AUSTRALASIAN OIL & GAS REVIEW

DRILLING LARGE DIAMETER HOLES

By J. H. Allen
Manager - Mining & Industrial Sales
Smith Tool Co.
Compton, California

Smith TOOL CO. DIVISION OF SMITH INTERNATIONAL, INC.

DRILLING LARGE DIAMETER HOLES

By J. H. Allen
Manager - Mining & Industrial Sales
Smith Tool Co.
Compton, California

During the past ten years new methods, equipment and circulation systems have been developed for the rotary drilling of large diameter holes. Diameters of 144 in. have now become practical.

Big hole footage in the U.S.A. has increased from 5,000 ft. in 1959 to 117,000 ft. in 1967. Since 1959 500,000 linear ft. of hole larger than 36 in. have been drilled by rotary techniques in North America.

These holes are employed as mine shafts, tunnel access, ventilation and escape shafts, access shafts for liquified petroleum storage, and for nuclear testing.

Big Holes Drilled for A.E.C. and Industry

LARGE diameter rotary drilling techniques have advanced rapidly in the last four or five years, mainly because of the A.E.C. underground nuclear testing programme. During this programme a number of 72 in. diameter holes have been drilled to 4,000 and 5,000 ft. depths. Rotary holes drilled for the mining industry in the last five years have included the following:

1. A 72 in. diameter hole to 2,790 ft.
2. A 90 in. diameter hole to 710 ft.
3. A 108 in. diameter hole to 1,435 ft.
4. A 124 in. diameter hole to 935 ft.
5. A 130 in. diameter hole to 520 ft.

In 1967, approximately 51,000 ft. of large diameter shafts and underground mine raises were rotary drilled for the mining industry. Holes that can be added to this 1967 total are an estimated 66,000 ft. of big hole that were drilled for the A.E.C.

Big Holes in 1968

By mid-1968, one 90 in. diameter hole had been drilled to 5,000 ft. and preparations were being made to deepen it to 6,000 ft. One 120 in. diameter hole was 1,392 ft. deep and scheduled to be drilled to 5,600 ft. Equipment was being readied to commence drilling two 120 in. holes to 6,000 ft. Studies were being made for a 140 in. diameter hole to 6,000 ft. Several 64 in., 72 in., and 96 in. diameter holes were either drilling or were already completed to depths from 2,000 to 4,000 ft. All of these holes are for the A.E.C. underground testing programme. A copper mining company in Michigan awarded a contract in June to drill a 144 in. diameter hole to 1,650 feet for a ventilation shaft. A 72 in. mine ventilation shaft is being drilled in Missouri for a lead mine.

Because of recent large diameter rotary drilling technique improvements, the "big hole" is becoming an accepted economical and efficient method of shaft construction. Some of the past drilling techniques and some of the new techniques being employed to drill 120 in. diameter holes will now be described.

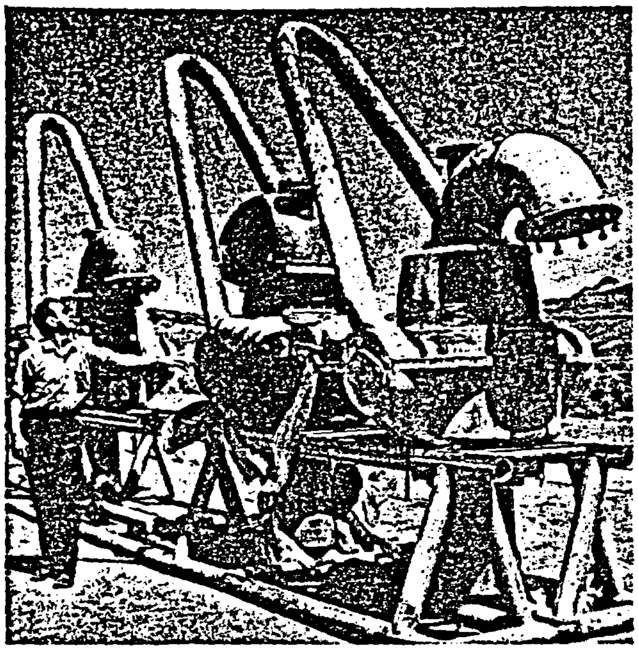
PAST TECHNIQUES

Conventional Drilling Equipment

Until the late 1950s most large diameter holes were drilled with positive displacement rig pumps or air compressor, direct mud or air circulation, conventional sized oil well drilling strings, and multipass reaming techniques. A few bit manufacturers marketed large diameter hole openers for water well drilling. These hole openers were used on large diameter mine vent shafts with conventional oil well drilling equipment by drilling a 12¼ in., 15 in., or 17½ in. pilot hole and then reaming the hole in successive passes to 26 in., then 36 in. and on to 42 or 48 in. and sometimes to 60 in. in diameter. In some very soft formations it was possible to run a pilot bit with one or more hole openers in tandem to drill the hole in a single pass. The main problem with single pass drilling using tandem hole openers was in providing sufficient circulation fluid for proper hole cleaning through conventional sized drill pipe.

Special Drilling Equipment

The first tools designed specifically for big hole drilling were introduced in 1959 and 1960 by the Hugh B. Williams Manufacturing Company of Dallas,



A group of 250 ton, 12 in. I.D. large diameter rotary drilling swivels.

Texas. These tools consisted of the following equipment:

1. A 14 in. x 12 in. centrifugal pump, capable of pumping 7,000 g.p.m. at 110 ft. of discharge head.
2. A 12 in. I.D. x 50 ft. long rubber rotary hose.
3. A 250 ton drilling swivel with a 12 in. I.D. wash pipe.
4. A 14 in. square x 50 ft. long kelly with a 12 in. bore.
5. A string of 13⅜ in. O.D., J-55 drill pipe with splined tool joint connections.
6. Four 40 in. O.D. x 8 ft. 10 in. long drill collars weighing 42,000 pounds each. The drill collars were equipped with 40 in. flanges on the ends for bolting together. The annulus of each collar between the 12 in. bore and 40 in. shell was filled with lead.

Single Pass Drilling Methods

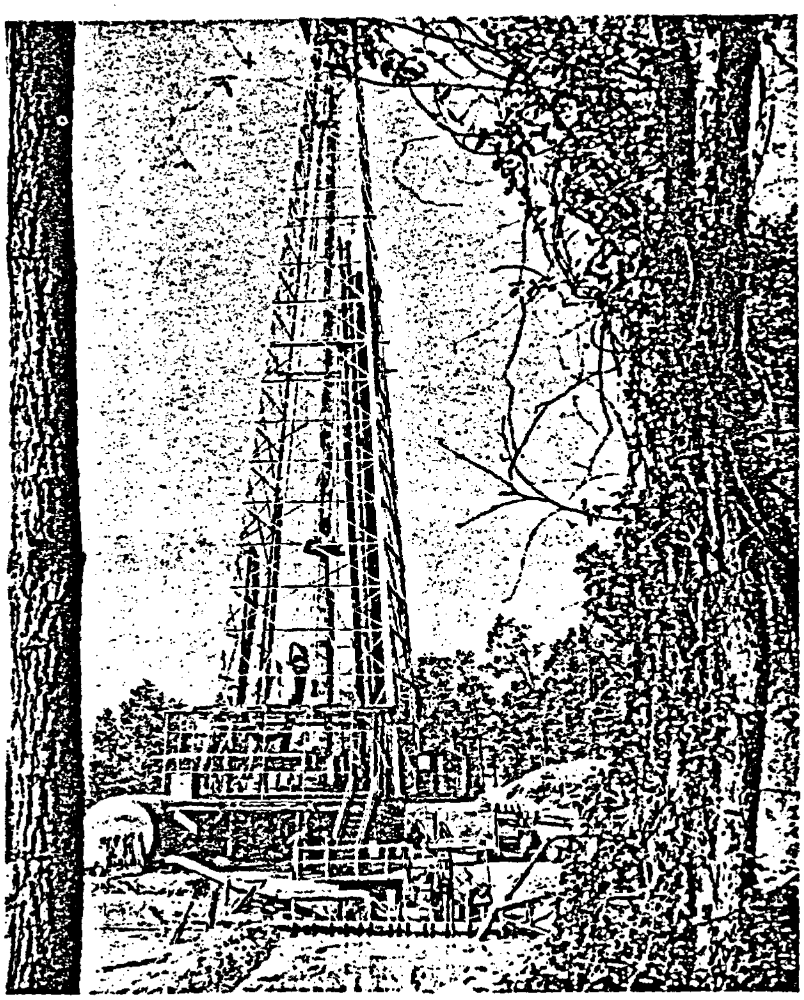
In 1960, a uranium mine ventilation shaft was drilled with the large bore special tools. A 710 ft. deep, 15 in. pilot hole was reamed to 90 in. in diameter in a single pass. Many engineers and contractors believed that a pilot hole was still necessary even though a big hole could be drilled efficiently in a single pass with the new tools. The pilot hole served as an exploration or test hole to check for lost circulation zones and formation changes and served as a guide to drill the bigger hole straight.

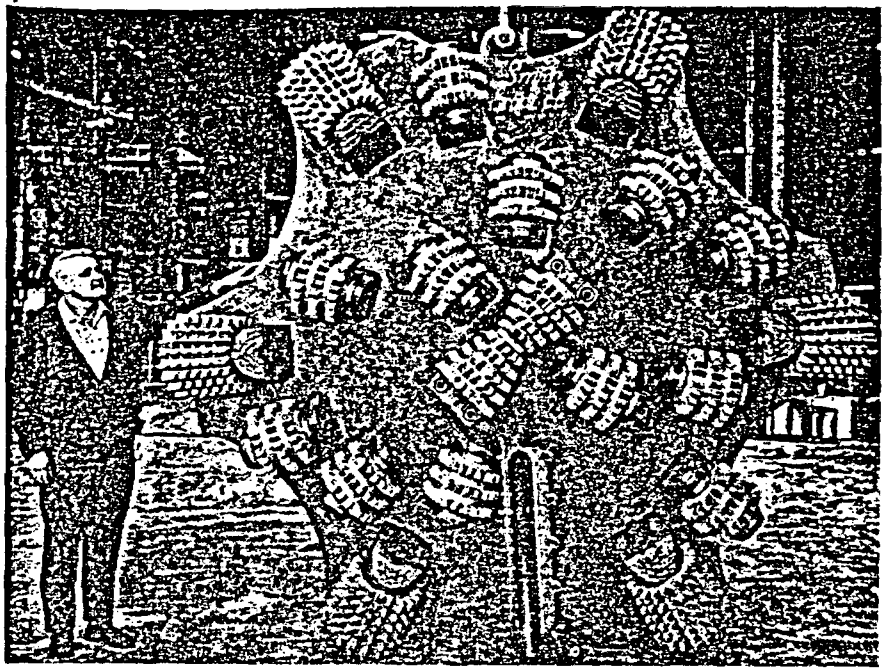
In 1961, the special equipment was used to drill a 60 in. diameter hole in 24 hours to 200 ft. with a single pass but without a pilot hole. After several more single pass holes were drilled without experiencing deviation or lost circulation problems, several engineers and contractors questioned the need for pilot holes and multipass reaming.

It was concluded and later proved that a large diameter hole drilled with a properly designed (reamer and stabiliser equipped) drill collar assembly could be drilled as straight or even straighter than most small diameter pilot holes. Many engineers also concluded that lost circulation could be either controlled in a big hole, or that circulation techniques could be altered to prevent lost circulation.

Air Foam Circulation Techniques

In 1962, drilling engineers with Reeco, the A.E.C. support contractor, perfected an air-foam circulation method for tandem hole opener and other single pass





A 120 in. flat bottom bit used in the drilling of emplacement holes for the Atomic Energy Commission.

drilling methods. This circulation method proved quite successful for single pass drilling in dry or damp, soft formations where air circulation was practical. In this air-foam circulation technique a mixture of bentonite, detergent and chemicals is injected into a direct circulating air stream. This mixture produces a steady return flow of foam which increases the cuttings carrying ability of the circulation media.

A.E.C. Deep Hole Drilling Programme

In 1963, the A.E.C. commenced a drilling programme for drilling 72 in. diameter holes to 3,000 and 4,000 ft. depths. The programme was premised on drilling the 72 in. holes with specially designed large diameter tools and single pass methods in fractured and porous formations that were water bearing below 2,000 ft. To insure that the holes would be drilled straight, new type 60 in. diameter drill collars were designed and built as well as new 72 in. reamer and stabiliser assemblies. Larger load carrying capacity swivels and large diameter rotating heads or kelly packoff assemblies were also built. New 72 in. bit and cutter design concepts were tested.

Most big hole bits used prior to 1963 had a stringer for a three-cutter pilot bit in the centre. The new 72 in. diameter bits were equipped with centre and outer cutters that cut the hole in a flat bottom profile. Many of the bit bodies were equipped with shrouds to effect a better flow of air across the bottom. Larger cutters mounted in yokes or saddles and equipped with sealed bearings were introduced. Two reverse air circulation techniques were developed for the fractured formations. The first reverse air circulation technique, used in the upper dry sections of the formation, consists of blowing approximately 24,000 cubic ft. per minute of air, at approximately 4 to 8 p.s.i. pressure, through the rotating head and down the annulus, with the air and cuttings returning to the surface through the drill pipe. Mine ventilation rotary blowers are used to circulate the air.

The second reverse circulation air technique is used below the water table and employs a dual drilling string. A 7 in. casing string is installed on the inside and concentric to the 13¾ in. drill pipe. The 7 in. string is "landed" in a casing pack-of bowl in the 72 in. bit. High pressure air is pumped down the 7 in. x 13¾ in. annulus and through gas lift valves in the 7 in. string near the bottom hole assembly. This passage of air below the water table creates an air lift effect and returns water, air and cuttings to the surface through the 7 in. inner pipe string.

Other Circulation Techniques

Other circulation techniques that have been employed with success in other types of formations are as follows:

1. Reverse circulation of mud with air lift assist. This technique is being used in the drilling of 120 in. diameter holes and will be discussed in more detail later.

120 in. bit and bottom reamer assembly.

horsepower d.c. motor driving the 14 in. x 12 in. centrifugal pump and another 850 brake horsepower d.c. motor on a C-350 mud mixing pump. Other electrical power is required for lighting and the 16 shale shaker screen motors.

Rotating Equipment

1. Rotary Tables

The rotary tables in use for the 120 in. holes are new 37½ in. tables driven by chain drives from the drawworks. These tables are rotated from 2 to 10 r.p.m.

2. Swivels and Rotary Hoses

Rotary drilling swivels with 750 ton load ratings and 12 in. I.D. removable wash pipes are used on the 120 in. holes. The swivels are equipped with a flanged connection on top of the 12 in. goose neck for installation of the 3 in. air tubing string and a 7 in. inner circulation string. The rotary hoses in use on the 120 in. holes are 12 in. I.D. and have an oil resistant liner. Flanges are provided on the ends for bolting to the standpipe and swivel. These large rotary hoses are quite stiff and have a minimum bending radius of 6 ft.

3. Kellys

The kellys are 14 in. square and 60 ft. in length. They are equipped with special drive bushings that fit the master drive slots of the 37½ in. rotary table.

Down-Hole Tools

1. Drill Pipe

The new drill pipe currently in use on 120 in. holes to be drilled below 5,000 ft. depth is fabricated from 13⅜ in. O.D., 54 pound per ft. casing, rolled from a special grade of steel, X95S. The drill pipe, with tool joints, weighs 65 pounds per ft. and varies in length from 42 to about 45 ft. The total joints are quadruple lead with a "Vee" thread form, called a Reed V4. Hughes Tool Co. manufactures a similar tool joint, the H-490, and Drilco manufactures a DI-22 tool joint. The V4 tool joints are "made up" to 110,000 ft.-pounds and break out at approximately 85,000 ft.-pounds of torque. The tool joints make up with 1¾ turns. The torsional yield strength of the 13⅜ in. pipe averages from 650,000 to 720,000 ft.-pounds. The tensile yield strength averages from 1,600,000 pounds to 1,800,000 pounds. The pressure loss through the drill pipe, when circulating 3,400 g.p.m., averages about 1.0 p.s.i. per 100 ft. or about 60 p.s.i. for a 6,000 ft. string.

2. Drill Collar and Reamer-Stabiliser Assembly

The 60 in. diameter drill collar assemblies in use on the 120 in. holes consist of a series of doughnut shaped cast iron weights that fit around a 60 ft. long, 16 in. O.D. centre drill collar mandrel or stem. The drill collar stem, with a tool joint on top, has a flanged-end, weight support stool at the lower end, on which the drill collar weights rest. With all of the weights (sometimes up to 30, weighing a total of 390,000 pounds) supported on the weight stool, the drill collar stem is subjected to tensile loading only, in nearly all drilling weight conditions.

The cast iron weights are 60 in. in diameter, 16¾ in. I.D., 18 in. thick and weigh 13,000 pounds each. They are of split, interlocking construction, so they do not have to be installed by inserting over the top of the stem. A bit reamer-stabiliser assembly is fabricated on and is an integral portion of the drill collar weight stool. A similarly designed stabiliser assembly is used on the stem just below the uppermost weight. A hold-down clamp keeps the weights and upper stabiliser in place. Each weight nests in the next weight by intermeshing grooves cast in the top and bottom.

The reamer-stabiliser demountable rollers are 12 in. O.D. and 24 in. in length and are equipped with grease lubricated anti-friction roller bearings. The bearing elements are protected from contamination by pressure compensated seals. These seals provide bearing protection for either air or mud circulation. Reamer-stabiliser assemblies used on a 140 in. hole can be modified for use in a 120 in. hole simply by changing brackets.

The drill collar, reamer and stabiliser assembly for a 120 in. diameter hole weighs approximately 480,000 pounds. This great weight provides a very good "plumb-bob" effect, or vertical force component, to keep the bit drilling vertical. This effect, coupled with the stiff bottom hole assembly (designed with proper reamers and stabilisers) has virtually eliminated deviation in large diameter holes. Holes having no more than 1 ft. of horizontal displacement at 4,000 ft. of depth have been drilled.

3. Bits and Cutters

The bits used on the first 140 in. surface hole were a Smith Tool Company 140 in. flat bottom surface bit equipped with 26 sealed bearing cutters, and a Smith Tool Company 120 in. flat bottom bit (for the hole below the surface casing) equipped with 20 sealed bearing cutters. Both bits have 60 in. diameter top flanges for bolting to the 60 in. drill collar assembly. The bits have a pickup chamber that is approximately 4 in. wide and 24 in. in length.

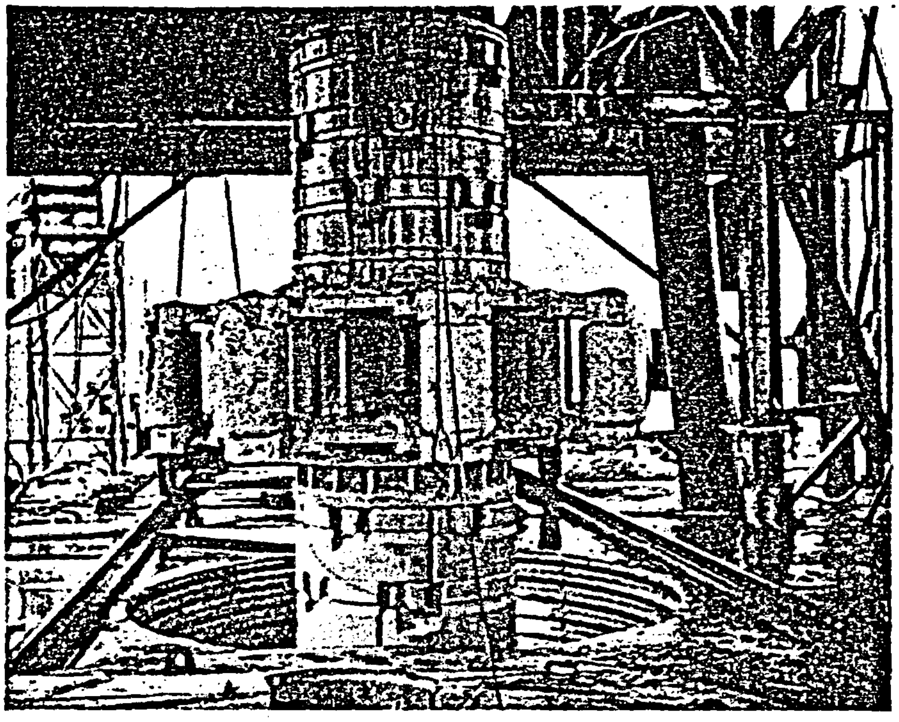
With reverse circulation, the pickup chamber sweeps the bottom of the hole and transports cuttings and mud to the 12 in. centre bore in the bit. There are three different sizes and types of cutters on the 140 in. and 120 in. bits. On gauge are six ST type cutters that are 15 in. in diameter and 12 in. in length. The inner cutters are type MT and are 12¾ in. in diameter. Two companion MT cutters in the same row cut a 9 in. wide path. The centre cutters are type CT and cut a 24 in. diameter path in the centre of the hole.

All of the cutters are demountable and are supported by heat treated yokes that are welded to the bit body base plate. A dull bit can be removed from the drill collar assembly and be replaced by a bit with sharp cutters in approximately two hours. The dull cutters can be removed and replaced with new cutters in six hours. Much design and development work has been done on cutter spacing and cutter quantities in the various rows. Cutter spacing is purposely unbalanced to eliminate harmonic vibrations resulting from rotation. The number of cutters installed in any one row is carefully considered, so that each row will drill the required area in approximately the same time as a corresponding row, and so that tooth wear patterns in each row will be similar.

Cutters are designed to provide optimum service at a loading of approximately 20,000 pounds each. On a 120 in. bit, this loading would amount to a drilling weight in excess of 400,000 pounds. While this much weight can be provided from the drill collar assembly, it cannot be effectively applied to the cutters because of inadequacies in the hole cleaning and rotary table torque capacities.

Rapid advancements have been made in the design and manufacture of large diameter cutters in the last five years. Many drilling contractors and engineers believe that more cutter improvements are needed. However, these improvements would necessarily still have to be accompanied by rotary table torque improvements and better hole cleaning techniques before any economic benefit would be derived. In the last five years, on-bottom rotating time has increased from an average of about 30 hours to about 200 hours. A few contractors have experienced 300 hour runs when drilling 72 in. holes with air.

Big hole cutters are available from stocks in several different milled tooth types and tungsten carbide insert types. In many medium hard to hard forma-



"Doughnuts" or drill collar weights that are 60 in. O.D. by 16½ in. I.D. by 18 in. high. The weights fit around the 16 in. O.D. stem of the drill collar.

2. Reverse circulation of mud or water with a jet eductor. This technique is primarily used on shallow, large diameter water wells.
3. Reverse circulation of air employing a "vacuum" created with rotary blowers connected to the drill string at the surface. Air at atmospheric pressure flows down the annulus of the hole, sweeps the bottom of the hole under the bit and returns to the surface with cuttings through the 13⅜ in. drill pipe. It is necessary to have a cuttings removal separator upstream of the rotary blowers to prevent cuttings from passing through the blowers.
4. Reverse circulation of air by pumping high pressure air down a dual drilling string annulus. The high pressure air is jetted on the bottom of the hole and cuttings and air are returned to the surface through the inner string of the dual drill string. A jet eductor, activated by other high pressure compressors at the surface, is tied to the inner string to create a vacuum to further the aid of the return flow of air and cuttings.

The techniques of equipment employment, casing, cementing and fishing used for the 72 in. holes are similar to those currently being employed on 120 in. diameter holes and are dealt with later.

TECHNIQUES FOR DRILLING 120 INCH HOLES

Drilling and Casing Programme

1. 140 in. Surface Hole

If the drilling of a deep 120 in. diameter hole requires a surface hole to case off water bearing surface formations, the proper hole size will range from 136 in. to 140 in. depending upon depth. On the first 120 in. hole drilled for the A.E.C., a 140 in. hole was drilled with a flat bottom bit in a single pass to 411 ft. This hole was drilled to 221 ft. by direct circulation using a 14 in. x 12 in. centrifugal pump. From 221 ft. to 411 ft., the hole was drilled by reverse circulation air assist using 9.0 pound per gallon mud. The 140 in. hole was cased with 122 in. I.D. casing with ⅜ inch wall thickness. This string weighed approximately 500,000 pounds (in mud) and was run with the rig hoisting equipment. The 122 in. casing was cemented to the surface in three stages by cementing in the annulus through 2⅜ in. grout pipes.

2. 120 in. Emplacement Holes

The first 120 in. hole is being drilled with a flat bottom bit in a single pass from the surface casing at 411 ft. to the projected depth of 5,600 ft. The drilling tools will weigh approximately 800,000 pounds at this depth. Circulation for the 120 in. hole is reverse mud with air assist. A 3 in. air injection tubing string was lowered to 360 ft. inside the 13⅜ in. drill pipe. By injecting 1,800 c.f.m. of air at this depth, the reverse flow rate of mud and cuttings was 3,400 g.p.m. At this circulation rate, some of the penetration rates averaged 2.5 to 3.0 ft. per hour. The 120 in. hole will be cased with 54 in. I.D. casing having a wall thickness varying from 1⅜ in. at the bottom to ⅜ in. thickness at the top. There will be an enlarged casing section on the bottom of the 54 in. casing. The casing will be cemented to the surface in several stages through 2⅜ in. grout pipes run in the annulus.

Surface Equipment

1. Drawworks

The drawworks for the 120 in. holes require the capacity to hoist the 800,000 pound drilling tools at a hoisting rate probably no greater than about 30 ft. per minute. Hoisting tools this heavy at greater speeds can cause severe shock loading on the derrick, block and tackle system, and other components of the hoisting system, if the tools momentarily hang up in the hole. Also, it has been found that the large diameter bits and drill collars tend to have a swabbing action on the hole if they are hoisted too rapidly in mud. Drawworks that are being used on 120 in. diameter holes include National 160 Es and Emsco 3000s.

2. Derricks

The derricks used on 120 in. holes are rated from 1,400,000 pounds to 2,000,000 gross nominal capacity. All are capable of racking in excess of 6,000 ft. of 13⅜ in. drill pipe and are designed for wind loads of 150 miles per hour. Ample floor space is necessary for setting back drill collar assemblies and/or handling the large diameter casings. One rig has a special drum, 60 in. crown block sheave and 54 in. travelling block sheave grooving to accept a 12 line system of 1⅝ in. drilling line.

3. Prime Movers

The ideal power for hoisting heavy drill strings at very low initial hoisting speed is electrical power from direct current motors. All of the rigs currently drilling 120 in. holes are diesel electric rigs. Most have at least 3,000 brake horse power diesel engine capacity. The diesel engines drive d.c. and a.c. generators to supply electrical power. One rig has five 500 h.p. d.c. generators and two 350 kVA. a.c. generators supplying power for two 850 brake horse power d.c. motors connected to the drawworks and rotary table, one 850 brake tions the cutters equipped with tungsten carbide inserts (teeth) experience bearing and seal wear before appreciable insert wear occurs. Some of these tungsten carbide insert cutters can be rebuilt and re-used by installing new bearing and seal assemblies.

Shown in the appendix is a 140 in. bit run record for the surface hole on the first 120 in. hole drilled for the A.E.C. This bit was rotated between 4 and 6 r.p.m. with 35,000 to 70,000 pounds of weight. Circulation was direct from a centrifugal pump providing only 5,000 g.p.m. of mud. All of the cutters have been graded and listed on the record as to tooth and bearing wear. The AAODC eight-point system for grading dull bits was used by a field engineer for grading these cutters.

The 120 in. bits weigh approximately 27,000 pounds while the 140 in. bits weigh 31,000 pounds.

Casing and Cementing Procedures

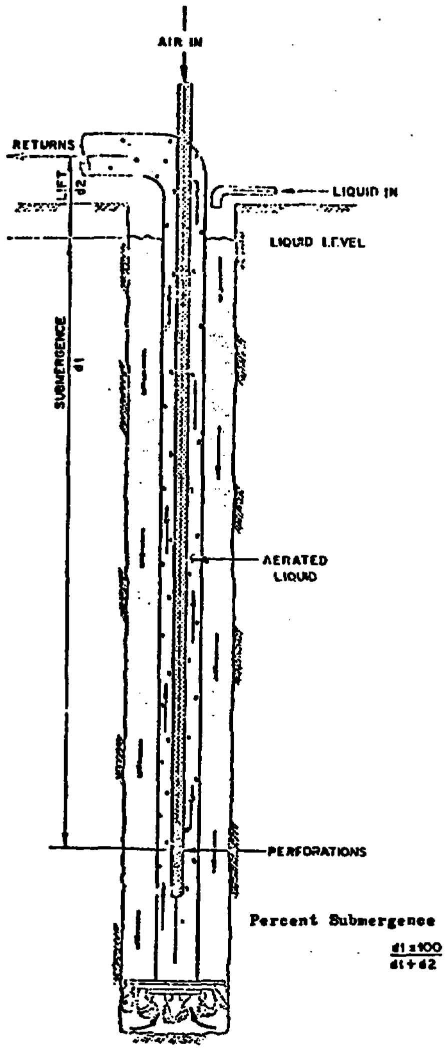
The 122 in. I.D. x ¾ in. wall casing run in the 140 in. surface hole was fabricated from A-441 steel. Bands about 8 in. wide by ¾ in. thick are installed at intervals on the outside of the 122 in. casing to serve as both casing stiffener rings and rings for casing elevator bearing support. The casing with stiffener bands weighs approximately 1,200 pounds per foot. Double elevators on the rig hoisting equipment were used to run the casing in the 140 in. hole. Each 20 ft. long section of the casing was welded as it was lowered in the hole. After the casing was landed, a 10 ft. cement plug was laid in the bottom and on the outside of the 122 in. casing. The string was cemented to the surface with two different stages of cement pumped through 2⅞ in. tubing strings inserted in the 140 in. hole annulus.

The 120 in. emplacement holes will be cased with 54 in. I.D. casing. A 5,600 ft. string of this casing will weigh approximately 5,000,000 pounds. The long string of casing is run with large diameter hydraulic casing jacks. It will be cemented to the surface in several stages to prevent collapse. Approximately 280,000 sacks of pre-hydrated gel cement having a 1.8 yield factor will be pumped down 2⅞ in. tubing strings installed in the annulus.

Auxiliary Equipment

Auxiliary equipment that is in use or will be available for use in the drilling and completion of 120 in. diameter holes includes the following:

1. Heavy duty air operated winches on the rig floor.



Air assisted, reverse liquid circulation. Perhaps the simplest air-assist system consists of air injection into the drill pipe liquid column through a smaller concentric tubing string which is perforated or open-ended. The aerated liquid is then discharged to surface tanks, the air separated and the liquid returned to the annulus. The liquid flows down to the bit and back up the drill pipe carrying cuttings with it.

2. A hydraulic line pulling device hooked to the drill pipe tongs to provide adequate make up and break out torque for the tool joints.
3. A hydraulic powered bridge crane mounted in the derrick to assist in racking the 13⅜ in. drill pipe.
4. A heavy duty flat car that runs on rail and straddles the hole is used to convey dull bits from under the floor and transport sharp bits back to the hole for installation on the collar.
5. Six pen drilling recorders that record weight, penetration rate, r.p.m., torque, air or mud volume, and compressor or pump pressure.
6. Deviation instruments with 0 to 1½ degree chart records.
7. Drilling bridge plugs for 54 in. casing.
8. Retrievable packers for pressure testing 54 in. casing. A newly designed 54 in. packer can be used in the 54 in. casing above the floor to align two joints of casing for welding as well as for a 3,000 p.s.i. bursting pressure test.

Fishing Tools

Big hole drilling has had a number of very unusual fishing jobs and casing collapses. The author has been involved in a number of jobs where bits and complete drill collar assemblies were lost in the hole. In every case, the tools have been recovered and the hole cleared, in no longer than two weeks. A variety of unusual fishing tools have been used for big holes. The more common fishing tools are as follows:

1. 13⅜ in. casing spears.
2. Dumble or alligator grabs.
3. Drilling buckets similar to those employed in foundation pier hole drilling.
4. Large diameter magnets.
5. Overshots of 40 and 60 in. diameter.
6. Junk catchers 36 in. and larger in diameter.
7. Hydraulically operated grabs.

One of the most difficult fishing jobs ever experienced was the recovery of an AAX casing tong for 13⅜ in. pipe lost to a depth of 600 feet in a 44 in hole drilled in granite. This tong was removed after about 11 days with a Dumble grab.

Big Hole Drilling Contractors

U.S. contractors presently engaged in drilling large diameter holes and operating equipment capable of drilling 120 in. diameter holes to depths greater than 2,000 ft. include the following:

1. Parco Drilling Company, Tulsa, Oklahoma.
2. Shaft Drillers, Inc., Las Vegas, Nevada.
3. Loffland Brothers Company, Tulsa, Oklahoma.
4. Camay Drilling Company, Los Angeles, California.
5. Rowan Drilling Company, Houston, Texas.

DRILLING LARGE DIAMETER HOLES

PART II

CIRCULATION TECHNIQUES FOR 120 INCH HOLES

Mud System for 120 inch Holes

1. Mud Type and Preparation

In the drilling of the first A.E.C. 120 in. diameter holes through water bearing formations, it was decided to use a ferro-chrome lignosulphonate light-weight, low-solids mud. The mud was mixed to an initial weight of 8.8 pounds per gallon. Viscosity was controlled at 40 to 42 seconds. The mud was mixed in 1,500 barrels of steel mixing storage tanks with a G-350 mud pump. It was transferred from the mixing tanks to three earthen storage pits in the mud circulation system. In drilling the 140 in. hole to 411 ft. and then drilling a 120 in. hole to 5,600 ft., it will be necessary to mix and/or treat approximately 80,000 barrels of mud.

2. Mud Storage

The mud is stored in three earthen pits of approximately 100,000 total barrels capacity. The pits were constructed on a favourable terrain so that mud will flow by gravity to the annulus of the drilled hole. If terrain conditions are not conducive to gravity flow to the hole annulus, the 14 in. x 12 in. centrifugal pump, used in drilling the initial portion of the 140 in. surface hole, can be used to pump mud to the hole.

3. Cuttings Removal

Mud, air and cuttings flow from the drill strings by air lift and through a 24 in. flow line to a 66 in. O.D. de-aeration standpipe. From the standpipe the mud flows by gravity over 16 shale shaker screens. From the shale shakers the mud flows by gravity back to the earthen storage pits to complete the system. If the drilled formations have a swell factor of 50 per cent, as predicted, approximately 33,000 cubic yards of cuttings will be removed from the 140 in. x 411 ft. deep hole and the 120 in. hole to 5,600 ft.

The Air Lift-Reverse Mud Circulation Technique

1. Background

Air lift pumping is one of the most simple methods devised for lifting fluids. Most of the empirical formulae are copyrighted and were developed by Ingersoll Rand from tests on one of their plant water wells. The system operates as follows on the 120 in. holes:

a. Approximately 1,800 cubic ft. per minute of air is injected down the inside of the 13⅜ in. drill pipe through a 3 in. tubing string. The tubing string is suspended from the swivel goose neck.

b. The 3 in. tubing extends to a depth of approximately 360 ft. below the mud level in the hole.

c. The injected air, diffused as fine bubbles into the cuttings-laden column of mud in the 13⅜ in. drill pipe, lightens this column.

d. Atmospheric pressure acting on the mud column in the annulus of the 120 in. hole creates a hydrostatic unbalance and forces the lighter mud, cuttings and air column up the drill pipe at a rate of approximately 3,400 gallons per minute.

2. Calculations

Shown on figure 17 of the Appendix is a sketch that depicts and describes air lift pumping terms. The maximum

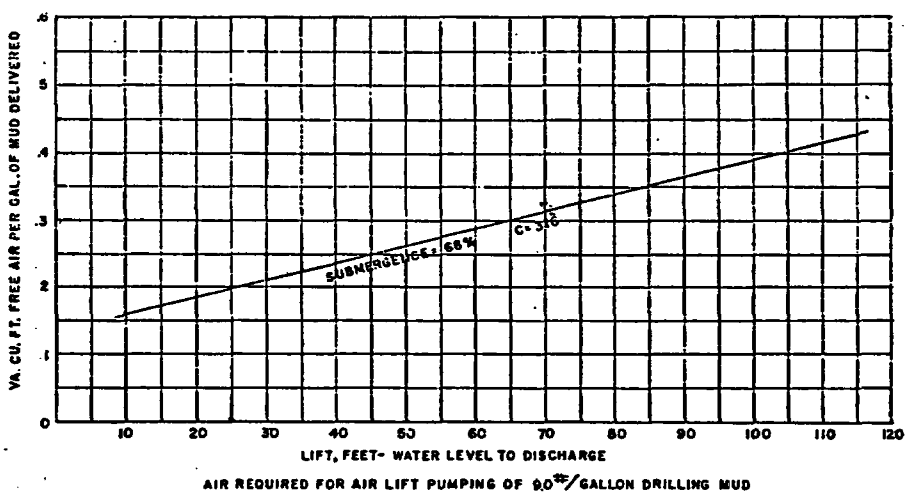


Chart for estimating the air volume required for airlifting 9 lb./gallon mud.

$$V_A = \frac{\text{Lift} \times \text{Specific Gravity}}{\frac{C \log_{10} (\text{Submergence} + 34) \times \text{Specific Gravity}}{34 \times \text{Specific Gravity}}}$$

lift for the surface equipment employed on the 120 in. holes is the substructure height of 24 ft. plus the kelly height of 60 ft. (at the uppermost position) plus the swivel height of 8 ft., or about 92 ft. For a lift in this range the Ingersoll Rand data prescribes a submergence of 70 per cent. The submergence of the airline below the mud level at the surface can be calculate as follows:

% submergence =

$$\frac{\text{Length of air line}}{\text{Lift plus length of air line}} \times 100$$

The formula and chart shown in Figure 18 of the Appendix (not contained in this printing) provides *information on the methods for determining* minimum air requirements for lifting 9.0 pounds mud. This chart and the air line submergence calculations indicate that only about 1,200 c.f.m. of air and submergence of only 233 ft. would effect a reverse flow of 3,400 g.p.m. In actual practice 1,800 c.f.m. of air injected at 360 produces a 3,400 g.p.m. flow. The formula for determining the minimum air requirements does not provide for the weight of the cuttings that are in the returning fluid. This discrepancy, plus the high friction pressure losses attributed to a mixture of air, mud and cuttings in the 3 in. x 13⅜ in. annulus, probably accounts for the divergence between calculated and actual operating conditions.

On other air lift mud circulation systems, calculations have never checked with actual operating conditions. The compilation of accurate air-assist data on holes drilled with mud would be of benefit in improving big-hole circulation techniques.

3. Triple String-Reverse Mud Circulation

A reverse mud circulation-air assist technique using a 3 in. air line on the inside of a 7 in. casing string, both inside the 13⅜ in. drill pipe was tested on a 72 in. hole in 1967 and on the 120 in. hole in June, 1968. Approximately 500 g.p.m. of 900 p.s.i. mud were pumped down the 13⅜ in. x 7 in. annulus and jetted through the 120 in. bit to the hole bottom. The high pressure mud plus approximately 3,200 g.p.m. of mud from the 120 in. hole annulus was returned to the surface cuttings through the 7 in. inner string. Air injected down the 3 in. tubing string effected the reverse flow. The test was short in duration because of wash pipe packing leakage in the 12 in. swivel. Instantaneous penetration rates of up to 5 ft. per hour in the 120 in. hole were observed with *the high pressure mud jetting on the* hole bottom.

New Technique for a 96 inch Hole

In late May of 1968, the senior drilling engineer of Reeco developed a new reverse circulation air technique in a 96 in. diameter hole that may offer *much promise for a better circulation* method for 120 in. holes drilled in dry or slightly wet formations. This circulation method is described as follows:

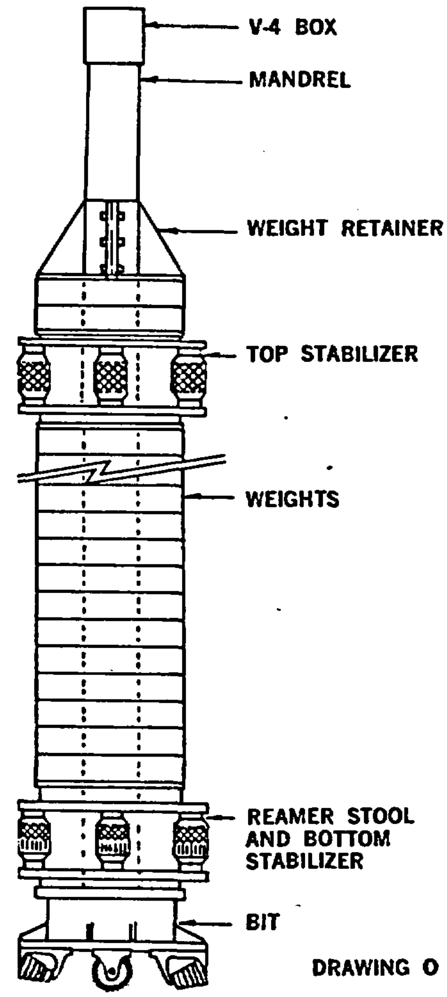
1. A 7 in. string of casing is installed on the inside and concentric to the 13⅜ *in. drillpipe*. The 7 in. string is landed in a casing pack-off bowl in the bottom of the bit.
2. Approximately 2,500 to 3,000 c.f.m. of air at 110 p.s.i. discharge pressure is pumped down the 7 in. by 13⅜ in. annulus and through eight ⅜ in. nozzles in a 96 in. bit bottom. Injected into this air stream are approximately 40 barrels of water per hour.
3. At the surface a large rotary blower is connected to the 7 in. string, downstream of a separator that removes the returning water and cuttings. This low pressure, high volume rotary blower creates 12 in. of mercury vacuum on the 7 in. string at the surface.
4. With this new circulation technique the 96 in. hole was drilled from 1,875 feet to 1,948 feet in a 12 hour drilling operation. Some of the 73 ft. of 96 in. hole were drilled at instantaneous penetration rates of 12 ft. per hour. During one 4½ hour drilling period on the 96 in. hole the penetration rate averaged 8.6 ft. per hour. The formation was described as a damp, compacted tuff.

CONCLUSIONS

Rapid Growth of Large Diameter Drilling

The development of large diameter rotary drilling techniques and equipment in the last nine years has been the main factor for the rapid advancements made by this method of shaft construction. In 1959, four holes larger than 36 in. were drilled in the United States for the mining and construction industries. Six holes greater than 36 in. diameter were drilled for the Atomic Energy Commission. These ten big holes drilled in 1959 would not total more than 5,000 ft. Eight years later in 1967, the large diameter hole footage had increased to 117,000 ft.

The increase in footage of big holes drilled for the A.E.C. is largely due to the discontinuance of atmospheric testing of nuclear devices. The increase in footage for holes drilled for the mining industry can be attributed only to the economics or cost savings of shaft construction by rotary methods as compared to conventional blasting methods. Faced with increasing labour costs and the shortage of experienced shaft sinking man-power, the mining industry will consider the rotary drilling method even more in the next five years.



DRAWING O

Assembly for drilling large diameter holes. Hookload at 4,350 ft. in 120 in. hole will exceed 800,000 lb. despite buoyancy of the mud column.

Perhaps within the next five years the Atomic Energy Commission's Operation Plowshare will be in full progress. This is the A.E.C. programme for peaceful applications for atomic energy. Studies have been completed for the construction of harbours and canals, the extraction of hydrocarbon from oil shales and tight producing fomations and the solution mining of minerals from underground deposits. All of these projects will require large diameter holes.

Comparisons of Large Diameter Holes

Drilling a 72 in. diameter hole at the rate of 5 ft. per hour, or drilling a 120 in. hole at the rate of 2 ft. per hour does not appear to be an impressive penetration rate to the oil well drilling contractor. Several 72 in. holes have advanced over 100 ft. in a day. The 120 in. hole advanced 36 ft. in one 18 hour drilling period. These penetration rates for both holes compare to drilling 12 in. hole at the rate of 3,600 ft. per day. A 120 in. hole drilled to 6,000 ft. is comparable in volume to drilling 600,000 ft. of 12 in. hole. The drilling of 600,000 ft. of 12 in. with one rig over an 18-months period at a penetration rate (during drilling days) of 3,600 ft. per day would be a pleasant accomplishment for many drilling contractors. While large diameter drilling comparisons with oil well drilling are not realistic, these comparisons of excavation do indicate that the big hole techniques and equipment employment are efficient.

Needed Improvements in Techniques and Equipment

1. Rotating Equipment

Large diameter kellys have been lengthened to 60 ft. for use with the longer joints of 13⅜ in. drill pipe. Substructure heights have been increased to provide more room under the rig floor. These increases in lengths and heights have increased the amount of lift required for the reverse circulation — air lift circulation methods being used on the 120 in. holes. The development of a down-the-hole swivel that would fit in the string just below the kelly would decrease the lift and make the circulation system much more efficient. Down-the-hole swivels have been used on big holes in Germany and Holland.

If the 120 in. hole cleaning could be improved, weights up to 400,000 and 500,000 pounds could be run on the bits. Drilling weights of this magnitude would require rotary table torques in excess of 400,000 ft. pounds. Larger rotary tables (or large power swivels, as suggested by one contractor) would be required for bit rotation with increased drilling weights.

2. Circulation

The first 200 ft. of the 140 in. surface hole is drilled with the centrifugal pump at a direct circulation rate of 5,000 g.p.m. This volume provides an annular, or rising, velocity of only 6.3 ft. per minute. Better hole cleaning and increased penetration could be gained by employing two 14 in. x 12 in. centrifugal pumps piped in parallel.

Data needs to be compiled on reverse circulation-air lift mud systems in order that more accurate calculations can be made.

A reverse-air circulation system comparable to the system used by Reeco on the 96 in. should be tested on 120 in. holes.

ACKNOWLEDGEMENTS

Thanks are expressed to James H. Allen, the U.S. Atomic Energy Commission; Fenix and Scisson Inc.; Shaft Drillers Inc.; Loffland Bros. Co.; Camay Drilling Co.; Parco Drilling Co.; Rowan Drilling Co.; Drilco; and Smith Tool Company for information and photographs.

REFERENCES

1. *Allen, James H., "The Special Equipment and Problems Associated with Large Diameter Rotary Drilling", ASME Petroleum Mechanical Engineering Conference, Kansas City, Missouri, September, 1961.*
2. *Allen, James H., "The Development of Large Diameter Rotary Drilling Machines for the Mining and Construction Industries". Presented at the Ninth Annual Drilling Symposium at the Pennsylvania State University, University Park, Pennsylvania, October 8-10, 1959.*
3. *Bawcom, J. W., "Rotary Drilling of Large Diameter Vertical Holes". Paper presented at the Symposium on Salt, Cleveland, Ohio, May, 1962.*
4. *Crews, Sim H., "Big Hole Drilling Progress Keyed to Engineering". Published in* The Petroleum Engineer, *October, 1964.*
5. *Dellinger, T. B., "Economic Factors Relative to Drilling Large Diameter Holes". Paper presented at the Second Symposium on Salt, Cleveland, Ohio, May, 1965. The Northern Ohio Geological Society, Inc.*
6. *Holbert, William J., "Advancements in Big Hole Drilling". API Pacific Coast Division, Spring Meeting, Bakersfield, California, May, 1968.*
7. *Kemnitz, George E., "Drilling Project Long Shot". Published by* Drilling Magazine, *July, 1966.*
8. *Morlan, Erwin A., "Boring Large Hole Mine Openings", Society of Mining Engineers of AIME. Paper No. 61, AV27.*
9. *Presley, Charles K., "Big Hole Drilling Techniques of the Atomic Energy Commission". API Division of Production, Mid-Continent District, Spring Meeting, March, 1963, Paper No. 851-37-E.*
10. *Presley, Charles K., and Glass, William A., "Large Diameter Shaft Drilling". SME, Fall Meeting, Rocky Mountains Minerals Conference, September, 1967.*
11. *Wirtz, H. A., "Circulation Systems for Large Diameter Holes". Unpublished Engineering Report, Hughes Tool Co.*

Reprinted by permission of the
SOCIETY of MINING ENGINEERS of A.I.M.E., preprint no. 76-AU-67
and by
WORLD MINING magazine, from
the January, 1976, issue.

A Review of Reverse Circulation Air Lift Methods for Big Hole Drilling

James H. Allen, Director of Technical Services,
SMITH TOOL

ABSTRACT

The air lift method of pumping water is discussed. A review of several large diameter hole drilling projects that used reverse circulation air lift techniques is presented.

Proposals are made for reverse circulation flow rates for slow rates of bit penetration (5 fph) as well as reverse circulation flow rates for faster rates of bit penetration (10 fph). The Ingersoll-Rand air lift equations are modified for rotary drilling operations.

By establishing minimum reverse circulation flow rates and utilizing the modified air lift equations, the establishment of minimum circulation equipment sizes and a more definitive requirement for improved bit body design should result.

INTRODUCTION

The air lift method of pumping water and other liquids has been in use for 175 years. It is one of the most simple, yet often misunderstood, pumping methods known. Compressed air is injected through an air line (pipe) and diffused into a large pipe submerged in a liquid. Bubbles of air rising through the liquid to be lifted, lighten the column and the liquid is elevated by atmospheric pressure. The air can also be injected into the annulus of two concentric pipes submerged in a liquid and diffused into the center pipe for air lifting. See FIGURE 1.

Air lift methods have been used for dredging sand and gravel; agitating viscous liquids; pumping chemicals, brines and corrosive materials and de-watering mines. The principal usage has been connected with water wells where the method has been used for well clean-out, water production and well drilling.

Between 1900 and 1960[1,2] over thirty large diameter mine ventilation and access shafts were rotary drilled in Germany and Holland using reverse circulation-air lift techniques. In the early 1960's[3,4] North American Drilling Co. used the method to drill a 130" diameter salt mine shaft in southern Louisiana. During the mid and late 1960's[6,8,10] air lift drilling methods were used at the AEC Nevada and Amchitka test sites to drill 72", 90", 96" and 120" holes. Several dual and triple drilling string innovations, all using some form of reverse circulation and air, were proposed and tested by the AEC or AEC related engineering firms. Outstanding drilling projects that were completed during this period included the following:

1. A 90" diameter hole to 6000' depths was drilled by Parker Drilling Co. on Amchitka Island in the Aleutians.
2. A 120" diameter hole to 5600' depths was drilled by Shaft Drillers in central Nevada.
3. A 120" diameter hole to 4800' was drilled by Loffland Bros. Drilling Co. in central Nevada.

Most of the AEC holes were drilled with 13⅜" O.D. drill pipe and circulation system equipment that had a 12" to 12½" inside diameter. Reverse circulation-air lift drilling fluid rates of up to 3400 gpm could be established with equipment of this size. During the period of 1965-1970 reverse circulation technology was advanced by the AEC drilling projects.

REVERSE CIRCULATION WITH AIR LIFT

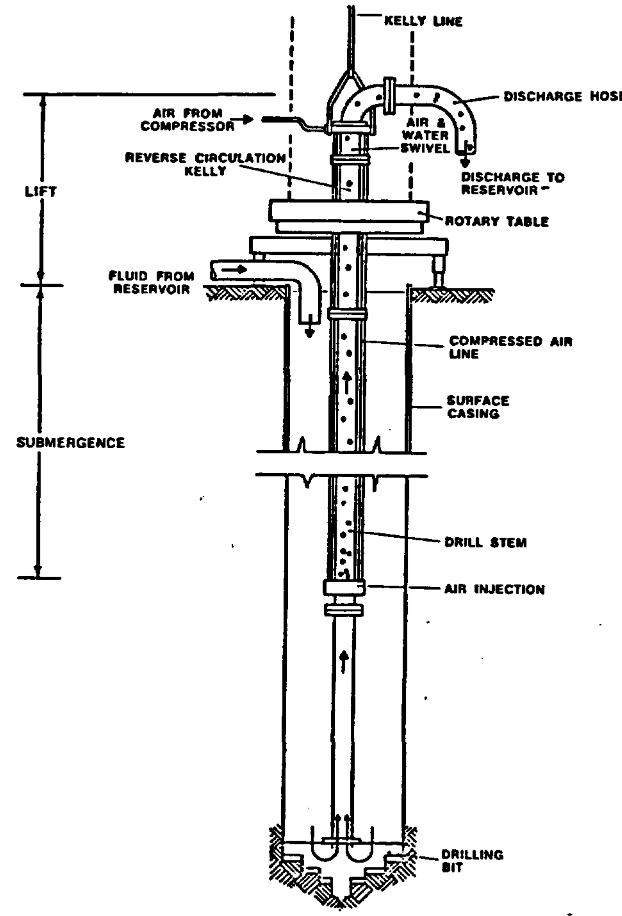


Figure 1

Since 1970 the reverse circulation-air lift technique has been used on many construction drilling projects throughout the world. Most of the construction drilling projects have been connected with foundation pile and pier holes. While most of these projects have been very successful, some minor problems and troubles have been experienced.

The main problem has been inadequate drilling fluid circulation rates caused by inadequate equipment size or insufficient submergence. Inadequate circulation rate, or cross flow under a bit, causes bit flounder and slow penetration rates.

Before reverse circulation-air lift calculations can be made, certain criteria must be established such as proposed circulation rates, entrance and exit fluid velocities and minimum and optimum submergence to lift ratios.

The purpose of the paper is to review the reverse circulation-air lift technique and establish these necessary parameters for proper rotary drilling calculations.

DISCUSSION

Background

The Ingersoll-Rand Company experimented with air lift over a 15 year period in a test water well at one of their plants. The data compiled and information developed, including empirical formulae, are used universally in air-lift water calculations.

Very little information has been published covering data compilations and calculation methods that are necessary for rotary drilling systems.

Wirtz[11] made a study of rotary drilling reverse circulation methods for Hughes Tool in 1961, but his work was not published. Other studies, mostly unpublished, were made by various personnel connected with the AEC big hole projects.

Data Requirements and Determinations

There appears to be some lack of understanding by people using reverse circulation drilling as to what information can be calculated and what data is required for the calculations.

Information or data that is needed for a reverse circulation-air lift drilling calculation includes the following:

1. Hole diameter.
2. Hole depth.
3. Hole depth where air lift drilling will commence.
4. Height or distance of lift (distance from fluid level in hole to top of swivel above Kelly).
5. Size of drill pipe. (Inside and outside diameters for both single drill string and dual strings.)
6. Size of air line if inside drill string.
7. Type of drilling fluid (including specific gravity or density).
8. Rate of penetration expected or desired.

Calculations that can be made from the above data are as follows:

1. Submergence of air line (or percent submergence) or amount of hole depth required for minimum submergence.
2. Cubic feet of air required per gallon of drilling fluid circulated. Also total cubic feet of air per minute.
3. Air compression ratio.
4. Discharge velocity of air, drilling fluid and cuttings at swivel.
5. Entrance velocity of drilling fluid, cuttings and air at point of air injection.
6. Entrance velocity of drilling fluid and cuttings at bit.
7. Required inside diameter of swivel and Kelly if these sizes are not predetermined.
8. Required inside diameter of drill string if not predetermined.
9. Required Kelly length if minimum air line submergence requirements cannot be met.
10. Air compressor working pressure.

Circulation Rates

Direct circulation rates or cross flow rates for optimum bottom hole cleaning under three cutter bits up to 26″ diameter have long been established.

In 1961, Morlan[9] proposed direct circulation rates for big holes of $Q = 50d$.

Where: Q = circulation rate in gpm

d = diameter of hole in inches

This volume recommendation has proved to be satisfactory for drilling holes up to 60″ in diameter with water. High volume, low head centrifugal pumps are used with large bore circulation equipment. Holes larger than 60″ require drilling mud (water plus bentonite for density and viscosity increases) for cuttings removal at rates where $Q = 50d$.

Flow rates for reverse circulation with large diameter bits has not been established.

A review of big hole drilling literature revealed the following information pertinent to flow volumes, flow velocities and bit body fluid pick up methods.

1. The theoretical cross flow or radial flow velocity for optimum cuttings horizontal transport when reverse circulating with air is from 4000 to 7500 feet per minute.
2. The theoretical radial flow velocity for optimum cuttings horizontal transport when reverse circulating with water is 600 fpm. Other studies indicate sand and gravel is transported in a stream bed at 300 fpm.
3. Vertical transport of cuttings requires an air velocity from 3000 to 5000 feet per minute.
4. Vertical transport of cuttings requires a water velocity from 100 to 120 feet per minute.
5. The reverse circulation rate of 3400 gpm on the AEC 120″ diameter holes resulted in a vertical or rising velocity of 535 fpm. The radial flow velocity at the bit periphery was 10 fpm and 535 fpm at the center fluid pick up.
6. Reverse circulation bits are equipped with center fluid pick up systems for slow drilling in hard formations.

7. Reverse circulation bits are equipped with sweep fluid pick up systems for faster drilling in softer formations.

8. To obtain better bottom hole cleaning and higher radial flow velocities, reverse circulation bits have been equipped with both skirts and shrouds.

The theoretical crossflow of 600 fpm for best horizontal transport of cuttings is worthy of consideration but difficult to achieve with a shrouded, center pick up bit. The radial flow is approximated as follows:

$$Vr = \frac{Q}{2 \pi rh}$$

Where: Vr = radial flow velocity in fpm

Q = flow rate in cfm

r = radius from center of bit in ft.

h = distance from hole bottom to shroud on bit bottom in ft.

The reverse circulation rate for a 48" flat bottom bit with a shroud 1½" from hole bottom and with a 600 fpm radial velocity at a 12" radius is calculated as follows:

$$Q = Vr\ 2 \pi rh = \frac{(600)\ (2)\ (3.14)\ (12)\ (1.5)}{144} = 471 \text{ cfm}$$

$$Q = (471)\ (7.48 \text{ gal/ft}^3) = 3523 \text{ gpm}$$

The rate is higher than the direct circulation rate of Q = 50d or 2400 gpm.

A 1" shroud clearance at a radius of 12" would require 2349 gpm for a radial velocity of 600 fpm. A shroud clearance of less than 1" is probably impractical. To obtain a constant radial flow velocity of 600 fpm across the bit face would require an increasing shroud to bottom hole clearance toward the bit center.

The author proposes a minimum reverse circulation rate of Q = 10d for penetration rates to 5 feet per hour.

Where: Q = flow rate in gpm

d = hole diameter in inches

An optimum reverse circulation rate of Q = 15d for penetration rates of 10 feet per hour and greater is also proposed. At this rate, the radial flow velocity at mid point of the gage cutters on a 48" bit with 1" shroud clearance would be:

$$Vr = \frac{(720)\ (144)}{(7.48)\ (2)\ (3.14)\ (21)\ (1)} = 105 \text{ fpm}$$

At a radius of 4" from center, the radial velocity with 1" shroud clearance would be:

$$Vr = \frac{(720)\ (144)}{(7.48)\ (2)\ (3.14)\ (4)\ (1)} = 551 \text{ fpm}$$

As discussed later, the radial velocity of 551 fpm at a radius of 4" is in fairly close agreement to the center pick up or bit entrance velocity of 600 fpm that is recommended for air lift calculations.

Reverse Circulation Methods

From Gibbs[7] the equation for air lifting water is:

$$Va = \frac{L}{C \text{ Log}\left[\frac{S + 34}{34}\right]}$$

Where: Va = Volume of air (cfm) per gallon of water

L = Lift in feet

S = Submergence of air line in feet

C = A constant determined by the overall efficiency of the system and the submergence

For drilling operations, the lift would be from the fluid level in the hole to the top of the swivel. For lifts from 20' to 100', which are compatible for most drilling operations, the recommended optimum submergence is 65 to 70%. The minimum rated submergence for this lift range is 50%.

Submergence is the distance the air line is submerged below the fluid level in the hole. Percent submergence is the submergence divided by the submergence plus lift times 100.

$$\% \text{ submergence} = \frac{\text{Submergence x 100}}{\text{Submergence + Lift}}$$

The constant "C" varies for different percentages of submergence and the values differ depending on whether the air is injected through a pipe on the inside of the drill pipe or in a pipe or annular space (dual string) down the outside of the drill pipe.

Values of "C" are as follows:

Percent Submergence	Inside Air Line	Outside Air Line
30	140	188
35	160	216
40	188	248
45	214	272
50	240	300
55	264	316
60	288	336
65	308	348
70	324	356
75	338	364

To modify the air lift equation for rotary drilling, it is suggested that the lift and the submergence be corrected for the specific gravity of the fluid and drilled cuttings being pumped.

$$Va = \frac{\text{Lift x S.G.}}{C \text{ Log}\left[\frac{\text{submergence x S.G. + 34}}{34}\right]}$$

When drilling with water at the minimum circulation rates recommended (10d) and when penetrating at a rate of 5 feet per hour the addition of the drilled cuttings' weight will increase specific gravity from 1.0 to 1.03 - 1.05 on hole sizes from 36" to 72" diameter. If drilling mud is used for hole stability, lost circulation, or prevention of formation fluid encroachment, the specific gravity of the drilling mud-cuttings mixture should be used to correct lift and submergence.

The most neglected items of the reverse circulation calculation are the determination of required entrance area at the bit and required discharge area at the swivel or rotary hose. When comparing the work done in lifting the drilling fluid and cuttings a certain distance to the work done by the air compressor, one would find that the overall efficiency is probably no greater than 30%. Because of this low efficiency, it is essential that the bit entrance area and the swivel or rotary hose discharge area (and for that matter the entire rotary drilling string) be of proper size to keep fluid friction losses as low as possible and to get complete expansion of the injected air. These areas can be calculated as follows:

1. $$A_d = \frac{144}{Vd} (Qf + Qa + Qc)$$

Where: Ad = Area of swivel discharge - in²
Vd = Discharge velocity - fpm
Qf = Volume of drilling fluid - cfm
Qa = Volume of free air - cfm
Qc = Volume of cuttings - cfm

Ingersoll-Rand data indicates that the maximum discharge velocity for a lift of 60' is 900 fpm.

2. $$Ae = \frac{144}{Ve} (Qf + Qa + Qc)$$

Where: Ae = Area at point of air injection - in²
Ve = Entrance velocity (where ideal velocity would be 600 fpm)
Qf = Volume of drilling fluid - cfm
Qa = Volume of compressed air at entrance - cfm
Qc = Volume of cuttings - cfm

Qa = Volume of compressed air and is determined as follows:

$$Qa = \frac{Va \times gpm}{\text{Compression Ratio}}$$

The Compression Ratio is:

$$CR = \frac{\text{Submergence} \times \text{S.G.}}{(2.31)\ (14.7)} + 1$$

Bit Design Considerations

Design considerations for approaching theoretical cross flow of 600 fpm on center pick up bits would require cutter shrouding and flow rates approaching 50d. This would require very large drill pipe and high air volumes. FIGURES 2 AND 3 illustrate how bits have been shrouded

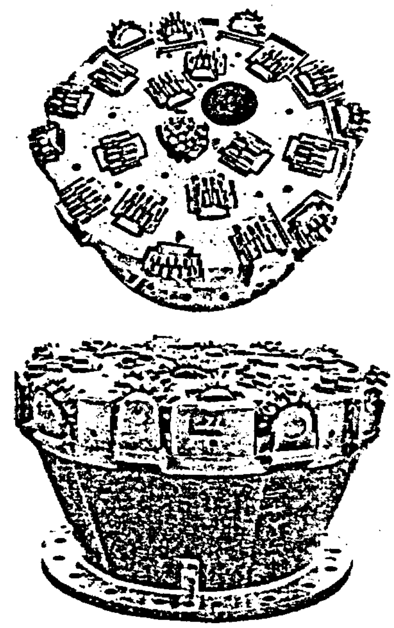


Figure 2

72" BIG HOLE BIT — FLAT TYPE FOR REVERSE AIR CIRCULATION

to improve bottom hole cleaning. The disadvantages of bit shrouding are:

1. More design and fabrication time with higher costs.
2. The shrouds have to be removed when changing cutters.
3. The shrouds have to be cleaned out occasionally to prevent cutter locking by cuttings build up.

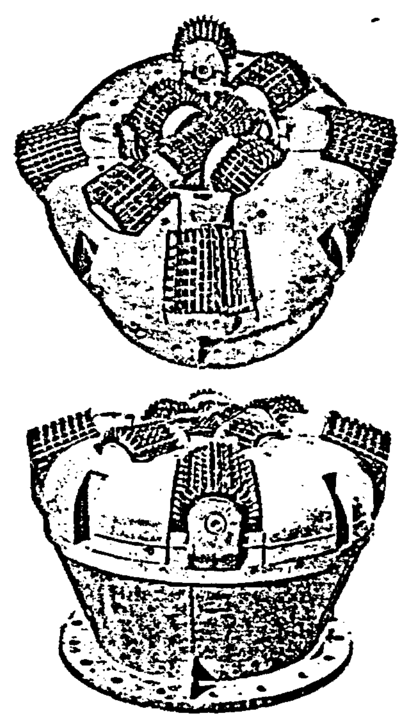


Figure 3

72" BIG HOLE BIT — FLAT DESIGN LARGE CUTTER TYPE FOR REVERSE CIRCULATION

Sweep pick up bit design is illustrated by FIGURES 4 AND 5. The radial velocity determination for this type design is very complicated. Sweep cross sectional areas should equal the bore area through the bit. The sweep length should not extend to the periphery of the bit. Considerations should be given to the clearance between the hole bottom and the sweep pick up.

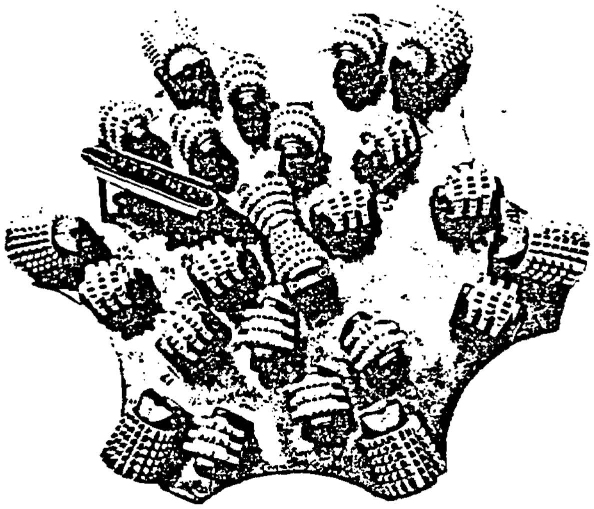


Figure 4
136" FLAT BOTTOM BIT
USING ST AND MT SEALED BEARING DEMOUNTABLE CUTTERS

Figure 5

FIGURE 6 illustrates a center pick up shroud or skirt on a 48" bit. Very good bottom cleaning was achieved with this bit but as the cutter teeth shortened because of wear the pick up skirt tended to ride on the hole bottom. Bits equipped with tungsten carbide insert cutters can be shrouded with less shroud to bottom hole clearance because such cutters have less insert or tooth wear.

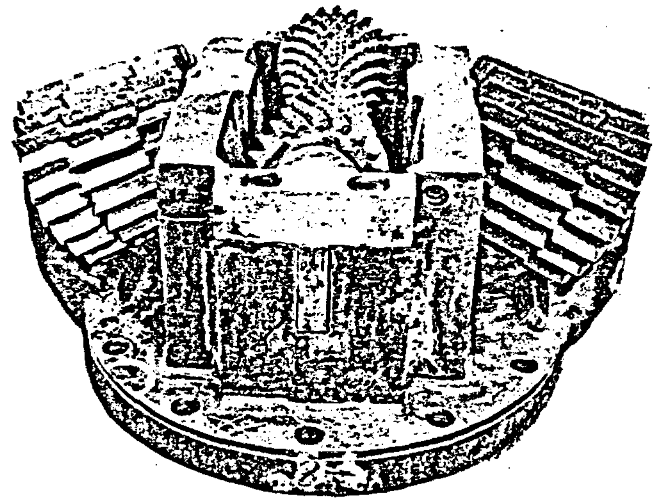


Figure 6

Over the years several proposals have been presented and bits have been fabricated that incorporated stage or tapered cutter designs as opposed to flat bottom designs. A staged cutter, reverse circulation design is illustrated by FIGURE 7. There is no evidence that these designs resulted in better bottom hole cleaning and cuttings pick up than flat bottom designs. Cobbs[5] has suggested that tapered bottom bits with the cutters mounted on an angle (greater than the angle of repose of the cuttings) might aid in cuttings transport to the bit pick up.

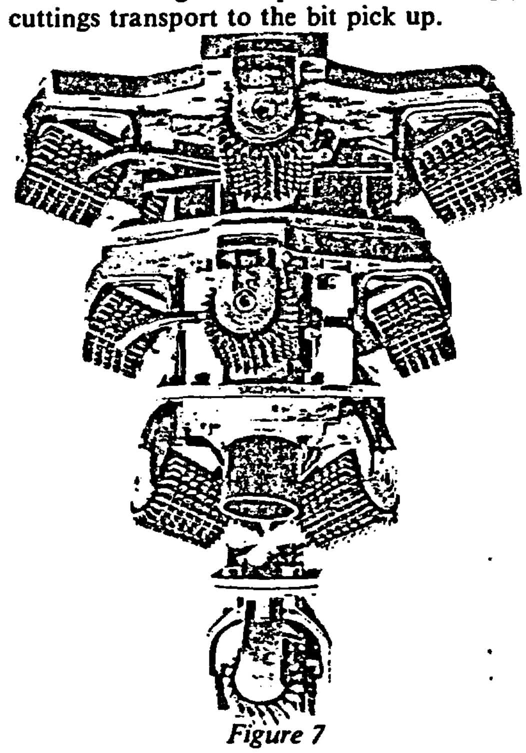


Figure 7
86" BIG HOLE BIT—STAGE TYPE

Conclusions

As a result of this review of reverse circulation air lift methods for rotary drilling large diameter holes, it is believed the following criteria or parameters should be established.

1. A minimum reverse circulation flow rate of Q = 10d for slow drilling rates of 5 fph or less increasing to Q = 15d for faster drilling rates of 10 fph and greater should be established as a starting point for calculations.

2. Rotary hose, swivel and Kellys should be sized based on a drilling fluid, cuttings and free air discharge velocity of 900 fpm.

3. Drill pipe and bit body pick up tube or sweep sizes should be based on a drilling fluid, cuttings and compressed air entrance velocity at 600 fpm.

4. If sufficient starting hole is not available for 50% submergence to start air lift operations, consideration should be given to shorter Kelly and drill stem lengths or other drilling methods to obtain sufficient starting hole.

Tables I through IV in the Appendix show the minimum fluid discharge and entrance diameters based on the above criteria and with lifts of 30′ and 50′ and at submergence percentages of 50% and 70%.

The acceptance of these parameters should result in the establishment of minimum circulation equipment sizes for various hole sizes and a more definitive requirement for improved bit body shroud and fluid pick up design.

Acknowledgements

The assistance and guidance of Bob Dixon, Bob Ricks and Jim Boaz of Sii SMITH TOOL in preparing this paper is appreciated.

References

1. Allen, James H. - "The Special Equipment and Problems Associated with Large Diameter Drilling," ASME Petrol. - Mech. Engr. Conf. Kansas City Mo., Sept. 1961. Preprint No. 61-Pet-34, 1961 9 pp

2. Allen, James H.: "Drilling Large Diameter Holes", *Australian Oil and Gas Review,* June 1968, 10 pp

3. Bawcom, J.W.: "Rotary Drilling of Large Diameter Vertical Shafts", North American Drilling Co.; unpublished

4. Bowman, G. A.: "Large Diameter Drilling Methods, Equipment and Problems", *Drilling Contractor Magazine,* Nov. 1964.

5. Cobbs, James H.: "Shaft Drilling State of the Art", Bureau of Mines Contract SO 122047, March, 1973.

6. Frederick, R. O.: "The Mighty Bite at UC4", *Drilling Magazine,* June, 1968.

7. Gibbs, C. W.: *Compressed Air and Gas Data,* Ingersoll-Rand Company, New York, 1969.

8. Holbert, W. J.: "Advancements in Big Hole Drilling", API Div. of Prod., Pacific Coast Division, Bakersfield, Calif., May, 1968.

9. Morlan, E. A.:"Boring Large Hole Mine Openings", 90th AIME Meeting, St. Louis, MO., March, 1963.

10. Presley, C. K. and Dellinger, T. B.: "Large Diameter Shaft Drilling with Reverse Circulation Air, Casing and Cementing for AEC Emplacement Holes", API, Div. of Prod., Mid Cont. Dist. Hot Springs, Ark., May, 1964.

11. Wirtz, Howard A.: "Circulation Systems for Large Diameter Holes", Hughes Tool, 1961; unpublished.

APPENDIX

Sample Calculation

Situation: A contractor has several 48″ diameter holes to drill to a depth of 90 feet. The holes can be drilled to a depth of 50 feet with buckets or augers but at this point hard rock is encountered and a rolling cutter bit and reverse circulation is required. The distance from the ground level to the rig rotary table is 4 feet. The desired penetration rate is 10 fph. The rock has an estimated swell factor of 50% and the density is 160#/ft.[3]

Determine the following:

1. Circulation rate
2. Percent submergence
3. Volume of air required
4. Specific gravity of drilling fluid cuttings mixture
5. Length of Kelly and bore of Kelly, swivel and hose
6. Lengths and bore of drill pipe
7. Compressor discharge pressure

Solution:

1. Circulation rate = 15d = 15 (48) = 720 gpm, for ROP = 10 fph

2. Percent submergence - Starting hole depth = 50′. Assume 2′ height for bit = 48′ to surface. Hole depth = 90′; 90′ - 50′ = 40′ of hole to drill. Use two 20′ lengths of drill pipe to drill from 50′ to 90′. With 20′ drill stem lengths use a 25′ Kelly. Amount of Kelly in hole = hole depth minus bit

height minus 40′ of drill pipe 50′ - 42′ = 8′. Assume lift = 25-8 = 17′ plus 1′ for swivel = 18′

$$\% \text{ submergence} = \frac{48}{48 + 18} \times 100 = 73$$

3. Volume of air required =

$$Va = \frac{\text{Lift} \times \text{S.G.}}{C \text{ Log} \left[\frac{\text{submergence} \times \text{S.G.} + 34}{34}\right]}$$

Specific Gravity of Fluid cuttings mixture:

Pounds of water per minute =
720 gal/min x 8.33 #/gal = 5997.6

Pounds of rock per minute =

$$\frac{.7854\ (16)\ (10)\ (160\ \#/ft^3)}{60} = 335.1$$

Total weight of water and cuttings = 6332.7 #/min.

Cubic feet of water = $\frac{720 \text{ gal/min}}{7.48 \text{ gal/ft}^3}$ = 96.26 ft^3/min.

Cubic feet of rock = $\frac{.7854\ (16)\ (10)}{60}$ = 2.09 ft^3/min.

Total volume water and cuttings = 98.35 ft^3/min.

Density of mixture = $\frac{6332.7 \text{ \#/min}}{98.35 \text{ ft}^3\text{/min}}$ = 64.39 #/ft^3/min.

Specific Gravity of mixture = $\frac{64.39 \text{ \#/ft}^3}{62.4 \text{ \#/ft}^3}$ = 1.03

$$Va = \frac{18 \times 1.03}{363 \text{ Log} \left[\frac{48 \times 1.03 + 34}{34}\right]} = \frac{18.5}{363 \text{ Log } 2.45} = .13 \text{ ft}^3\text{/gal}$$

Volume of air required = 720 gal/min x .13 ft^3/gal
= 94 cfm

4. Specific gravity of drilling fluid-cuttings mixture = 1.03

5. Length of Kelly = 25′

Bore of Kelly $d = \sqrt{\frac{\text{Area}}{.7854}}$

Area = $\frac{144}{Vd}$ (Qf + Qc + Qa)

Vd = 900 fpm = discharge velocity

Qf = $\frac{720}{7.48}$ = 96.26 ft^3/min
drilling fluid (water)

Qc = $\frac{(.7854)\ (16)\ (10)}{(.50)\ (60)}$ = 4.19 ft^3/min
(cuttings)

Qa = 94 ft^3/min free air

Area = $\frac{144}{900}$ = (96.26 + 4.19 + 94) = 31.11 in^2

$d = \sqrt{\frac{31.11}{.7854}}$ = 6.29″ (Kelly inside diameter)

6. Length of drill pipe joint = 20′

Bore of drill pipe = $d = \sqrt{\frac{\text{Area}}{.7854}}$

Area = $\frac{144}{Ve}$ (Qf + Qc + Qa)

Ve = 600 fpm = entrance velocity

Qf = 96.26 ft^3/min (water)

Qc = 4.19 ft^3/min (cuttings)

Qa = Volume of compressed air - cfm

CR = Compression ratio =

$\frac{48 \times 1.03}{(2.31)\ (14.7)} + 1 = 2.46$ at start of hole

Qa = $\frac{94}{2.46}$ = 38.2 ft^3, min (volume of compressed air)

Area = $\frac{144}{600}$ (96.26 + 4.19 +38.2) = 33.28 in^2

$d = \sqrt{\frac{33.28}{.7854}}$ = 6.51″ (drill pipe inside diameter)

CR = Compression ratio =

$\frac{98 \times 1.03}{(2.31)\ (14.7)} + 1 = 3.97$ at end of hole

Qa = $\frac{94}{3.97}$ = 23.7 ft^3/min

Area = $\frac{144}{600}$ (96.26 + 4.19 + 23.7) = 29.8 in^2

$d = \sqrt{\frac{29.8}{.7854}}$ = 6.19″

N. B. **Inside diameter of drill pipe, Kelly swivel and rotary hose should be greater than 6″.**

7. Compressor discharge pressure

$$P = \frac{\text{Submergence} \times 1.03}{2.31} + \text{Air line friction}$$

$$P = \frac{98 \times 1.03}{2.31} + 10\% = 43.7 + 43.7\ (.1) = 48 \text{ psi}$$

TABLE I

Rate of Penetration = 5 fph, 30′ lift, 50% Submergence

Bit Diam. Inches	Circ. Rate GPM	Air Vol. CFM	Swiv. Bore Inches	Bit Bore Inches
36	360	131	6.08	6.04
48	480	175	6.97	6.90
60	600	219	7.81	7.79
72	720	262	8.57	8.50
84	840	306	9.26	9.18
96	960	349	10.0	9.83
120	1200	440	11.10	11.0

TABLE III

Rate of Penetration = 5 fph, 50′ lift, 50% Submergence

Bit Diam. Inches	Circ. Rate GPM	Air Vol. CFM	Swiv. Bore Inches	Bit Bore Inches
36	360	155	6.45	5.86
48	480	207	7.42	6.70
60	600	258	8.40	7.50
72	720	310	9.12	8.25
84	840	362	9.86	8.92
96	960	414	10.50	9.54
120	1200	518	11.80	10.70

TABLE II

Rate of Penetration = 5 fph, 30′ lift, 70% Submergence

Bit Diam. Inches	Circ. Rate GPM	Air Vol. CFM	Swiv. Bore Inches	Bit Bore Inches
36	360	63	4.86	5.09
48	480	85	5.92	5.40
60	600	105	6.17	6.40
72	720	127	8.30	7.10
84	840	148	7.80	7.50
96	960	169	8.11	8.10
120	1200	213	9.10	8.90

TABLE IV

Rate of Penetration = 5 fph, 50% lift, 70% Submergence

Bit Diam. Inches	Circ. Rate GPM	Air Vol. CFM	Swiv. Bore Inches	Bit Bore Inches
36	360	80	5.20	4.56
48	480	106	5.87	5.15
60	600	133	6.60	5.80
72	720	159	7.24	6.40
84	840	187	7.85	6.93
96	960	213	8.40	7.41
120	1200	267	9.40	8.30

TABLE V

Radial flow velocities (Vr) with 1″ shroud to bottom hole clearance.

Bit Diam. Inches	Circ. Rate GPM	Vr 6″ from Center fpm	Vr 3″ from Periphery fpm
36	360	187	75
48	480	249	71
60	600	312	69
72	720	374	68
84	840	437	67
96	960	499	66
120	1200	624	65

PROPOSED REVERSE CIRCULATION RATES

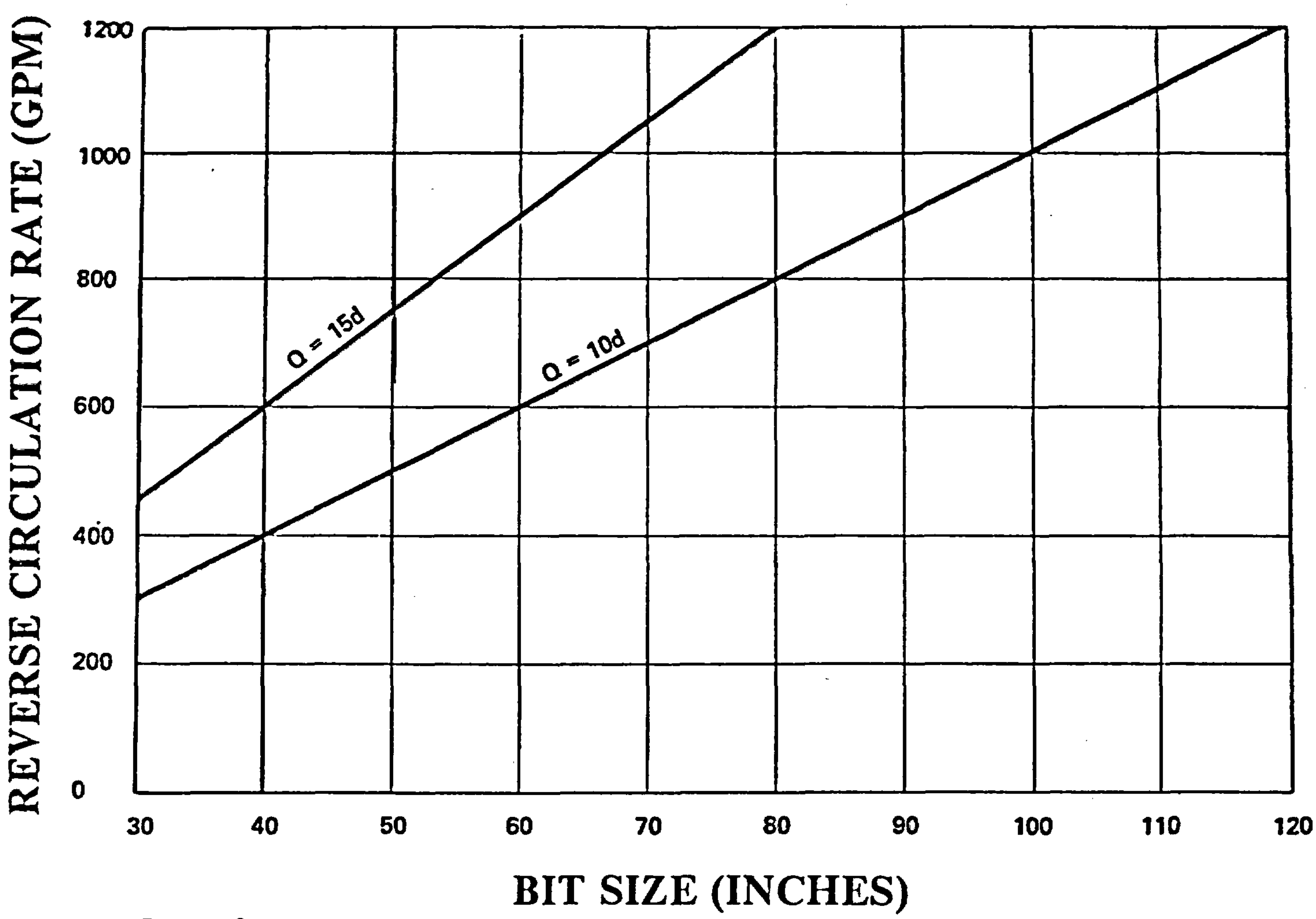


Figure 8