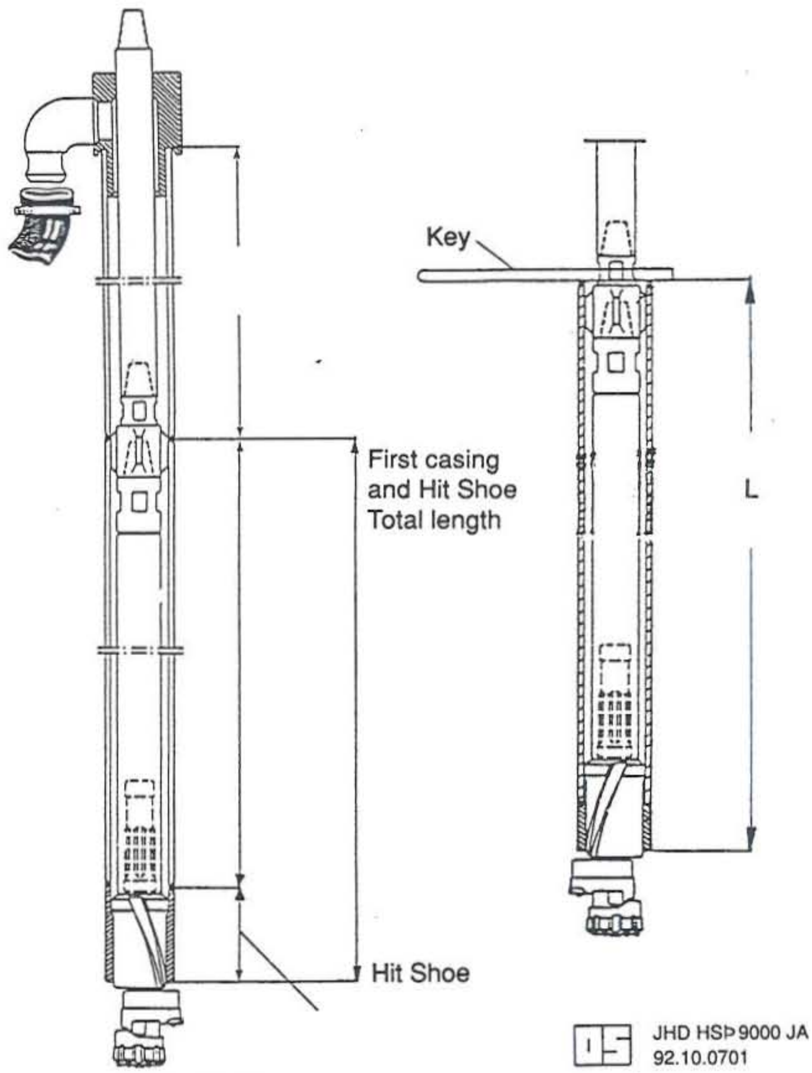


FIGURE 16: Odex string make-up (Sandvik Rock Tools)

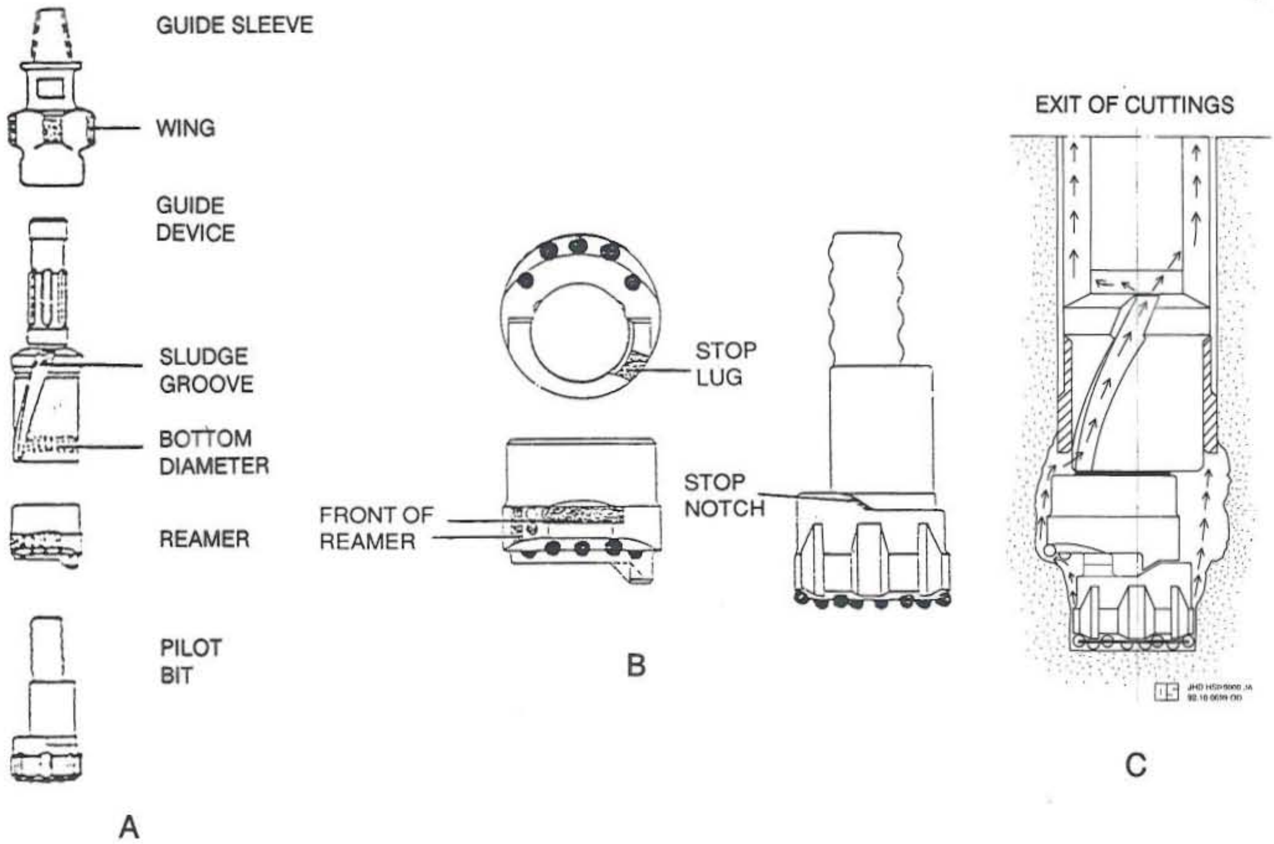


FIGURE 17: Details of an Odex drill bit; a) Odex assembly; b) Reamer detail; c) Exit of cuttings (Sandvik Rock Tools)

a) Bit;
b) Guide accesory;
c) Reamer with excentric axis respect to bit axis;
d) Casing shoe (hit shoe);
e) Casing string;
f) Guide accessories inside casing;
g) Drill string.

Recommended rpm, torque and depth values for the Odex method (with 12 bar pressure) are listed in Table 4. Another important fact is that the casing must have the same length as the drill pipe.

TABLE 4: The Odex method, recommendations for rpm, torque and depth (Sandvik Rock tools)

Odex	76	90	115	127	140	165	190	215	240
rpm	50-70	20-30	20-25	15-25	15-20	15-20	10-15	10-15	10-15
Min torque (N-m)	800	900	2000	2000	3000	4000	>6000	>6000	>6000
Max depth (m)	40	60	100	40	100	100	100	100	100

4.8 Maintenance

a. Beware of several major sources of damaging pollutants to the down hole drill system: acid water; dirty water; bentonite; dirty drillpipe (especially pipe that has been previously used for mud drilling); and, of course, a faulty check valve, which would allow water and dirt to back up into the hammer during drill pipe changes.

b. When storing drill pipe, keep ends capped to keep out dirt, rust.

c. Periodic disassembly and inspection is an important part of preventive maintenance.

d. The drill must be inspected at regular intervals for worn or damaged parts, and replacement parts installed when necessary. Under normal drilling conditions, disassemble the drill and inspect the parts every 200 hours of operation. In water well work and wet holes where mud is encountered, clean and inspect the drill parts every 100 hours of operation.

e. Remember to routinely replace simple parts such as check valve springs and bits exhaust tubes. Do not wait for these parts to fail. Replace them every disassembly inspection.

f. The importance of an adequate supply of the proper lubricant cannot be overstressed. The operator should always see a film of oil on the bit shank and a film of oil on the inside diameter of the drill pipe when making joints. If foam or water is being used, increase the oil injection rate.

On venturi-type lubricators, low ambient temperatures require an increased oil feed setting, while high ambient temperatures require a decreased oil feed setting. Positive displacement injection lubricators are usually unaffected by viscosity (Ingersoll-Rand Construction Equipment).

5. RESULTS OF AIR-HAMMER DRILLING AT LAUGALAND IN THELAMORK

The air drilling method with all the implied novelties offers interesting possibilities in drilling geothermal wells. The author witnessed the use of this method at Laugaland in Thelamork, N-Iceland during his stay in Iceland. It is simply fascinating to know how effective its use is in increasing the rate of penetration. The best way for assimilating this knowledge is to observe how the equipment works and the procedures used.

The author had the opportunity to appraise all the equipment characteristics, crew requirements, equipment maintenance, daily loggings, and pump tests made on the borehole. The well is called LÞN-11. Another low temperature well, called LÞN-10, was drilled 60 m away to a depth of 250 m in April, 1991. It did not yield enough hot water.

5.1 Rig and equipment description

Name	: Narfi / Type: Failing 3000.
Derrick height	: 18 m.
Rig capacity	: 1200 m.
Draw-works	: 120,000 pounds.
Pumps	: Gardner Denver, two pumps, Duplex, 5 ½ " ϕ piston : 15 l/sec, 3 ½ " ϕ piston : 7 l/sec.
Air Compressor	: Sullair (Sullair Corporation), Michigan City, Indiana, Helicoidal rotor system, Model No.: H900DU/350, Pressure: 350 psi, Air flowrate: 900 cfm.
Engine of compressor	: Type: Diesel, 500 HP (375 KW), 1950 rpm.
Tool	: Tungsten carbide inserts hammer: DHD-112 (12 ½"), DHD-380 (8 5/8"ϕ), Stabilizer (8 1/8" ϕ), Drill collar: 6 3/4" ϕ, 149.4 kg/m, Drill pipe: 4 ½" ϕ, 16.6 #/ft, Heavy weight drill pipe: 4 ½ " ϕ, 42 #/ft.

5.2 Drilling procedures and well design

The main objective in witnessing the drilling of Laugaland Þelamörk well LÞN-11 was to become acquainted with the procedure of drilling with the air hammer method. One of the main advantages is the good rate of penetration; another is that drilling fluid is not lost because circulation is maintained by air flowing.

The well was drilled for Hitaveita Akureyrar and the drilling contractor was Jardboranir hf. The well LÞN-11 was drilled to get hot water for the Akureyri community. The design of the well is shown in Figure 18. Drilling started on Friday, July 17. The first stage was drilled with 15 " ϕ rock bit using water and bentonite drilling fluid. The final depth of this stage was at 14 m. and 14 " O.D. casing was set and cemented after that. The second stage was drilled with a 12 ½" air

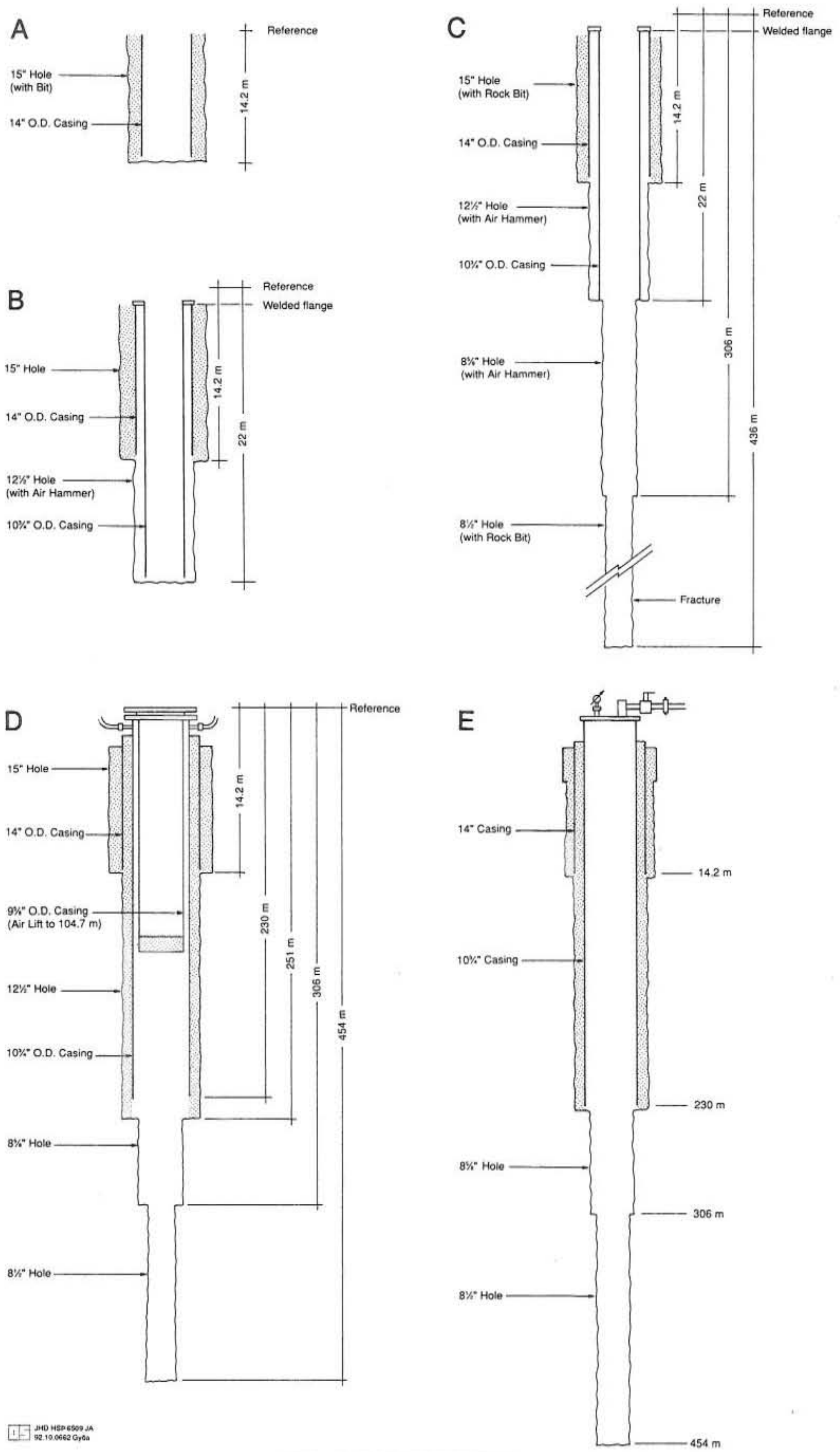


FIGURE 18: The progress and final design of well LÞN-11; a) First stage; b) Second stage; c) Third stage; d) Air lift; e) Final well design

hammer, using air as the drilling fluid. This hole was finished at 24 m depth and temporary 10 ¾" O.D. csg was placed but not cemented.

Third stage was drilled with an 8 ⅝" ϕ air hammer. This drilling started on Wednesday, July, 22. On that day they drilled with a 7.5 m/h average rate of penetration, compressor pressure 13 kg/cm^2, 2 ½ tons weight on hammer and 35 rpm rotation. The hammer was changed for a rotary drilling bit (8 ½") on Friday, July 24 after the interval from 24 m to 306 m had been drilled with the air hammer. A considerable change in the rate of penetration could be seen. The rotation speed and weight on the bit was changed to 64 rpm and 7.5 ton, respectively. The average time to recuperate the drill pipes was 1.5 min/pipe.

Pressure loss in drill string can be calculated from Formulae 3, 4 and 5 for drilling with an air hammer. To obtain the air kinematic viscosity, air density and the Fanning friction factor it is necessary to see the tables and diagram, Appendix II-C and Appendix II-D, respectively.

At the first stage (24 m depth), the pressure loss in drill string was 0.01 bar and 0.11 bars for the second stage (306 m depth). These results agree with the pressure loss obtained from the Table in Appendix II-E (see 25.5 cmm with 95.2 mm inner diameter).

Also the bailing velocity can be calculated with Equation 1, considering 23 m^3/min air flowrate to 12 ½" and 8 ⅝" bits, the bailing velocities to 4 ½" drillpipe diameter are 5.5 m/sec and 13.8 m/sec, respectively.

Table 5 summarizes the drilling of LÞN-11 from July 17 until August 19:

TABLE 5: Activities during the drilling of well LÞN-11

Activities	Date	Day	Hours	Hole ϕ	m/day	m/hour	Comments
First stage							
Beginning	Jul 17	1	9	15"	14	2	15" rock bit (mud)
14 " csg cementing	" 18	2	14	15"			Surface casing
Second stage							
Activities	Date	Day	Hours	Hole ϕ	m/day	m/hour	Comments
Drilling	Jul 19	3	3	12 ½"	6	4.3	12 ½" air hammer
10 ¾" OD csg placing	" 20	4	14	12 ½"			Temporary csg welding
Third stage							
Activities	Date	Day	Hours	Hole ϕ	m/day	m/hour	Comments
Drilling	Jul 21	5	14	8 ⅝"	138	17.8	ROP 40 m/h at 44, 60 and 140 m, resp.
Drilling	" 22	6		8 ⅝"	64	7.5	ROP 24 m/h at 200m
Drilling	" 23	7	15	8 ⅝"	58	7.73	Dev: 0.5° (250 m)

Drilling hamm.chg.	" 24	8	15	8 ⅝"	10	2	8 1/2", J44 Hughes rock bit placed (306 m)
Drilling	" 25	9	15	8 ½"	12	4.4	Pumping problems
Drilling, mechan. rep.	" 26	10	14	8 ½"	34	4.75	Old piston replaced
Drilling mechan. rep.	" 27	11	15	8 ½"	24	3	Pumping problems
Drilling, mechan. rep.	" 28	12	15	8 ½"	40	3.6	Piston rod repaired
Drilling	" 29	13	15	8 ½"	20	4.48	Total loss of circulat. found at 436 m
Air lift test	" 30	14	14	8 ½"			40-60 l/s measured
Well in observation	" 31	15	14	8 ½"			5.5 m^3 of red rock placed inside the hole and 1 m^3 of sand
Fourth stage							
Activities	Date	Day	Hours	Hole ϕ	m/day	m/hour	Comments
8 ½" hole, cementing	Aug 1	16	16	8 ½"			14 sacks of Portland cement
Cementing	" 2	17	16	8 ½"			26 sacks of Portland cement
Reaming	" 3	18	15	12 ½"			Reaming from 22.4 m to 51.2 m
Reaming	" 4	19	15.5	12 ½"			Reaming from 51.2 m to 128.2 m
Reaming	" 5	20	16	12 ½"			Reaming from 128.2 m to 212.2 m
Reaming	" 6	21	16	12 ½"			Reaming from 212.2 m to 251 m
Running casing	" 7	22	16				10 3/4" casing
Waiting on cementing	" 8	23	15				Cementing, waiting (15.2 m^3 slurry)
Test	" 9	24	16				Air-Lift casing
Cement drilling	" 10	25	16	8 ½"			Top of cement from 234 m. Drilling to 340.5 m
Cleaning the sand	" 11	26	17	8 ½"	2.9		Cleaning sand from 437.7 m to 438.9 m
Drilling	" 12	27	15	8 ½"	12.8		Drilling from 438.9 m to 451.7 m. Problems 440-445 m

Pulling out the drill pipe	" 13	28	16	8 ½"			Pulling out drill pipe
Test	" 14	29	16	8 ½"			Air lift casing to 104.7 m
Trying to drill	" 15	30	16	8 ½"	2.3		Drilling to 454 m, slough 440 - 445 m
Test	" 16	31	16	8 ½"			Pump test finish
Preparing for transport	" 17	32	16.5				Prep. to transport
Preparing for transport	" 18	33	15				Prep. to transport

5.3 Rate of penetration for wells LÞN-10 and LÞN-11

Figure 19 shows a comparison of the rate of penetration for wells LÞN-10 and LÞN-11. It shows clearly the higher penetration rates achieved with air hammer drilling down to 400 m in LÞN-10 and 306 m in LÞN-11.

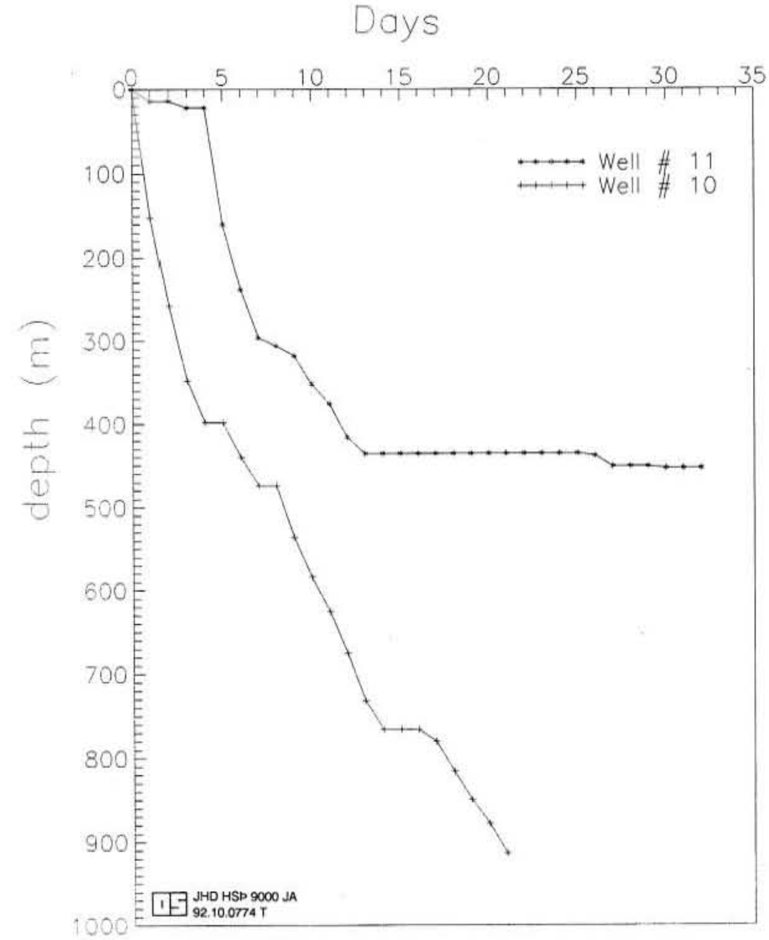


FIGURE 19: Comparison for rate of penetration for wells LÞN-10 and LÞN-11

5.4 Reservoir analysis for Laugaland

1) Drilling of wells 1-4 during 1941-1970. Wells 2 and 3 are productive and give 2-3 l/s of 90°C in long term production (artesian).

2) Extensive mapping of vertical zones of high electrical conductivity and of the near surface magnetic field, resulted in location map of dykes and low resistivity fractures.

3) Drilling of 5 exploration wells in 1989 and 1990 (wells 5-9). Resulted in determination of the formation temperature and indicated a lateral flow from an upflow zone, north of wells 5 and 6.

4) The upflow zone was proposed to follow the NE-SW low resistivity fracture on the banks of Hörgá river, and this fracture was, furthermore, believed to be inclined toward the east. Well

LÞN-10 was intended to intersect this structure at 600-800 m depth. However, no permeable zones were detected in the well.

5) The geological informations, obtained by the drilling of LÞN-10, showed that the permeable zone in the reservoir had to be inclined to the west, either along a dyke which is permeable in wells 2, 3 and 5, or along the low resistivity fracture.

6) Well LÞN-11 was, therefore, located 50 m west of LÞN-10. The permeable dyke has an inclination of 6° and should be intersected at 430 m depth in the well. The inclination of the low resistivity fracture is unknown, but drilling down to 800-1000 m depth was recommended in order to estimate this inclination.

7) Well LÞN-11 intersected a permeable zone at 426 m. Airlifting showed that wells 2, 3, 5 and 6 are in good hydrological connection with LÞN-11, whereas wells 8, 9 and LÞN-10 are outside the permeable region (see Figure 20) . Recovery of the water level implies that a deep recharge from deep below is taking place in the reservoir.

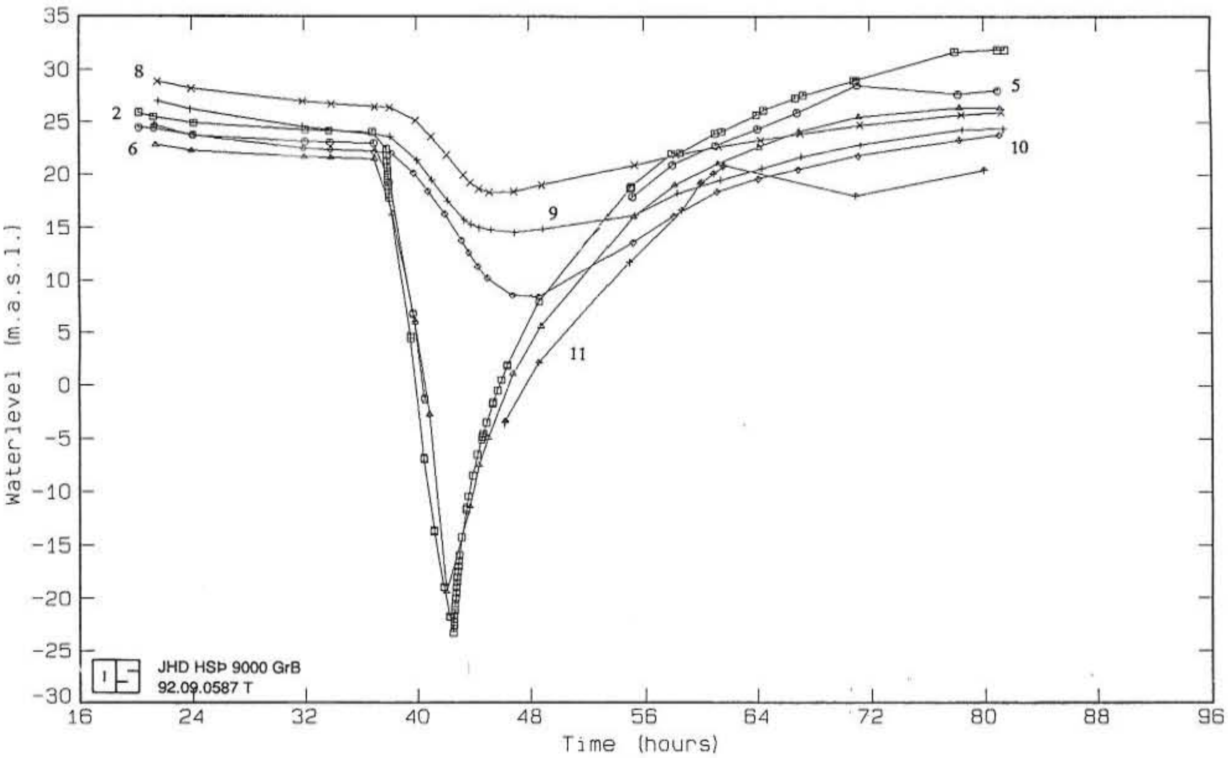


FIGURE 20: Variation in water level in Thelamork wells during airlifting in LÞN-11

6. CABLE TOOL DRILLING

6.1 Definition

This method uses only the basic principle of percussive forces. Dropping of the tools is not enough, it is the snap of the tool that makes the hole. In this method, all tools used in drilling operations are lowered into the well on steel cables.

6.2 History

The percussion drilling method is thousands of years old. The ancient Egyptians used tubular drills rotating under pressure with abrasive quartz for obtaining cores in hard rocks. Chinese use of percussion drilling to obtain salt and water from a depth of nearly 1,200 m is also reported in ancient literatures (Chugh, 1979)

Cable tool drilling methods have been employed continuously in the petroleum industry since the first oil well, the Drake well, was drilled near Titusville, Pennsylvania, in 1859.

6.3 Applications of the cable tool

This type of method is used in Iceland to drill the first stage in geothermal wells (24"ϕ hole for 20" OD casing). The main surface machinery consists of a hoist for withdrawing the various cables from the hole and some means of imparting reciprocal motion to the drilling cable. No fluid is circulated in the hole. However, water as drilling fluid can be used and is recommended if the geothermal field is very hot and shallow high temperature springs are expected. Figure 21 shows a typical cable tool drilling rig.

Cable tools are often used for drilling sensitive formations which might be damaged by rotary drilling mud, even though rotary methods were used to drill down to the top of the formation.

The drilling operations are intermittent in nature and tend to give slower rates of penetration than rotary methods. However, the investment and operating costs are much lower. Although many cable-tool wells have been drilled to depths of 2,400 m or more, the best operating total depth limits are probably less than 600 m (McCray and Cole, "Oil Well Drilling Technology", 1959).

The general drilling procedure consists of drilling about 1 to 2 m of hole, withdrawing the drilling tools, then removing the drilled rock material from the hole with a bailer and again proceeding with actual drilling.

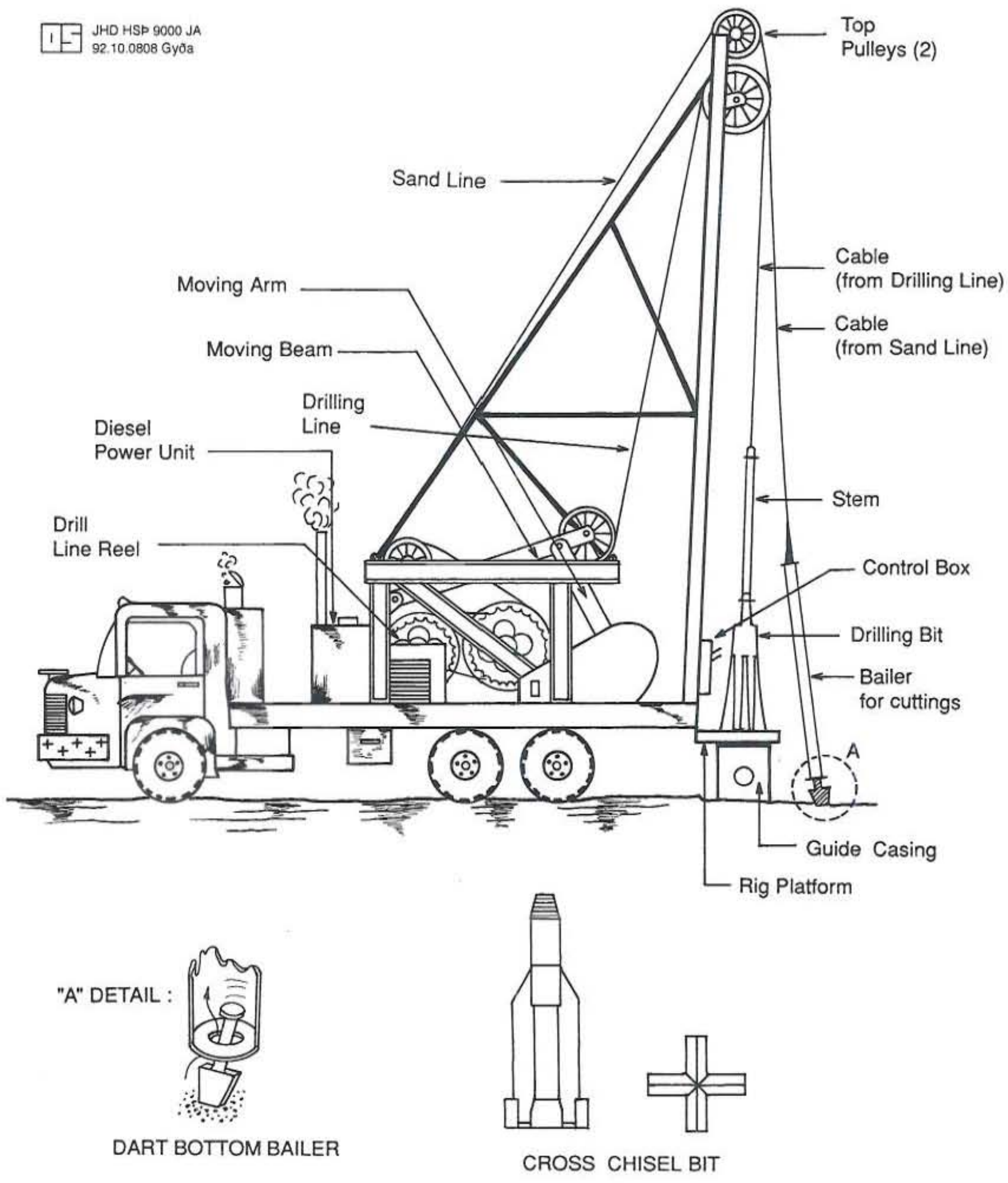


FIGURE 21: Diagram for a cable tool drilling rig

7. CONCLUSIONS

Because of the many benefits directional drilling should be considered as an viable alternative when a geothermal well is being designed. The technology is proven, but is only applied when it is considered necessary. Directional drilling increases the cost of a geothermal well by about 20-25%.

Air hammer drilling can be considered as an alternative for reducing drilling costs and to increase rates of penetration; nevertheless, initial investments must be considered (compressors, tools). The ground characteristics may dictate the use of the Odex method for loose overburden drilling.

The first stage of geothermal drilling, for the large diameter surface casing, can be drilled with a cable tool rig. The benefits can be realized for all geothermal wells in a project area by lower costs and by insuring that the large rotary rig can start drilling with more weight on bit, free of the common problems of loose overburden at shallow depths in many geothermal fields.

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APPENDIX I: Information about directional drilling

A. A typical directional drilling program

Location

Wellhead coordinates
Elevation m a.s.l.

Objectives

Well data

Target depth:
Measured depth
Vertical depth (true depth)
Kick off point (KOP)
Build-up angle
Bottom hole throw
Throw azimuth
Drift angle

Hole Sizes

26" ϕ hole
17 ½" ϕ hole
12 ¼" ϕ hole
8 ½" ϕ hole

Casing/Liner Data

20" surface casing
13 3/8" anchor csg
9 5/8" production csg
7 5/8" production liner

Casing cementing design

Surface
Anchor csg

Drilling fluid (fresh H_2O base mud)

26" ϕ hole
17 ½" ϕ hole
12 ¼" ϕ hole
8 ½" ϕ hole

Viscosity
Mud weight
Gel strength
Plastic viscosity
Yield point
Water loss
Sand content

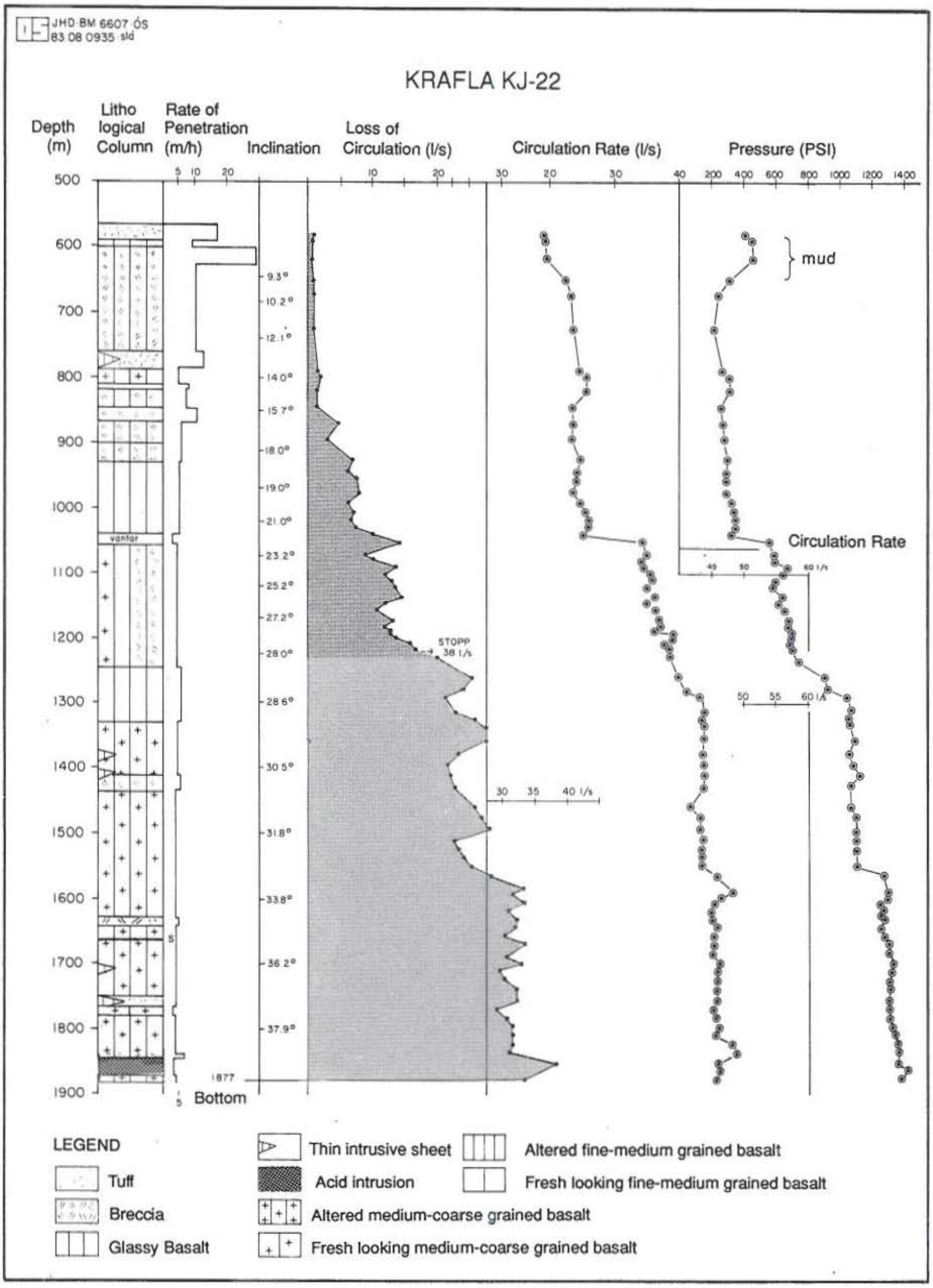
Completion test

Rig release

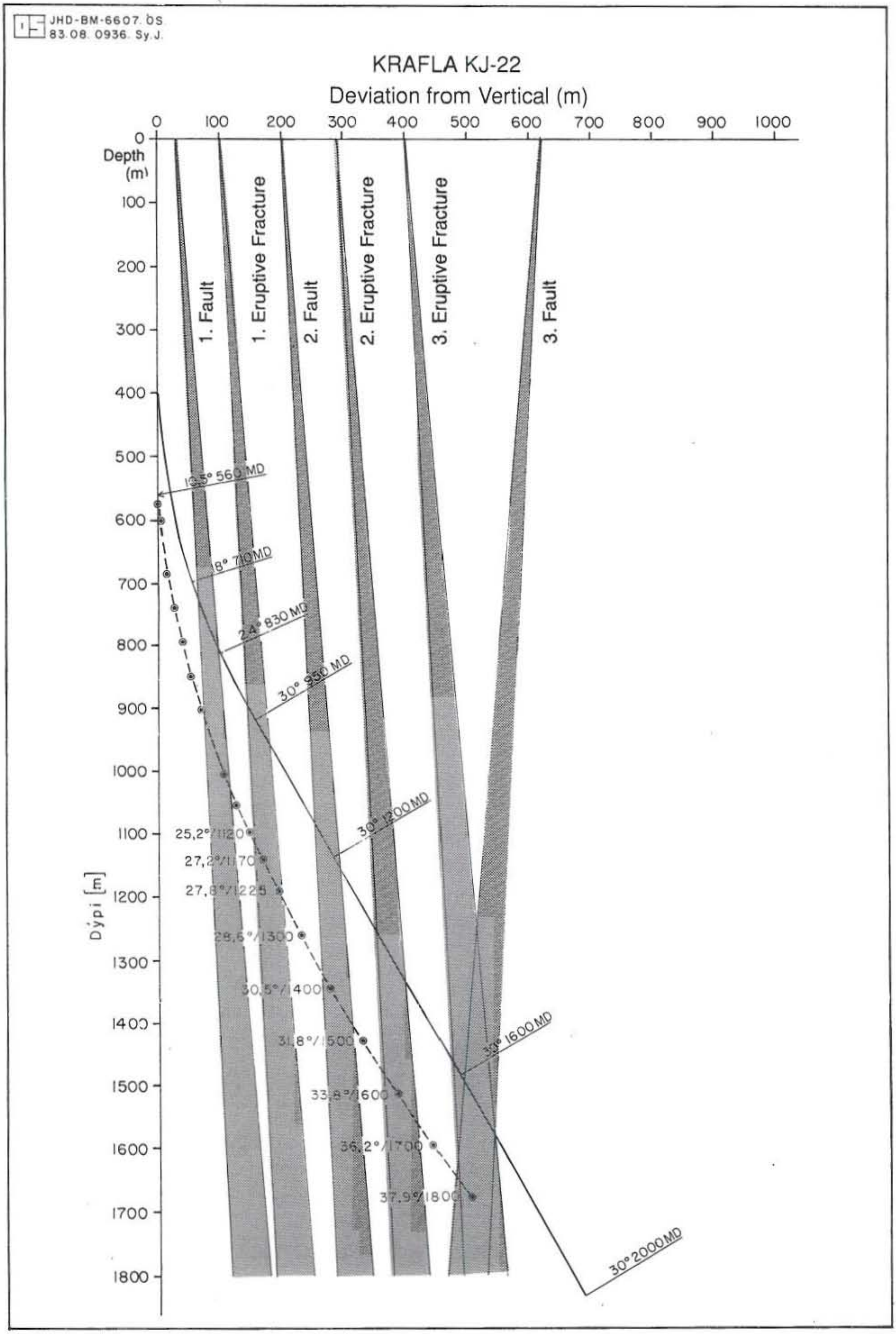
B. Equipment required

Item	Description	Qty.		Company
1.	6 ½" PDM	2	Rent	Dynadrill
2.	Kick sub 1 ½° and 2 ½°	2	Rent	
3.	12 ¼" near bit stabilizer	1	Purch	
4.	8 ½" string stabilizer	3	Purch	
5.	8 ½" near bit stabilizer	2	Purch	
6.	12 ¼" bit (rolling element)		Purch	JBR
7.	8 ½" bit (rolling element)		Purch	JBR
8.	Gyro (MS & SS)	2	Rent	Sperry Sun
9.	Key Seat Wiper for 6 ½" collars		Purch	
10.	Collars 6 ½"	15 pcs	Purch	JBR

C. Drilling parameters and geological sections from deviated part of Krafla well KJ-22

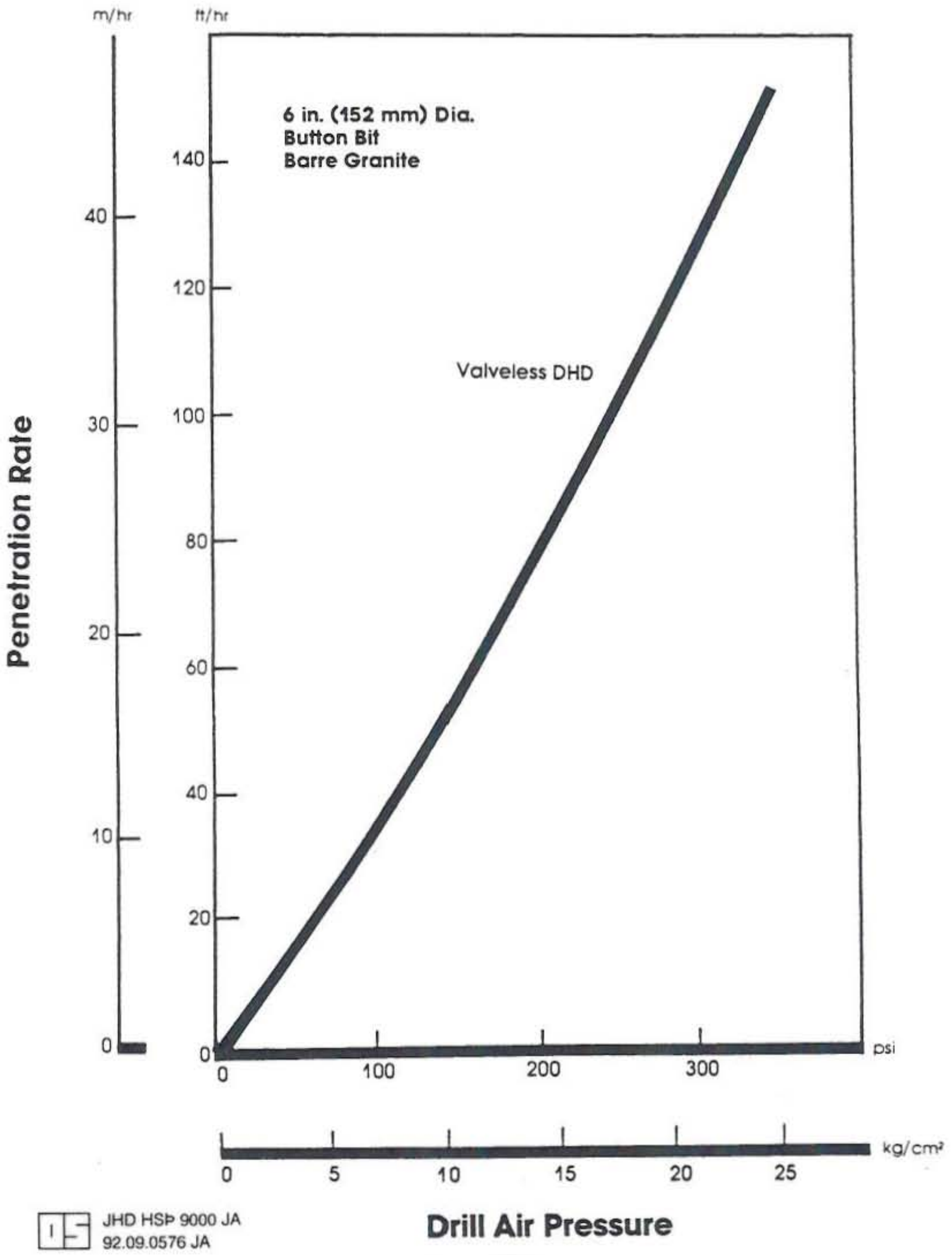


D. Deviation from vertical, Krafla well KJ-22



APPENDIX II: Tables and diagrams for air hammer drilling

A. Air pressure vs. penetration rate (Ingersoll-Rand Construction Equipment)



B. Air Compressibility factor (Verein Deutscher Ingenieure, 1963)

Tabelle 11. Spezifisches Gewicht γ der Luft in kg/m³ in Abhängigkeit von Druck und Temperatur

Druck	Temperatur in °C							
ata	0	20	50	100	150	200	300	400
1	1,2514	1,166	1,057	0,915	0,807	0,722	0,596	0,507
1,033	1,2930	1,204	1,092	0,9458	0,8343	0,7457	0,6157	0,5242
20	25,28	23,46	21,19	18,26	16,08	14,35	11,83	10,07
40	50,98	47,14	42,39	36,38	31,97	28,51	23,49	20,02
60	77,01	70,84	63,47	54,29	47,61	42,45	34,97	29,80
80	103,0	94,54	83,34	72,03	63,05	56,15	46,26	39,43
100	128,9	118,0	105,0	89,45	78,22	69,60	57,33	48,90
150	191,2	174,5	154,9	132,5	114,9	102,3	84,18	71,87
200	248,8	226,9	201,5	171,2	149,6	133,3	109,8	93,88
250	297,8	273,4	243,7	207,9	182,0	162,4	134,1	114,9
300	342,9	316,5	283,3	242,5	218,8	190,2	157,3	135,0

Tabelle 12. $(p\,v)$-Werte der Luft bezogen auf $p_0 v_0 = 1{,}000$ für 0 °C und 1 ata

Druck	Temperatur in °C												
ata	−100	−75	−50	−25	0	25	50	75	100	150	200	300	400
0	0,634	0,726	0,817	0,909	$1{,}000_6$	1,092	1,184	1,275	1,367	1,550	1,733	2,099	2,466
1	0,632	0,724	0,816	0,908	1,000	1,092	1,184	1,275	1,367	1,550	1,734	2,100	2,467
10	0,611	0,710	0,806	0,901	0,995	1,089	1,182	1,275	1,369	1,553	1,739	2,107	2,475
20	0,587	0,693	0,794	0,893	0,990	1,086	1,181	1,276	1,371	1,557	1,744	2,115	2,485
40	0,536	0,659	0,772	0,879	0,982	1,082	1,181	1,278	1,376	1,566	1,756	2,131	2,501
60	0,487	0,627	0,751	0,866	0,975	1,081	1,183	1,283	1,383	1,577	1,769	2,147	2,520
80	0,445	0,601	0,735	0,857	0,972	1,081	1,187	1,289	1,391	1,588	1,783	2,164	2,539
100	0,416	0,582	0,724	0,852	0,971	1,083	1,192	1,296	1,399	1,600	1,798	2,183	2,559
150					0,982	1,099	1,212	1,321	1,417	1,634	1,835	2,230	2,612
200					1,006	1,127	1,242	1,353	1,462	1,673	1,878	2,280	2,666
300					1,095	1,209	1,325	1,438	1,548	1,764	1,974	2,386	2,782
400					1,198	1,315	1,429	1,541	1,650	1,867	2,079	2,497	2,900

Aus dieser Tabelle erhält man das spez. Gewicht von Luft nach der Beziehung:

$$\gamma_{p,t} = \frac{p\,\gamma_0}{p_0\,(p\,v)} = 1{,}2514\,\frac{p}{(p\,v)} \quad \text{in kg/m}^3$$

Tabelle 13. Kompressibilitätszahlen der Luft $\dfrac{(p\,v)_{t,p}}{(p\,v)_{t,p=1}}$

Druck	Temperatur in °C												
ata	−100	−75	−50	−25	0	25	50	75	100	150	200	300	400
0	1,003	1,003	1,001	1,001	$1{,}000_6$	1,000	1,000	1,000	1,000	1,000	0,999	1,000	1,000
1	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
10	0,967	0,981	0,988	0,992	0,995	0,997	0,998	1,000	1,001	1,002	1,002	1,003	1,003
20	0,929	0,957	0,973	0,983	0,990	0,995	0,997	1,001	1,002	1,005	1,005	1,007	1,007
40	0,848	0,910	0,946	0,968	0,982	0,991	0,997	1,002	1,006	1,010	1,012	1,015	1,014
60	0,771	0,866	0,920	0,954	0,975	0,990	0,999	1,006	1,012	1,017	1,020	1,022	1,021
80	0,704	0,830	0,901	0,944	0,972	0,990	1,003	1,011	1,017	1,025	1,028	1,030	1,029
100	0,658	0,804	0,887	0,938	0,971	0,992	1,006	1,016	1,023	1,032	1,036	1,040	1,037
150					0,982	1,006	1,024	1,036	1,037	1,054	1,058	1,062	1,059
200					1,006	1,032	1,049	1,061	1,069	1,079	1,083	1,086	1,081
300					1,095	1,107	1,119	1,128	1,132	1,138	1,138	1,136	1,128
400					1,198	1,204	1,207	1,209	1,207	1,205	1,199	1,189	1,176

C. Reynolds number vs. Fanning friction factor (Verein Deutscher Ingenieure, 1963)

VDI-Wärmeatlas 1963	Widerstandsbeiwerte von rauhen Rohren	Lb 3

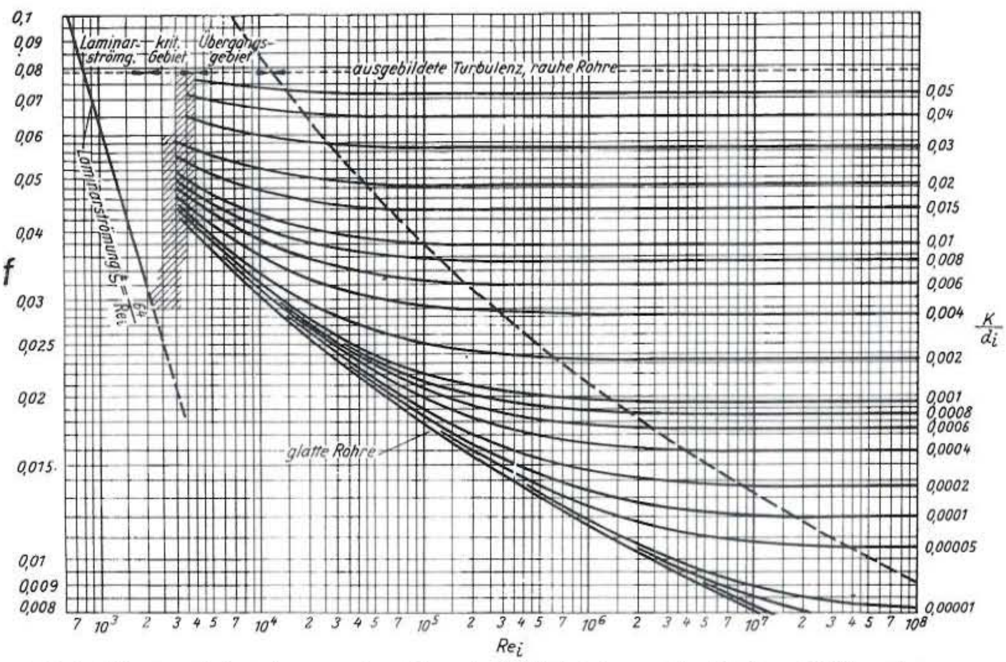


Bild 1. Widerstandsbeiwert ζ von rauhen Rohren in Abhängigkeit vom Rauhigkeitsmaß K/d_i und von der Reynolds-Zahl Re_i

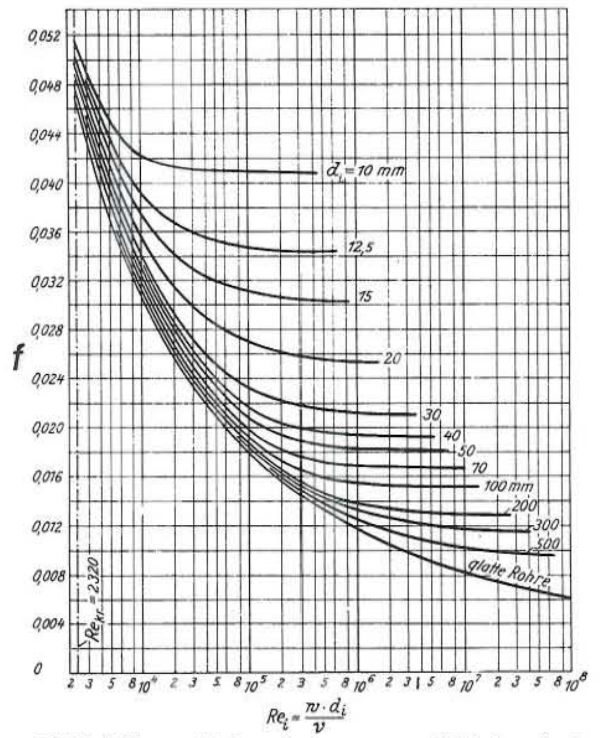


Bild 2. Widerstandsbeiwert ζ von gezogenen Stahlrohren (neu) in einer Zussmmenstellung von *Hausen* [14] nach experimentellen Werten verschiedener Forscher

D. Air properties tables (Verein Deutscher Ingenieure, 1963)

VDI-Wärmeatlas 1953	Stoffwerte für Luft*)	Db 4

Tabelle 8. Stoffwerte für trockene Luft bei 760 mm QS (1,033 ata) (normale Zusammensetzung)

t Temperatur
γ spezifisches Gewicht
c_p spezifische Wärme bei konstantem Druck
λ Wärmeleitzahl
η dynamische Zähigkeit
ν kinematische Zähigkeit
β Wärmeausdehnungszahl
a Temperaturleitzahl
Pr Prandtl-Zahl

t °C	γ kg/m³	c_p kcal$_{IT}$/kg grd	λ kcal$_{IT}$/m h grd	$\eta \cdot 10^6$ kg s/m²	$\nu \cdot 10^6$ m²/s	$\beta \cdot 10^3$ 1/grd	a m²/h	Pr
−150	2,793	0,245	0,0103	0,887	3,11	8,21	0,0151	0,74
−100	1,980	0,241	0,0142	1,203	5,96	5,82	0,0298	0,72
− 50	1,534	0,240	0,0177	1,494	9,55	4,51	0,0481	0,72
0	1,2930	0,240	0,0209	1,754	13,30	3,67	0,0673	0,715
20	1,2045	0,240	0,0221	1,855	15,11	3,43	0,0763	0,713
40	1,1267	0,240	0,0233	1,950	16,97	3,20	0,086	0,711
60	1,0595	0,241	0,0245	2,042	18,90	3,00	0,096	0,709
80	0,9998	0,241	0,0257	2,134	20,94	2,83	0,1065	0,708
100	0,9458	0,241	0,0270	2,224	23,06	2,68	0,118	0,703
120	0,8980	0,242	0,0282	2,311	25,23	2,55	0,130	0,70
140	0,8535	0,242	0,0295	2,397	27,55	2,43	0,143	0,695
160	0,8150	0,243	0,0308	2,481	29,85	2,32	0,155	0,69
180	0,7785	0,244	0,0320	2,564	32,29	2,21	0,168	0,69
200	0,7457	0,245	0,0332	2,635	34,63	2,11	0,182	0,685
250	0,6745	0,247	0,0362	2,832	41,17	1,91	0,217	0,68
300	0,6157	0,250	0,0390	3,005	47,85	1,75	0,253	0,68
350	0,5662	0,252	0,0417	3,178	55,05	1,61	0,292	0,68
400	0,5242	0,255	0,0443	3,340	62,53	1,49	0,331	0,68
450	0,4875	0,258	0,0467	3,508	70,54		0,371	0,685
500	0,4564	0,261	0,0490	3,653	78,48		0,411	0,69
600	0,4041	0,266	0,0535	3,938	95,57		0,497	0,69
700	0,3625	0,271	0,0573	4,202	113,7		0,583	0,70
800	0,3287	0,276	0,0607	4,451	132,8		0,669	0,715
900	0,301	0,280	0,0637	4,68	152,5		0,756	0,725
1000	0,277	0,283	0,0662	4,89	173		0,846	0,735

Tabelle 9. Wärmeleitzahl λ von Luft in kcal$_{IT}$/m h grd in Abhängigkeit von Druck und Temperatur

Druck	Temperatur in °C					
ata	0	20	40	60	80	100
1	0,0209	0,0221	0,0233	0,0245	0,0257	0,0270
100	0,0256	0,0266	0,0275	0,0284	0,0294	0,0303
200	0,0314	0,0318	0,0323	0,0328	0,0334	0,0340
300	0,0380	0,0380	0,0381	0,0382	0,0383	0,0385
400	0,0442	0,0439	0,0436	0,0432	0,0428	0,0424
500	0,0505	0,0498	0,0491	0,0484	0,0477	0,0470

Tabelle 10. Dynamische Zähigkeit η in kg s/m² und kinematische Zähigkeit ν in m²/s von Luft in Abhängigkeit von Druck und Temperatur

Druck	0 °C		20 °C		50 °C		100 °C		150 °C	
ata	$\eta \cdot 10^6$	$\nu \cdot 10^6$	$\eta \cdot 10^6$	$\nu \cdot 10^6$	$\eta \cdot 10^6$	$\nu \cdot 10^6$	$\eta \cdot 10^6$	$\nu \cdot 10^6$	$\eta \cdot 10^6$	$\nu \cdot 10^6$
1	1,754	13,75	1,855	15,60	1,999	18,54	2,224	23,84	2,439	29,64
1,033	1,754	13,30	1,855	15,11	1,999	17,95	2,224	23,06	2,439	28,68
20	1,805	0,700	1,893	0,791	2,037	0,943	2,254	1,210	2,455	1,498
40	1,860	0,358	1,942	0,404	2,077	0,481	2,285	0,615	2,476	0,759
60	1,920	0,2445	2,002	0,277	2,118	0,327	2,318	0,419	2,500	0,515
80	1,983	0,1888	2,060	0,214	2,165	0,252	2,352	0,320	2,526	0,393
100	2,05	0,1559	2,11	0,1757	2,21	0,2065	2,39	0,262	2,56	0,320
150	2,22	0,1140	2,26	0,1272	2,35	0,1485	2,49	0,1843	2,64	0,225
200	2,41	0,0949	2,43	0,1050	2,49	0,1213	2,61	0,1494	2,73	0,1791
250	2,62	0,0863	2,61	0,0936	2,64	0,1064	2,73	0,1288	2,84	0,1529
300	2,83	0,0808	2,79	0,0864	2,80	0,0969	2,86	0,1156	2,94	0,1356

*) nach Zusammenstellungen der Phys.-Techn. Bundesanstalt (Dr.-Ing. W. Fritz)

E. Loss of air pressure due to friction (Compressed Air and Gas Institute, 1954)

TABLE 6-22. LOSS OF AIR PRESSURE DUE TO FRICTION
(In psi in 1,000 ft of pipe,* 125-lb gauge initial pressure)

Cu ft free air per min	Equivalent cu ft compressed air per min	Nominal diameter, in.															
		½	¾	1	1¼	1½	2	2½	3	3½	4	4½	5	6	8	10	12
10	1.05	5.35	0.82	0.23													
20	2.11	21.3	3.21	0.92	0.21												
30	3.16	48.0	7.42	2.07	0.47	0.21											
40	4.21	.....	13.2	3.67	0.85	0.38											
50	5.26	.....	20.6	5.72	1.33	0.59											
60	6.32	.....	29.7	8.25	1.86	0.84	0.23										
70	7.38	.....	40.5	11.2	2.61	1.15	0.31										
80	8.42	.....	53.0	14.7	3.41	1.51	0.40										
90	9.47	.....	68.0	18.6	4.30	1.91	0.51	0.20									
100	10.50	.....	.....	22.9	5.32	2.36	0.63	0.25									
125	13.15	.....	.....	39.9	8.4	3.70	0.98	0.38									
150	15.79	.....	.....	51.6	12.0	5.30	1.41	0.55	0.17								
175	18.41	.....	.....	.....	16.3	7.2	1.95	0.75	0.24								
200	21.05	.....	.....	.....	21.3	9.4	2.52	0.98	0.31								
250	26.30	.....	.....	.....	33.2	14.7	3.94	1.53	0.48	0.22							
300	31.60	.....	.....	.....	47.3	21.2	5.62	2.20	0.70	0.32							
350	36.80	.....	.....	.....	.....	28.8	7.7	3.00	0.94	0.44	0.22						
400	42.10	.....	.....	.....	.....	37.6	10.0	3.91	1.23	0.57	0.28						
450	47.30	.....	.....	.....	.....	47.7	12.7	4.92	1.55	0.72	0.37	0.20					
500	52.60	.....	.....	.....	.....	58.8	15.7	6.10	1.93	0.89	0.46	0.25					
600	63.20	.....	.....	.....	.....	.....	22.6	8.8	2.76	1.28	0.65	0.36					
700	73.80	.....	.....	.....	.....	.....	30.0	11.9	3.74	1.75	0.89	0.49					
800	84.20	.....	.....	.....	.....	.....	40.2	15.6	4.85	2.28	1.17	0.64					
900	94.70	.....	.....	.....	.....	.....	51.2	19.8	6.2	2.89	1.48	0.81					
1,000	105.1	.....	.....	.....	.....	.....	63.2	24.5	7.7	3.57	1.82	1.00					
1,500	157.9	.....	.....	.....	.....	.....	.....	55.0	17.2	8.0	4.1	2.25	1.24	0.47			
2,000	210.5	.....	.....	.....	.....	.....	.....	.....	30.7	14.2	7.3	4.0	2.24	0.82	0.19		
2,500	263.0	.....	.....	.....	.....	.....	.....	.....	48.0	22.3	11.4	6.2	3.4	1.30	0.31		
3,000	316	.....	.....	.....	.....	.....	.....	.....	69.2	32.1	16.4	9.0	4.9	1.86	0.43		
3,500	368	.....	.....	.....	.....	.....	.....	.....	.....	47.7	22.3	12.1	6.9	2.51	0.57	0.18	
4,000	421	.....	.....	.....	.....	.....	.....	.....	.....	57.0	29.2	15.9	8.9	3.30	0.77	0.23	
4,500	473	.....	.....	.....	.....	.....	.....	.....	.....	.....	37.0	20.1	11.1	4.2	0.98	0.29	
5,000	526	.....	.....	.....	.....	.....	.....	.....	.....	.....	45.7	24.8	13.9	5.2	1.21	0.36	
6,000	632	.....	.....	.....	.....	.....	.....	.....	.....	.....	65.7	35.8	19.8	7.5	1.74	0.52	0.20
7,000	738	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	48.8	26.9	10.0	2.37	0.72	0.27
8,000	842	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	63.7	35.2	13.2	3.10	0.93	0.38
9,000	947	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	44.7	16.7	3.93	1.18	0.47
10,000	1,051	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	55.2	20.6	4.85	1.46	0.57
11,000	1,156	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	25.0	5.8	1.76	0.68
12,000	1,262	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	29.7	7.0	2.09	0.81
13,000	1,368	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	35.0	8.1	2.44	0.95
14,000	1,473	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	40.3	9.7	2.85	1.11
15,000	1,579	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	46.5	10.9	3.26	1.26
16,000	1,683	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	53.0	12.4	3.72	1.45
18,000	1,893	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	66.9	15.6	4.71	1.83
20,000	2,150	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	19.4	5.8	2.20
22,000	2,315	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	23.4	7.1	2.74
24,000	2,525	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	27.8	8.4	3.17
26,000	2,735	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	32.6	9.8	3.83
28,000	2,946	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	37.9	11.4	4.4
30,000	3,158	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	43.5	13.1	5.1

* For longer or shorter lengths of pipe the friction loss is proportional to the length, *i.e.*, for 500 ft, one-half of the above; for 4,000 ft, four times the above, etc.