ROTARY DRILLING
FOR WATER

By
H. F. EGGINGTON
District Engineer,
Water Resources Branch,
Alice Springs.

M. G. BRACKEWELL
Senior Engineer, Groundwater,
Water Resources Branch,
Darwin.

DARWIN
April 1962.
SUMMARY

This paper after making reference to the evolution of present day drilling methods and some widely held misconceptions regarding the ability of rotary techniques sets out recent developments and practices adopted in the drilling for water in the Northern Territory of Australia.

The following topics are covered in some detail:

1. Selection of Hole Size and equipment.
2. Selection of a Rotary Machine.
3. Drilling Techniques.
   (a) Bit Selection
   (b) Faulty methods and the means of avoiding reputed shortcomings.
   (c) New Techniques developed for or suited to Water Well Drilling.
4. Potentials of the rotary method not available to other methods.
5. Topics for further Research.
6. Economics.
INTRODUCTION.

Drilling a hole in the ground is carried out for either or both of two objectives: to obtain information on the nature of the ground, or to obtain the hole itself. The objective will, to some extent, dictate the technique used when drilling.

Underground water, like oil, will be found where the subsurface geology is favourable and a scientific approach to drilling for water must necessarily include geological interpretation of the formations encountered. Thus a hole drilled during a search for underground water may vary from pure subsurface investigation to pure production drilling with many holes filling a dual function.

The recorded history of drilling methods dates from the days of the construction of the Pyramids when man-powered rotary drills were used for core drilling. Real development in drilling machines came at the middle of the 19th Century when oil drilling commenced. Logically, the methods used were those which required least theoretical design and yet permitted drilling to a depth of some hundreds of feet.

The machine developed, known as the "Churn Drill" was improved during the next 50 years but methods remained much the same. These drills entered the underground water field where their low capital cost and the fact that they could be operated by anyone willing to learn "as he want along" gave them universal appeal.

Meanwhile, in the latter part of the 19th Century, the need for machines capable of cutting cores to reveal the true nature of the formations encountered at depth was strongly felt and led to the development of the predecessor of today's diamond drilling machine.

As early as 1866, a combination Diamond Drill and Cable Tool machine was produced and succeeded in drilling to 5,734 feet, but generally the advantages of geological logging were still not accepted in the field of water drilling. With the
20th Century, the geologist began to take an interest in this field where he learnt to "log" the holes by an interpretation of churn drill cuttings and occasionally was able to check his log against a diamond drilled core.

At the turn of the Century the oil industry with its need for faster and deeper drilling developed the hydraulic rotary system for full hole drilling of the large diameter holes desired for production oil wells. This drilling process has steadily improved particularly during the last twenty-five years until now penetration rates drilling oil wells occasionally exceed 2,000 per 8-hour shift.

This development has come as the result of co-operation between the Drill Operator, the Drilling Engineer, the Design Engineer and the equipment manufacturer. If a similar development is to take place in the Water Drilling Industry identical co-operation must be achieved.

New and efficient equipment is available to the water driller but if it is to be employed to the best advantage it is necessary that drilling practices be altered to suit. This requires an intensive study of theoretical as well as practical aspects of the work contemplated. It may well be that, as in the oil industry, the detailed drilling methods for each stage of a hole will be laid down by the drilling engineer before the programme is commenced.

This is not a reflection upon the driller, but rather the application of statistically compiled results from earlier work of the driller. Thus the drilling programme must be under the control of a drilling engineer fully acquainted with the mechanical and manual processes of the drilling operation. At times the geologist may specify the work to be done but not the manner of its performance as he is frequently if not generally lacking in an adequate knowledge of the difficulties in the drilling of a bore and the dangers and
expense of violating sound drilling practices.

Prior to the last few years many efforts have been made to utilize rotary drilling methods in the search for water—some of these by men with considerable experience in the oil drilling industry. In this country, the efforts have frequently met with failure and each time weight has been added to the reputed disadvantages of the method. Thus rotary drilling acquired a reputation for crooked holes, and an inability to locate aquifers or even worse a tendency to "mud-off" known aquifers.

On top of this the undisputed high capital cost of a rotary machine instead of being spread over the high footage of which the machine is potentially capable has been loaded on the expected work availability to give a high contract rate per foot. This is not solely the fault of the drilling contractors, some of whom have endeavoured to ensure that their machinery is constantly employed, only to find that customers decline to accept the scheduled drilling when the machine reaches their area due to a fall of rain in the intervening period.

The purpose of this paper is to show how the rotary method can not only produce holes while avoiding the reputed disadvantages but can drill more cheaply for a positive result.

1. Selection of Hole Size and Equipment.

Applying the fundamentals of design the commencing point must be an analysis of the desired end result, with the methods of achieving that result and the requisite machinery being given subsequent thought.

Occasionally the object will be merely to drill a hole to a known depth and complete the bore with perforated casing or casing and a screen set through the aquifer.
But more usually the object is twofold:—

1. Locate water;
2. Produce the water;

and, in any case, the object is to be achieved in the most economical way possible.

The location of the aquifer depends on accurate logging of previous drilling and upon the ability of the drilling technique to produce recognizable samples as the hole progresses. The feature requiring immediate recognition is the penetration of a permeable bed together with a knowledge of the standing level of the underground water.

By tradition and experience it has become established that a hole size of 8" to 10" diameter, lined with 6" O.D. casing, is most suitable. For the percussion machine this size has advantages in that it permits some deflection whilst the casing can hang straight and vertical and allows heavy tools to be operated for maximum drilling efficiency.

The drilling efficiency of a rotary plant may be stated as dependent upon:—

1. Factors being functions of time of operation:
   (a) Capital cost amortization.
   (b) Maintenance.
   (c) Wages.
   (d) Fuels and lubricants.
2. Factors being functions of footage drilled:
   (a) Bit costs.
   (b) Wear on pipe, other subsurface equipment and cables.
   (c) Mud components.

Alternatively, drilling costs may be classified as:

A. Productive cost — being cost incurred whilst actually drilling.
B. Unproductive cost — being cost incurred whilst moving the plant, running pipe, fishing or any
activity other than actual drilling.

From an examination of these factors it is seen that the cost per foot of hole drilled will vary inversely as the penetration rate and directly as the volume of the hole drilled. Since the penetration rate will, to a large extent, vary inversely as the volume of the hole drilled, (this point will be discussed in greater detail later in the paper) roughly it is seen that total costs will increase in proportion to the volume of the hole drilled.

Thus contingent upon the purpose of the hole a rotary drilled hole should be as small as possible.

In the Northern Territory the following sizes were selected as being suited to the available casing:

- 6\(\frac{1}{4}\)" diameter - used only when a bore cased with 6" Australian Bore Casing is desired.
- 5\(\frac{1}{2}\)" diameter - used for the drilling of production bores to produce through 5" casing.
- 4\(\frac{1}{2}\)" diameter - suited to investigational drilling to depths up to 1,000 feet.
- 3\(\frac{1}{4}\)" diameter - suited to shallow investigational drilling.

These sizes allow the successive running of consecutive sizes of standard Australian Bore Casing but it has been found that the clearances are insufficient when using mud circulation unless drilling is through substantial rocks of low permeability. Probably improved mud control will reduce the wall cake and formation swelling problems but until more effective mud control can be exercised it has been found necessary to drill a 7\(\frac{1}{8}\)" diameter hole for 6" casing and then following the drilling of 5\(\frac{1}{2}\)" hole 4" diameter casing is run.

Air circulation where suitable, or air circulation with controlled water injection, has been proved to produce a clean hole tending to be oversize in erodible formations.
The close nesting successive size casing programs can here be profitably used.

Having decided on the minimum diameter hole which will achieve the desired purpose it remains to select the downhole equipment to allow a maximum penetration rate still maintaining a hole straight and vertical within allowable limits.

High penetration requires:
1. Maximum revolutions at the bit.
2. Effective bottom hole clearing.
3. Sufficient weight on the bit.
4. Freedom from drill-string vibration.

This must be coupled with high bit life. Bit life will increase with increasing rotational speed and weight up to the point where the bit becomes overloaded. Bottom hole clearing and elimination of vibration contribute to improved bit life.

The variables which may be adjusted are:
1. Drill collar or stabilizer, weight and size.
2. Drill pipe weight and size.

Light machines of a size economically suited to water well drilling cannot efficiently handle drill string weights greater than 10,000 lbs. except for short periods, and inefficiency due to wear, etc., will generally reduce this to an effective capacity of about 8,000 lbs. The effective maximum depth capacity will then be 1,500 feet, with lightweight 2¾" O.D. drillpipe (5.2 lb/ft. in 20 feet joints) and 600 ft. with ¾" O.D. drillpipe weighing 13.6 lb/foot. Lightweight ¾" O.D. drillpipe at about 8 lb/foot will increase the capacity to 1,000 feet.

This capacity makes no provision for the weight of drill collars and it has become common practice not to use collars on light rigs with the inevitable result of increased bit
costs and crooked holes.

An acceptable hole deviation for bores to be pumped by other than electric submersible pumps is 3" in 100 ft. or 1/7°. A hole within this tolerance is usually achieved if a collar or stabilizer diameter 1" less than the hole diameter and 40 ft. long is used. In unconsolidated or flat bedded formations half this length will frequently suffice, particularly if a full gauge reamer is run behind the bit.

The commonly used 5\(\frac{3}{4}\)" hole thus requires a 4\(\frac{1}{4}\)" collar, 40 feet of which would weigh only 2,000 lbs. approximately but to introduce a greater weight of collar would drastically reduce the depth capacity of the plant.

Since quartzite, jasper, chert, dolomite and the harder limestones and sandstones all require drilling weights of the order of 3,000 lbs. per inch diameter of bit to achieve an economical drilling rate it is obvious that weights in excess of the plant’s lifting capacity will be required in the most desired hole sizes. The plant manufacturers acknowledge this and water drilling machines are provided with some means of "pull-down" so that the weight of the machine may be applied to the rods.

This necessary alteration from oil drilling practice requires re-examination of drill-pipe sizes in the light of the fact that the pipe is to be operated in compression rather than in strict tension.

A drill string in compression may be considered as a long slender column which is supported by the walls of the hole after an initial deflection. A pipe which is too small will deflect excessively causing weight to be taken on the sides of the hole instead of on the bit and causing loss of power due to the friction on the sides of the hole.

An undersize pipe will also cause deterioration of the hole by removal of the wall cake and "scouring" of soft
formations.

Some work on drill stems in compression has been carried out by the diamond drilling industry with a figure for diametrical clearance equal to 7% of hole diameter being proved satisfactory. This clearance assumes water circulation and the fine flour-like cuttings produced by a diamond bit in hard rock. Rotary Drilling techniques require greater clearances due to the more viscous mud fluid circulation carrying cuttings of appreciable size, but due to the lubricating qualities of the mud a larger pipe deflection can be tolerated.

Although further work is required on this subject, it would appear that clearances of from 20% to 35% of hole diameter are acceptable provided that small holes (less than 4" diameter) have the smaller clearances.

Northern Territory experience points to the following as being satisfactory:

<table>
<thead>
<tr>
<th>Hole Size</th>
<th>Pipe Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 1/2&quot;</td>
<td>3 1/2&quot;</td>
</tr>
<tr>
<td>4 1/2&quot;</td>
<td>3 1/2&quot;</td>
</tr>
<tr>
<td>3 1/2&quot;</td>
<td>2 3/4&quot;</td>
</tr>
</tbody>
</table>

Holes diameter 7 1/2" or 6 1/2" are drilled using the 3 1/2" pipe as the machines in use will not readily handle a larger pipe but it is certain that better results would be obtained using a larger pipe if a large footage of holes in these sizes were contemplated.

2. Selection of the Rotary Machine.

Having selected the down-hole equipment to be used the selection of the machine is reduced to a matter of determining the specification of a machine which will handle the selected drill pipe in such a way as will most economically achieve the stated object of the drilling.

The requirements will be considered under the headings:

A. Hoisting and rotating ability.

B. Fluid circulation capacity.
C. Ability to case and bailer test where desired.

D. Ability to minimize "non-drilling" time.

A. The hoisting ability should be such that the rated capacity pipe loading can be hoisted at a rate of 120 feet per minute. The rigging should be so arranged and the mast should be of sufficient strength to allow pulls of the order of 20,000 lbs. above the normal string weight to be exerted in special circumstances such as the pulling of stuck pipe or casing.

Rotational speeds available should cover the range from 20 r.p.m. to 350 r.p.m. the drive from the rotary table to the kelly being free from back-lash and eccentricity.

B. The fluid circulating capacity is considered under this heading since most machines have the mud-pump included in their design.

In some cases careful control over the circulation rate must be exercised and this point is considered in detail later. However, it has been established that a liquid velocity up the annular space of 150 - 180 ft. per minute will enable efficient clearing without scouring, in the hole sizes under consideration. The pumping capacity to achieve this is:

<table>
<thead>
<tr>
<th>Fluid pumping rate</th>
<th>Pipe Size</th>
<th>Hole Size</th>
<th>Return Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>l.g./m.</td>
<td>c.f./m.</td>
<td>Size</td>
<td>Size</td>
</tr>
<tr>
<td>41</td>
<td>6.5</td>
<td>2½</td>
<td>3½</td>
</tr>
<tr>
<td>49</td>
<td>7.8</td>
<td>3½</td>
<td>4½</td>
</tr>
<tr>
<td>102</td>
<td>16.6</td>
<td>3½</td>
<td>5½</td>
</tr>
</tbody>
</table>

These capacities are within the range of standard 5" liner x 6" stroke duplex slush pumps. For the smaller capacities 4" liners are advisable.

The pump should ideally be driven by a power source independent of the drive for rotation and hoisting, but, failing this, the pump speed must be independently variable.
C. The machine must be capable of carrying out completion works of efficiently running casing, setting screens, developing and bailing.

The running of casing will be handled with ease utilizing the winch designed for pipe running. The rotary table should be of such a size as to allow the largest standard casing size to be run through the table. It should be able to be simply set aside to allow the running of a larger casing collar if desirable.

Northern Territory practice has established the suitability of a table passing 6" Australian Bore Casing, although a table passing 8" casing is an advantage.

The processes of screen setting, developing and bailing will normally be handled by a bailing or sand-line winch. This should have a bailing speed of 400 f.p.m. and be sufficiently robust to handle screen setting and surging tools.

D. An important feature in the reduction of drilling costs is the reduction of all time when the bit is not actually on bottom "making-hole".

This is largely an ability built in the machine.

Features to be sought are those which reduce:

1. Set up time.
2. Drillpipe pulling and running time.
3. Down-time for maintenance or repairs.
4. Between job travelling time.

Suggestions toward these are:-

(a) Hydraulic or other quick acting jacking for the machine.
(b) Hydraulic mast raising.
(c) Positive and easily handled slips or catching dogs for handling the drillpipe.
(d) Built-in break-out tongs to facilitate safe breaking out of drillpipe with the rotary table.
(e) Accessible lubrication points.
(f) Robust design, particularly in the primary drive.
(g) Provision for the pulling of pipe using a multiple block and a truck in an emergency.
(h) The unit should be mounted on a vehicle capable of traversing any country likely to be encountered without difficulty.
3. Drilling Techniques.

In formulating techniques for water-well drilling established methods used in both the oil-field and the diamond-drilling field have been drawn upon. In addition new techniques have been developed to overcome unique difficulties.

Hole size and pipe size selection have already been considered. Firstly under drilling techniques it is necessary to give consideration to bit selection. This will of necessity, be controlled by the strata to be penetrated.

Referring back to the objects of drilling bits must be selected to achieve two main ends.

1. Maximum penetration rate with low cost.
2. The return of identifiable cuttings.

Occasionally to identify a formation satisfactorily the cutting of a core may be deemed desirable and in hard formations it is not unlikely that the economic maximum penetration rate may be achieved with the use of a core bit and barrel. This method has not yet been fully investigated.

Water well drilling requires the penetration of formations varying in hardness from soft clays to hard cherty dolomite, quartzite, etc.

To obtain identifiable cuttings from the soft clays and sands it is desirable to drill rapidly with a high return velocity so that an undisturbed cutting can be recovered from the collar. Drag type bits with sharp cutting edges are most suited to this application. At times to obtain positive sampling it may be necessary to sacrifice penetration rate and circulate the hole clean before and after the drilling of a nominal interval say 2 feet, so that uncontaminated cuttings from this interval can be obtained. With care accurate logging can be achieved by
allowing short clearing periods whenever a change in strata is suspected or may be inferred by a change in penetration rate or in the behaviour of the kelly.

In boulder formations the drag bit is subject to severe shock loadings and breakage. Consequently the roller bit normally applied to hard and consolidated materials is employed. The high volume circulation as recommended for the unconsolidated strata should be maintained to ensure rapid clearing of the coarse cuttings and pebbles.

To meet the requirements of the infinitely variable terrestial material a large number of designs of roller rock bits have been developed. The roller cones can be arranged to roll or to scrape the bottom as the bit rotates and the degree of rolling or scraping action can be varied from the periphery to the centre of the bit; further, the number of teeth, their length and profile can be adjusted. Generalizing, the cutting action of a roller bit falls into one of three major classifications.

1. Chipping crushing action.
2. Twisting tearing action.
3. Mixed chipping crushing and twisting tearing action.

The drill operator must determine which type of cutting action will most effectively penetrate his formation and then select the bit with this cutting action.

Having selected the correct bit it remains to apply the technique which will achieve the highest overall penetration rate giving a satisfactory hole.

The softer and unconsolidated formations can be drilled as quickly as the circulating fluid can clear the cuttings. The concentration of solids in the return flow must be the criterion. Consider the sample of a 6½" diameter hole being cut by a plant using mud circulation with a circulation rate of 130 gallons per minute.
This plant will achieve the maximum desirable concentration of cuttings of 5% of the circulation volume when the penetration rate reached 4.3 feet per minute. Above this concentration cuttings of clays and shales are prone to "ball-up" and form blockages behind the bit.

At high penetration rates the rotational speed must be sufficiently high to produce cuttings that are not so large as to not be rapidly lifted to the surface. Using the clearances advocated above, a chip size of no thicker than \( \frac{1}{8} \)" could be considered satisfactory. With a three wing drag bit this means that at a penetration rate of 4.3 ft. per minute the rotational speed should not be lower than 80 r.p.m. (approximately).

Higher rotary speeds can be used with advantage provided that the pipe is running free from vibration and that the cuttings produced continue to be of sufficient size to enable positive identification.

The keen cutting edge of the tungsten carbide insert bit has been found to produce the cleanest cuttings which least contaminate the circulating liquid and are most easily separated from the circulation at the surface to give easily logged samples. These bits have averaged approximately twice the life of other types of drag bits and even in abrasive tough sandy clays usually drill more than 200 feet.

The bit life and the straightness of the hole are both improved by adequate bottom hole clearing with a fluid free from recirculated sand grains. When mud circulation is in use adequate settling pits must be provided to remove the sand in suspension and the mud viscosity must be carefully controlled so that while satisfactory water loss properties are maintained to prevent hydration and sloughing of the formation clays, the fluid remains mobile.
and transports the cuttings to the surface before they have become sufficiently hydrated either to plaster the wall of the hole or be absorbed into the mud.

It is a thorough understanding of the mechanics of hole clearing and hole stability that enable the rotary driller to show the desired improvement on percussion drill performances. There is no point in drilling at the rate of 300 feet for a shift if the next two shifts are going to be wasted while efforts are made to overcome caving and straighten the hole to enable casing to be inserted, for the average of 100 ft. per shift of cased hole is quite within the capability of many percussion machines drilling in these soft sandy clays.

It is in these same soft sediments that much of the "bad" reputation of rotary drilling has been given weight. To prevent caving of the loose sands and sloughing of the clays the operators have, correctly enough, mixed a low water loss mud fluid, usually employing a simple bentonite mud with a high bentonite content. This fluid is viscous before drilling commences and as formation clays and fine sands are added to the fluid the viscosity rapidly increases. By the time an aquifer is encountered the mud properties are such that no mud is lost and there is already so much sand in suspension that the slowly moving ascending mud column does not produce a formation sample noticeably differing from the sand with balled up clay nodules that have been logged for most of the hole.

Thus the hole is drilled to bedrock, or the target depth, without an aquifer being logged. Even if the hole is then bailed it is probable that a "dry" hole will result due to the effective "mudding-off" of the aquifer. Possibly if left for some days the wall cake will break down and move into the hole under the hydrostatic head and hydration of
the groundwater behind it. But as the hole is not cased or screened (the operator, in any case, would not know where to set the screen) then the overlying clays can be expected to slough along with the aquifer sands and any check made on the hole will only reveal a "dry" hole which has caved in.

Thus a dry hole has been drilled where an aquifer is known to exist. Further, the viscous mud and poor hole clearing have caused a slow drilling rate and probably a crooked hole.

Yet these formations can be successfully drilled using a machine and equipment as outlined above at penetration rates of 40 feet per hour or even faster where the depth to the aquifer is known or where the requirements of sampling are not critical. Territory experience drilling investigational holes in sediments consisting of interbedded sands and sandy clays has proved that satisfactory results are obtained with penetration rates of 2 feet per minute but that the accuracy of logging is improved by permitting the bit to dwell every two feet so that the adopted practice of 2 ft. sampling obtains a positive sample from each interval.

The cheapest and most readily available liquid for rotary circulation is undoubtedly a water based bentonite mud. This fluid is suitable for most water well drilling. A detailed discussion of mud-chemistry and control is beyond the scope of this paper but the general requirements can be summarized.

Bentonite is a product of volcanic action and deposits occur throughout the world. The largest and purest commercially developed deposit is at Wyoming in the U.S.A. and the material commonly used in Australia has been mined in Wyoming and crushed to pass a 200 mesh screen.
This fine powder readily hydrates when mixed with water to form a thixotropic colloidal suspension. Full thixotropic properties are developed if bentonite is mixed at the rate of 100 lbs. to 150 gallons of pure water. At this concentration the suspension has a specific gravity of 1.05 and when agitated has a viscosity measured by the Marsh Funnel as only of the order of 15% greater than that of water. But after standing for ten minutes the gel strength is sufficient to hold sand in suspension indefinitely.

The simple bentonite suspension constitutes a basic mud with excellent hole clearing properties and as it stands ideal for use when drilling consolidated formations, as while the hole is efficiently cleared as drilling proceeds should a delay occur the thixotropy of the fluid will prevent the settling of cuttings in the hole.

When in unconsolidated formations the ability of the fluid to maintain the walls of the hole assumes greater importance. As a bentonite suspension seeps into a sand the velocity of the motion is decreased and the bentonite begins to gel. This will proceed until the gelled bentonite gains sufficient gel strength to balance the hydrostatic head forcing it into the formation, when mud loss will cease and the gelled suspension will stabilize the wall of the hole.

However, if the formation is sufficiently permeable, or the hydrostatic head great enough the gel strength of a pure bentonitic suspension will not be sufficient. In such cases improved properties and a reduced "water-loss" under pressure will be achieved by the addition of another colloid; — pre-gelatinized starch.
Starches available in Australia vary greatly in suitability but usually a mud containing bentonite and starch in a 3:1 proportion will be found to have adequate wall cake building properties. If drilling of a hole using starch in the mud is likely to take more than 5-6 days steps should be taken to prevent the starch fermenting. The usual method is to increase the pH of the mud to approximately 11 by the addition of caustic soda.

Viscosity control is often necessary to prevent an increase in viscosity due to the accumulation of formation clays in the mud. The cheapest method of reducing viscosity is usually by watering the mud but care must be taken that the desired water-loss and wall-cake properties are not destroyed as a natural clay will be much less strongly thixotropic than bentonite. A safer method and a convenient one when water is not readily available is the addition of one of the polyphosphates or a soluble tannin added with caustic soda. This latter is often preferable as the tannins, in conjunction with caustic soda to control the pH, will improve the wall cake encouraging the formation of a thin, tough, impermeable lining on the hole. Occasionally a lack of sufficient pump capacity may be overcome by using a viscous mud to "float" large pebbles or chips out of the hole. The addition of lime at the rate of 2 lb. per 100 gallons of bentonite suspension will give a maximum viscosity increase. Smaller amounts should be tried to gain the desired result, but the addition of much more than this amount will cause a "break-over" to a calcium base mud with a decrease in viscosity.

Other additives used in rotary mud are bulk materials such as cellophane flakes, bran or mica to...
control water loss in extremely permeable or broken formations and weighting materials such as barytes carried in the suspension to provide hydrostatic head to control mobile shales or possibly kill an artesian flow.

The most important point to remember is that mud control must be preventative not curative. Once a hole has commenced to cave or clay to hydrate and slough no amount of mud technology will restore the hole, but a mud correctly mixed and maintained will prevent most troubles developing.

Mud circulation rotary drilling seeking an unknown aquifer depends to some extent on an approximate knowledge of the depth to the water table and of the geological sequence. With this knowledge a permeable strata logged below the water table can be expected to be an aquifer and be developed and tested as such. This permeable strata will be registered by a slight circulation loss which must occur until the colloids have moved into the aquifer sufficiently to gel and prevent further loss, or even by a complete loss of circulation if the aquifer is sufficiently permeable, and also will be revealed by the geological log of the cuttings. Both these indications are positive but neither will be noted unless proper mud control and sampling are carried out.

Once the aquifer is located and suitably screened the gelled mud fluid may be removed by bailing the hole until the hydrostatic head in the hole is lower than that in the aquifer and then breaking the gel by mechanical agitation while bailing continues to remove the colloid as it flows back into the hole; alternatively the mud may be displaced by water with one of the polyphosphate gel breaking chemicals in solution.
Once the aquifer has been partially cleared all traces of drilling mud may be removed and the aquifer developed at the same time by spotting a polyphosphate solution in the vicinity of the screen and allowing it to stand for in excess of 24 hours before pumping the well until clean. In the Northern Territory sodium hexametaphosphate has proved most successful in this application.

The recently developed technique of Air Circulation when applied to water well drilling has overcome two of the greatest problems of mud fluid circulation—those of lost-circulation and the possibility of drilling through without logging an aquifer.

As can be expected it has been found that air circulation is not a "cure-all" and does in fact introduce some new problems, particularly in heaving or blowing formations.

Drilling stable impermeable clays and rocks dry air circulation will give excellent hole clearing with a velocity up the annular space of 3,000 ft. per minute. The cuttings are rapidly moved from the bottom of the hole by the air expanding over the face of the bit and the sample obtained at the surface is generally larger and preferable to the sample returned by liquid circulation.

Penetration rates and bit life are improved although compressive loading in the drill pipe must be treated with increased caution due to the absence of the lubricating film on the walls of the hole.

The principal difficulties are those encountered when drilling through wet formations supplying water to the hole or through dry friable sands. The wet formations will produce damp cuttings which will tend to plaster the wall of the hole rapidly building up mud rings while the
Friable sands will tend to run continuously into the hole with frequently a complete collapse occurring when the air is cut off for the purpose of adding an additional length of drill pipe.

Other problems are the loss of air to permeable zones above the water table and the limitations placed on drilling through an aquifer by the hydrostatic head of water in the hole.

When liquid circulation has been used to drill a hole into a water bearing stratum for sufficient distance to obtain normal submersion for air lift pumping drilling can continue by injecting a small air flow and relying on the pumping action to raise the cuttings in the water being pumped. But the difficulty arises when drilling above the point of "air-lift" submergence but still within the aquifer.

It has been found that if a return velocity of greater than 4,000 feet per minute can be maintained even small amounts of water will be "blown" out of the hole. If the hole is making sufficient water to "set" the cuttings adequately so that they too are blown out as a slurry rather than accumulating as a damp mass then drilling can proceed. Extending this line of thought, if the water provided from the formation is insufficient to achieve this then additional water can be added to the air line.

This same technique of adding water, or in some cases mud to the air stream, has proved capable of binding the loose friable sands to cause the formation of a wall cake and permit continued penetration without reverting to full liquid circulation. Also damp air will "mud-off" the permeable zones above the water table preventing loss of air which if allowed to continue will build "dust-rings" of dry material filtered out of the air as it enters the formation.
Only small quantities of water are necessary although before pulling out or cutting off the air for any reason the injection of a considerable slug of water will ensure a clean hole.

Sloughing clays and shales have not yet been conquered and at the present when these are encountered the hole is immediately mudded up with a low water loss mud.

The great advantage of air circulation lies in the fact that extremely permeable formations can be drilled with a minimum of "lost-circulation" trouble. And almost as important is the immediate indication that is given when water is encountered with a continuing indication of the quantity that is available at the depth of the hole at any particular time.

Turning from the sands and clays to glacial moraines or boulder and coarse gravel beds it must be recognized that these formations are the most troublesome. The accepted techniques employ viscous muds and maximum pumping rates.

Gravels capable of moving up the annular space can be "stirred-up" using a rugged steel blade bit but those incorporating boulders and coarse gravel must be drilled. A short toothed rugged roller bit is recommended and should be used in conjunction with a reamer and a maximum size drill collar or stabilizer to maintain hole straightness. No risks should be taken with hole stability and the hole should be cased before the mud viscosity is reduced to drill on through the underlying formations.

Methods using blade bits and an extremely heavy mud which is not circulated but used to fill the hole have been advanced but these have not been tried in the N.T.
The technique which involves the use of a blade bit with the object of packing the larger boulders and pebbles into the clayey matrix or into the voids normally expected in boulder formations could be tried if normal drilling is unsuccessful.

The discussion above has referred mainly to drilling in the unconsolidated sediments where rotary drilling problems are greatest.

In consolidated formations the rotary machine is simple to operate and as only thin muds (or dry air circulation) are necessary it is unlikely that a permeable zone will go unnoticed.

The main points to be considered here are the achievement of maximum penetration rates and minimum costs. The bit selection and the employment of correct weight on the bit allied with correct rotational speed are all important.

While these factors are not to be overlooked when drilling softer formations their importance is here paramount.

Consideration has been given to the selection of drill pipe sizes which will permit support of the pipe by the walls of the hole so that the whole string can be operated in compression with the weight of the plant added to the top of the kelly. The plants likely to be employed for water well drilling are not usually capable of achieving the recommended 3,000 - 4,000 lb. weight per inch of bit diameter so the maximum available weight must be applied and the rotary speed adjusted to give maximum penetration with smooth running.

The roller bits used must be selected to cut with the action appropriate to the hardness of the formation (see above) and with a tooth size and shape that will produce the largest cuttings. Hard abrasive or broken formations necessitate the use of short tough teeth.
With the correct bit and operating technique a rotary machine can be expected to average a penetration rate approximately 10 times that of a percussion machine in the same material.

Bit costs may be a considerable proportion of the total, a figure of £1 per foot for 5½” ø hole in extremely cherty dolomite being within expectations, although 4/- per foot is the average, drilling in Central Australian limestones and sandstones.

The difference between low and high cost drilling in hard formations is often a function of the attention given to the machine by the operator. An enthusiastic man keeping the weight on the bit and possessing an understanding of bit operation will achieve a penetration rate twice that achieved by a less diligent operator.

Drilling costs in hard brittle formations may be reduced by pneumatic down hole hammer techniques to be tried in the near future. Some operators are reporting penetration rates of in excess of 5 feet per hour in very dense Basalt. However, at the time of writing contract costs for machines using down hole hammers, whilst economical where significant footages of hard drilling are involved, are not competitive with established percussion drill contractors in other circumstances.

One major advantage to be gained by using down hole hammer drills is the small weight requirement. As already pointed out, it is difficult for the light machines in use to provide adequate weight for optimum performance of roller bits in hard formations; however, weight requirements for down hole hammers and generally less than 2,000 lbs., a figure which can be very easily met.
As with all tools, the down hole hammer has its limitations, and since 1960 operators using these tools in the Northern Territory have reported continual mechanical failures in at least 3 different makes of tool. Part of the trouble is undoubtedly due to the fact that hammer drills were originally developed for quarry work, where conditions are normally reasonably uniform. Troubles occur when they are employed in the field of water well drilling, where uniform conditions are rare.

At the present time bit costs are high, and a careful comparison with roller bit costs, based on experience in particular formations, may be well repaid. In general, it is considered that the use of hammer drills, whilst a valuable addition to rotary drilling techniques, should be approached with caution. More will be learned of their use and better tools may be expected to be developed within a very few years.

4. **Potentials of Rotary Drilling.**

The rotary method of drilling opens the way to use, in the water drilling industry, of the many modern techniques developed by the oil drilling or the diamond drilling industry.

The chief of these are electrical and photographic survey methods that cannot be used in a cased hole. These are of greatest assistance in the search for water in formations of interbedded sands and clays.

Formation sampling when drilling by either rotary or percussion methods is unlikely to detect the existence of narrow sands within a majority strata of clay. Rotary core drilling using sampling barrels developed by the diamond drilling manufacturers would reveal these sands but a cheaper and more rapid method is the running of an electrical logger in a mud filled hole. This refinement although of
vast importance in an investigation programme is probably of little interest to the most water well drillers.

Of more interest is the ability to sample accurately by coring. In New Zealand where rotary drilling is generally adopted the accepted technique is to drill to the water table or to the vicinity of the expected aquifer as rapidly as possible and then to change to a coring bit and barrel. The aquifer is then cored to enable exact measurements of position and thickness to be taken as well as obtaining a full sample of the aquifer to permit the most suitable screen to be selected with absolute certainty.

With a fully equipped rotary plant in the field the standard rigging enables the ready use of methods, which although usable by the Percussion driller are not generally applied as the necessary pumps and piping are not on hand. In this category are the abilities to:-

(a) make formation tests using the drill pipe and a packer;
(b) develop formation by hydraulic fracturing;
(c) accurately place cement to seal off unwanted water supplies;
(d) set screens by "jetting in".

5. Further Research.

The potential of the method is high, but further work is needed to ensure continuing development. Whilst it is possible to utilise developments and methods of the oil drilling industry to a large extent, it must be remembered that the economics of oil and water drilling are vastly dissimilar, and many oil field practices must be drastically modified to bring them within a cost range acceptable to the water well drilling industry; in fact, quite a lot of oil field techniques will be too costly to use at any time.

There are still difficulties encountered, and methods
are capable of a good deal of improvement.

One of the main drawbacks to air circulation drilling is the high cost and great bulk and weight of the necessary compressors. In general, compressors with capacities of 450 to 600 cubic feet per minute, requiring engines of up to 180 brake horsepower, and weighing more than four tons, are needed for normal work. Such a compressor adds perhaps £5,000 to the cost of the plant, is expensive to operate, and reduces plant mobility, particularly in rough country.

Recently, experiments in the use of an air-water mixture as a circulating fluid have been carried out in the Darwin area. The object has been to reduce air requirements, to maintain effective hole clearing, and enable drilling to proceed in permeable zones without the considerable loss of mud fluid frequently experienced in this area. Experience to the present time indicates that these objectives may be substantially met with annular up-hole air velocities of 700 feet per minute and water injected into the air stream at the rate of about 8% by volume.

For example, 7½" diameter holes have been drilled with 3½" drillpipe, using a light portable compressor of 160 c.f.m. nominal capacity, and injecting water at the rate of 75 gallons per minute. Hole clearing has been adequate and water loss to permeable zones small. However, a good deal more work is needed for effective evaluation of the method.

Some pressing inadequacies are seen in the difficulty experienced in handling boulder formations and very permeable or caving formations.

Some work has already been done using a double table hammer technique in boulders. Penetration is achieved by drilling with a down-hole hammer working inside casing at the same time as the casing is drilled down by a percussion action operating at the surface.
Permeable formations may be overcome using air circulation with foam or aerated mud.

In the water drilling field a general improvement is necessary in the approach to fluid circulation. The hydraulic efficiency of high volume circulation must be considered in relation to the higher costs bearing in mind the errors of the haphazard conception that provided the hole is clean after the kelly is down then the circulation is satisfactory.

6. Economics

The final arbiter determining acceptance of the rotary method by the water well drilling industry will be one of cost per foot of hole with consideration being given to the value of any information obtained.

The industry has reached a stage where several factors combine to render the change from traditional percussion to rotary methods desirable. A rotary machine differs from a percussion machine in having

(a) Higher production.
(b) Higher capital investment.

It is the relative balance between these two factors which will determine whether rotary drilling is an economic proposition.

Other factors favouring a change are:

(c) Capital investment. Large companies and government authorities are doing more and more of the drilling. These bodies are able to afford the higher capital investment better than the individual contractor who had largely dominated the field in the past.

(d) Stability. Pastoralists in the Northern Territory are realising that the time to drill bores is before the urgency arises. It is therefore becoming possible to arrange contract programmes well ahead with
reasonable assurance of continuous employment rather than a seasonal glut with nothing for the rest of the year.

(e) Equipment. Manufacturers of drilling equipment are coming to appreciate that the requirements of a machine for water well drilling are different to those for stratigraphic and blast hole work. Machines are now coming on the market which are specifically designed for water well work, and consequently may be expected to give far better performance than the unsuitable types of machine available in the past.

(f) Research into improved methods of water well construction and drilling methods is favouring the introduction of new techniques which are well suited to rotary machines.

As a result of Northern Territory experience, both of contracting companies and of the Water Resources Branch of the N.T. Administration, the authors are of the opinion that if a plant is to be truly competitive in all phases of the work, the capital investment should not exceed £30,000. This figure is inclusive of everything required to make a drilling plant operative under isolated conditions, and must include all necessary trucks, camping gear, operating equipment such as drillpipe, downhole hammer, etc., in addition to the basic drilling machine with both slush pump and compressor.

This is based on the current N.T. requirement of a drill capable of producing 5" or 6" cased holes to 500 feet using 3½" drillpipe (the maximum pump setting normally adopted) and 4" cased holes to 1,500 feet, using smaller (2½") drillpipe.

On a comparable basis, a modern cable tool plant of approximately equivalent capacity would cost approximately
£12,000. (truck, tools, etc., included). Amortization and maintenance rates for rotary and cable tool plants respectively may be taken as £75 and £30 per shift.

Comparative drilling costs based on N. T. experience may be now considered. A hole to take 6" casing is used for comparison.

**Drilling Saturated Sandy Clays.**

<table>
<thead>
<tr>
<th></th>
<th>Rotary</th>
<th>Cable Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amortization and maintenance per shift</td>
<td>£75</td>
<td>£30</td>
</tr>
<tr>
<td>Operating costs, including wages, fuels, etc.</td>
<td>£28</td>
<td>£17</td>
</tr>
<tr>
<td>(3-man crew)</td>
<td></td>
<td>(2-man crew)</td>
</tr>
<tr>
<td>Total cost per shift</td>
<td>£103</td>
<td>£47</td>
</tr>
<tr>
<td>Footage drilled per shift* including time lost running pipe, bailing, etc.</td>
<td>250</td>
<td>80</td>
</tr>
<tr>
<td>Cost per foot</td>
<td>8/3</td>
<td>11/9</td>
</tr>
<tr>
<td>Add bit and pipe cost per foot</td>
<td>6d.</td>
<td>Negligible</td>
</tr>
<tr>
<td>Total cost per foot</td>
<td>8/9</td>
<td>11/9</td>
</tr>
</tbody>
</table>

**Drilling Hard Sandstone.**

<table>
<thead>
<tr>
<th></th>
<th>Rotary</th>
<th>Percussion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating costs per shift</td>
<td>£103</td>
<td>£47</td>
</tr>
<tr>
<td>Footage drilled per shift*</td>
<td>40</td>
<td>4</td>
</tr>
<tr>
<td>Cost per foot</td>
<td>£2.11.6</td>
<td>£11.15.0</td>
</tr>
<tr>
<td>Add bit costs, etc., per foot (dressing percussion bits with welding rod)</td>
<td>£1.15.0**</td>
<td>£1.0.0</td>
</tr>
<tr>
<td>Total cost per foot</td>
<td>£4.6.6</td>
<td>£12.15.0</td>
</tr>
</tbody>
</table>

* These figures are based on Central Australian conditions and are about average for competent operators.

** Based on 7½" roller bits costing £70 with a life of 40 feet. Note that the use of a down-hole hammer would reduce this figure.

If a 5" cased hole is considered instead of a 6" cased hole, the figures for the rotary drill will be reduced by up
to 40%, whereas very little reduction of percussion drilling costs could be expected.

Although these figures are calculated for two extreme conditions, they do in fact agree with actual drilling costs throughout the Territory. For example, since replacing a percussion machine with a rotary, the average cost of drilling carried out by the Water Resources Branch for farmers in the Darwin area has dropped from £2. 10s. 0. per foot to under £2, these costs including pump testing for 24 hours, and casing and completion times, which would be about the same for both machines. In this area conditions would be intermediate between the examples given.

Again, contract drilling in basalt and silicified sandstones of the Victoria River District is costing around £10 per foot for percussion machines, whilst a company operating a rotary machine using down-hole hammers is charging £4 per foot.

ACKNOWLEDGEMENTS.

The permission of His Honour the Administrator of the Northern Territory, and Mr. R. N. Eden, Director of Water Resources, to present this paper, is gratefully acknowledged.