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Small Diameter Horizontal Hole Drilling—State of Technology

The Robbins Company
7615 South 212th Street
Box C8027
Kent, WA 98031-0427

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by

The Robbins Company
7615 South 212th Street
Box C8027
Kent, Washington 98031-0427

for

Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185

Under Sandia Contract: 50-4832

Sandia Contract Monitor
Kenneth D. Young
Nuclear Waste Engineering Projects Division 6311

ABSTRACT

The purpose of this study is to determine the existing state of the art for small diameter, horizontal pilot hole drilling. The data were collected by contacting worldwide owners of raise or slant hole drill equipment, manufacturers of drills and bits, and manufacturers of survey tools. The study was limited to existing equipment and completed trials. Most attempts at directional pilot hole drilling; and most survey tools are designed for near vertical, downward drilling. Several types of controllable bits are available which depend upon in-hole motors and bent or wedged assemblies to bias the direction of drilling. Accurate horizontal drilling can be achieved in this way by alternately drilling and surveying at frequent intervals. This procedure is impractical, however, from both a production and a cost standpoint. A few attempts at directional drilling have been made using ordinary drilling tools, a rotary drill string and a tricone bit. Good equipment and a well trained drill crew appeared to be the most significant factor in practical, accurate drilling, whether horizontal or vertical. Because of the cost, no one uses steerable bit drilling except for correction, and then only for short portions of an overall drill program. No satisfactory continuous readout surveying tool, coupled with a remotely controlled bit capable of direction correction, exists. An industry need exists for a high speed, directional drill bit, coupled with a continuously monitored survey tool.

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SMALL DIAMETER HORIZONTAL HOLE DRILLING --
STATE OF TECHNOLOGY

1.0 INTRODUCTION

The work described in this report was performed for Sandia National Laboratories as a part of the Nevada Nuclear Waste Storage Investigations (NNWSI) project. Sandia is one of the principal organizations participating in the project, which is managed by the U.S. Department of Energy's Nevada Operations Office. The project is a part of the Department of Energy's program to safely dispose of the radioactive waste from nuclear power plants.

The Department of Energy has determined that the safest and most feasible method currently known for the disposal of such wastes is to emplace them in mined geologic repositories. The NNWSI project is conducting detailed studies of a area on and near the Nevada Test Site (NTS) in southern Nevada to determine the feasibility of developing a repository.

Sandia National Laboratories awarded a contract on July 15, 1982 to The Robbins Company to identify the hardware requirements for the drilling of the horizontal and vertical emplacement holes. That study developed a feasible concept for drilling each mode of hole and estimated the schedule and costs of the operation. The results were documented in a report entitled, "Repository Drilled Hole Methods Study." This report is an addendum to the earlier report. Its purpose is to further investigate a method of horizontal emplacement hole construction which employs a pilot drilling operation, followed by a reaming operation.

1.1 BACKGROUND

During the principal contract effort, several options for the construction of horizontal holes were considered. Among them was the concept of drilling a pilot hole to the full depth of the storage hole. The pilot hole could be constructed blind, to be followed by a reamer which used the pilot hole as a guide. Alternatively, the pilot hole could break through into a handling drift. From this drift, a reamer head could be attached and the reamer pulled back in the manner of a raise drill, operating for pilot drilling in a horizontal mode.

In both of the above drilling methods, the accuracy of the pilot hole will determine the location of the final hole. While there are many commercial applications for drilling pilot hole sizes (8-12 inches diameter) in a vertical mode, little information is readily available about a horizontal mode.

Sandia, as an adjunct to the final report for contract 50-4832, requested Robbins to conduct a brief survey of the technology currently available for drilling a horizontal pilot hole. This document contains the results of the horizontal drilling study. Additional information about the available equipment and technology is available from the Sandia contract monitor.

1.2 SUMMARY AND CONCLUSIONS

The study involved several steps:

a. Investigate available equipment for drilling pilot holes.

b. Determine what available equipment has potential for horizontal drilling.

c. Seek case histories where horizontal drilling has been attempted.

d. Investigate hole survey equipment (hole location) and comment on applicability.

Table 1 shows drill tool manufacturers and manufacturers of special directional correction drills and gives specifications for their equipment.

Table 2 gives case histories of horizontal/low angle pilot hole drilling.

In addition to just listing equipment some judgments were made as to the applicability of the method to a production drilling situation. Conclusions in summary are:

a. Drilling straight, accurate horizontal pilot holes is possible, but is not an economical production method. The only accurate way of producing a hole is to alternately drill, survey, correct the bit to the desired heading, and drill again. In-hole motors provide directional correcting capability.

b. Production-type deep holes nearly always utilize a rotary tri-cone bit in harder ground or a rotary pick-type bit in soft ground. Steering capability is minimal, and accuracy depends more upon the skill of the drilling crew than any other factor.

c. A relative and well-documented case history was found in Norway. A pilot hole was drilled as accurately as possible, in a near horizontal mode. A reamer was then attached and pulled through. The pilot hole was 9.875 in. diameter and 262 ft long. Deviation of the first hole was 6.5 ft sideways and 3.3 ft in height. More care was used on a second attempt, and a deviation of 35 in. sideways and 11.5 in. height was attained. Drilling was done by an ordinary rotary tri-cone bit.

Table 1

Equipment Manufacturers and Specifications

Equipment Type	Trade Name	Manufacturer	Source	Air and/or Water Requirement	Diameter Range	Capabilities: Hardness	Capabilities: Accuracy	Capabilities: Hole Length	Downhole Connection	Method of Function	Angle Capabil.	Length Required for Tool
Rotary Hydro	Big John	Acker	Toby Turman (717) 586-2061		3 to 6 in	Variable	Depends on driller and survey capability	650 ft	Rotating drill rod	Drill string and bit turned by rig	Horizontal ±15°	16 ft, 4 in
Hydraulic Percussion	Herbert Drill	Tamrock, CO	Bob Thompson (303) 289-4141		8 to 9 in		Only for blast holes	Only to approx. 100 ft			Up to 26°	
Rotary Tricone		Smith Gruner Woodinville, WA	Ray Peterson (206) 485-8838	Air, 1000 cfm @ 120 psi Water, 150 gpm @ 85-100 psi or 10 gpm @ 120 psi for dust suppression	Up to 13.25 in	Bit type correspondent to hardness	Relies on extensive survey, placement of stabilizer, and experience of driller	Not a factor	Drill rod only	Rotated and weighted from machine at collar of hole	Any angle	
		Security (Dresser) Houston, TX	(713) 750-3642									
		Reed Grand Prairie, TX	Speed Collingsworth (214) 988-3322									
		Hughes Houston, TX	(713) 924-2222									
		Varil Dallas, TX	(214) 351-6487									

Table 1 (Continued)

Equipment Manufacturers and Specifications

Equipment Type	Trade Name	Manufacturer	Source	Air and/or Water Requirement	Diameter Range	Capabilities: Hardness	Capabilities: Accuracy	Capabilities: Hole Length	Downhole Connection	Method of Function	Angle Capabil.	Length Required for Tool
Down-the-hole motors	Navi-drill	Christensen	Neil Willden (801) 298-2461	Water, 450 gpm @ 250 psi Air/water mist 4,700 cfm	6 to 12.25 in	Bit type chosen for hardness	Depends on how extensive survey program is	Any length	Nonrotating drill rod	Bit rotated by Moineau type motor directly above bit driven by fluid	Any	31 ft overall
	Dyna-drill	Smith Tool Co. Houston, TX	John Nicholas (713) 652-2101	Water or mud, 450 gpm @ 250 psi (lubrication must be used with air)								26 ft including drill bit
	Posi-drill	Eastman Whipstock	Randy Cobbley (303) 623-7151	Water, mud, or air mist 4,700 cfm	6.5 to 10 in	Any hardness	Depends on driller and survey capability	Depends on drill rig	Nonrotating drill rod	Rotary bit actuated by PDM	Any	22.2 ft

Table 2

Case Histories
Horizontal/Low-Angle Pilot Holes

Contractor	Equipment Used	Pilot Hole			Rock Type and Condition	Cutting Removal Method	Production Rate	Survey Method	Statement of Accuracy	Source of Reference
		Dip	Length	Diam.						
OCISA	Raise bore, Reed tricone bit (521J), Std. steel stabilizer, anti-mag 8-in rod and stabilizer, 10-in H.S. rods	45°	656 ft	12.25 in	Medium hard and faulty	Bentonite	38 days for pilot hole	Each 16 ft with single shot magnetic (checked with gryo tool 4 times).	At 263 ft, started to drop. Increased thrust. Did not help. At 328 ft, dropped 1° to 9 in off. Changed stabilizer. Stackup at 466 ft. Obtained 4.9° in opposite direction. Replaced original stackup. At 656 ft, only 8.5 ft off.	Eurotunnel '83 Conference in Basel, Switz. Paper No. 12.
Sulitjelma Gruber, Norway 10/29/73	Raise bore, tricone bit. Stabilizers and 10-in drill rod, Reed MCJ	30°	492 ft	11 in	Amphibolite 40,000 psi	Air/water regular circulation	8.6 ft/hr net	None used	Offset 1° flatter than desired. Still 2.5 ft off.	Conference paper Nov. 1974 by Arnulf Hanson
West Drei Fontein S. Africa	Raise bore, tricone bit	34° (#17)	181 ft	11 in	Quartzite 25,000 to 35,000 psi	Air/water flush	2 ft/hr	None used	None given	Telex from Peter Graham
		34° (#18)	135 ft	11 in	Quartzite 25,000 to 35,000 psi	Air/water flush	1.7 ft/hr	None used	None given	Telex from Peter Graham
U.S. Bureau of Mines (by Robbins rep.)	22H with tricone bit	Horiz.	53 ft	12.25 in	Soft to medium 25,000 psi	Air/water	20 to 25 in/hr	None used	None checked	22H 2004 Field reports

Table 2 (Continued)

Case Histories
Horizontal/Low-Angle Pilot Holes

Contractor	Equipment Used	Pilot Hole			Rock Type and Condition	Cutting Removal Method	Production Rate	Survey Method	Statement of Accuracy	Source of Reference
		Dip	Length	Diam.						
American Mine Services	Diamond drill coring bit	Horiz.	800 to 900 ft	4 in	Hard	Water	10 ft/hr	None used	Within 1° at 600 ft would be 10.5 ft off (7 ft off at 400 ft)	Andy Armstrong (303) 371-9380
	Raise bore, tricone bit, 5 stabilizers	20 to 26°	400 to 500 ft	11 in	Strata undulates considerably	Water	10 ft/hr	None used	Drift right 13 to 20 ft and drop 3.5 to 7 ft	Telex by Clay Crane
J. S. Redpath	Raise bore, tricone bit	Horiz.	700 ft	11 in	Salt	Air only	30 ft/hr	None used	Not concerned but seemed fairly good	J.S. Redpath Jerry Ball (602) 968-3192
Johnson Rock Boring Tunnel Systems	Specially designed equip. using some parts of 61R, tricone bit, and stabilizers	Horiz.	320 ft max.	11 in	Majority in soft rock	Air/water	3 ft/hr average	None used	4 to 12 in per 400 ft	F.E. Johnson Ottawa, Ont. (613) 822-2631, (907) 456-6408
ZCCMAT Chingola by Gwen Paul (2 holes)	Raise bore, Smith 12.25-in tricone bit, 5 stabilizers on bottom with stab. spaced out in drill string	25°	730 ft	12.25 in	Quartz and granite, 35,000 to 45,000 psi	Air/water	6.5 days	None used	No info.	Telex from Graham Mould Turnpan, Zambia
		24°	750 ft	12.25 in	Quartz and granite, 35,000 to 45,000 psi	Air/water	9 days	None used	No info.	

Table 2 (Continued)

Case Histories
Horizontal/Low-Angle Pilot Holes

Contractor	Equipment Used	Pilot Hole			Rock Type and Condition	Cutting Removal Method	Production Rate	Survey Method	Statement of Accuracy	Source of Reference
		Dip	Length	Diam.						
OCISA at Reocin Mine	Raise bore, tricone bit, 10-in rod and stabilizer	18°	351 ft	11 in	Hard limestone, hard shales with pyrite inclusions and fault zones	Air/water	26 days (6 hr/day) Many problems in fault zone	No info.	No information	Telex through Bill Todd from Fernando Jansen
Zeni Drilling of West Virginia at Utah and PA Bureau of Mines	Hydrostatic rotary drill tricone	Horiz.	1000 to 1200 ft	4 in	Soft coal (book seam)	Water	5 to 11 ft/hr		Accuracy not a factor	Gary Viola of Zeni Drilling (304) 328-5666
Kristian Olimb A/S, Oslo, Norway Water Tunnel	Dresser 500 Rotary Tricone	3°	262 ft	9.875 in	Precambrian Gneiss	Water/compressed air	No info.		1st hole: 6.5 ft sideways, 3.3 ft up 2nd hole: 35 in sideways, 11.5 in up	Rock Mechanics/ Geotechnic Conf. 1977 Oslo, Norway

The major finding of this limited study is that there are expensive slow ways to drill a horizontal hole accurately, and there are ways to drill a hole rapidly. However, we found no technology for drilling a long horizontal hole rapidly, accurately, and economically.

2.0 TECHNICAL DISCUSSION

2.1 APPROACH

The main emphasis of the study was directed to the investigation of currently available technology to drill directionally accurate horizontal holes in hard rock.

The research project consisted of the following activities:

a. Bit Location Methods and Equipment.

   Section 2.5 discusses various methods of determining the drill bit location and the surveying equipment available.

b. Equipment Survey.

   A survey of directional drilling equipment manufacturers was made. The results are presented in section 2.6.

c. Case Histories.

   Mining contractors and Robbins representatives worldwide were contacted for case histories of horizontal bored holes. The results are contained in section 2.7.

2.2 PERCUSSIVE DRILLING

2.2.1 Tophammer Drilling

In this type of drilling, the percussive force is transmitted to the bit through the drill string. A machine, located out of the hole, axially impacts the drill string with rapid successive blows. The string is usually rotated while operating, thus exposing a new impact point to each cutting element of the bit. The length of the hole is limited because of energy dissipation within the drill pipe.

This drilling method is most commonly used to drill shot holes for advancing a face via blasting.

The small diameters associated with this drilling method and the length restrictions make it impractical for use in the prospective Nevada nuclear waste repository.

2.2.2 Downhole Hammers (DHH)

In this design, the impact mechanism is placed in the hole and delivers force directly to the bit. Rotation and thrust are applied through the drill pipe from a machine located out of the hole.

Holes of 6 to 10 in. diameter are considered medium to large for downhole hammers, although larger hammers have been built.

Hammer drills are generally air operated and require oil to be injected into the air stream for lubrication. Oil consumption may vary with different sized DHHs. The general rule is 1 pint of oil per hour for each 100 cfm of air going into the hammer. Using this formula, a DHH designed to drill 6-in. holes would require 2 pints of oil per hour.

The compressed air to operate the hammer is supplied via the hollow drill pipe. Exhaust air is directed to the drill face for cleaning and then to transmit the cuttings back to the surface via the annulus outside the drill pipe.

A consideration, unique to repository hole drilling, is contamination of the rock with drilling fluids. Air is the most desirable bailing fluid, but the in-hole hammer requires the addition of oil in substantial quantity. If oil would be detrimental to the storage of nuclear waste, then a subsequent cleansing operation of the hole would be required.

Hammer drills have been used for horizontal drilling; however, deviation control is difficult, and difficulty increases with longer holes. This type of drilling is best suited for vertical holes.

2.3 ROTARY DRILLING

The introduction of rolling conical cutters for rock bits vastly increased the economic feasibility of drilling hard rock formations and eventually led to the general acceptance of the rotary method of drilling. The vast majority of drilling today is with the rotary method.

There is a wide variety of drill bit designs available today. The following paragraphs discuss the most common types.

2.3.1 Diamond Bits

Many types and designs of diamond bits are available. The bit may be solid or hollow so as to cut a kerf and preserve the core.

The usual method of chip removal associated with diamond bits is by water circulation, which also serves to cool the frictional milling action of the bit.

Hole sizes are common below a 4-in. diameter and uncommon above a 6-in. diameter for any appreciable length.

This type of bit could be utilized to establish the initial contact between tunnels. However, the small diameters associated with diamond bits would require that the hole reaming be done in two steps to achieve the diameter required for the prospective repository.

Opinions vary about the accuracy of diamond-bit drilling. Some oil well drillers believe that diamond bits, when adequately loaded, tend to deviate more easily than rotary bits; others claim very good accuracy in very hard rock formations.

All are in agreement, however, that low penetration rates associated with diamond-bit drilling make costs high.

Diamond-bit drilling is generally best in situations involving low drilling penetration rates where a need exists for very long bit life or where a smaller than normal hole size is required.

2.3.2 Tri-Cone Bits

Rotary drilling employing tri-cone bits is commonly used for diameters between 6 and 12-1/4 in. (The term tri-cone is used here in a generic sense; however, it is noted that "Tricone" is a registered trademark of the Hughes Tool Company.) Larger sizes to approximately 24-in. diameter are used less frequently. Two distinct types of cutting elements are in current use in tri-cone bits.

The cutter elements are either of the steel or milled-tooth type, which are machined from the basic material of the cone, or the carbide tooth type, in which carbide inserts are pressed into holes drilled into the cone's surface. Each type may have many variations. When coupled with detail features such as bearing types and subtle geometric innovations, an infinite selection of bits is available.

Tri-cone bits are most commonly used on machines having high rotational torque and rpm. Occasionally they are used as the cutting tool for downhole motors.

Water or compressed air is commonly used for cuttings removal when drilling with tri-cone bits.

2.4 DEVIATION CORRECTIVE AND CONTROL METHODS

The causes of deviation of rotary drilled holes are many and varied. The trajectory of the borehole is controlled by a complex interaction of the drilling characteristics of the bit, the configuration of the in-hole drilling assembly, the rate of penetration, and the reaction of the rock formation to the bit.

Horizontal or angle holes near horizontal tend to wander off course more than vertical or steeply drilled angle holes. Holes drilled in bedded or voided rock deflect more than those drilled in competent rock formations. A drill hole intersecting a stratified formation at a low dip angle will tend to deflect the bit in a direction more nearly perpendicular to the bedding planes; on the other hand, holes drilled along the bedding plane will tend to remain parallel to them.

Holes, no matter how carefully drilled, and regardless of precautions to maintain them on their desired path, will deviate depending on the strata and depth of the formation drilled. Although the natural tendency of the bit to deviate from the true course cannot be entirely eliminated, tools and techniques are available to reduce deviation.

This section describes some categories of equipment and techniques available to the driller to control the borehole trajectory.

There are four general classes of tools to actively control or change the direction of a borehole while drilling:

a. Whipstocks (metal wedges)

b. Knuckle joints

c. Jet bits

d. Downhole motors

2.4.1 Whipstocks

A whipstock is a long, inverted steel wedge which is concave on one side to hold and guide the bottom hole assembly into a predetermined course as a new hole is drilled. The conventional whipstock was provided with a chisel point at the bottom to prevent the tool from turning and with a heavy collar at the top to withdraw the tool from the hole after use. There are various types of whipstocks, such as removable, circulating, permanent casing, full-gauge, and others.

Three major disadvantages inherent in using the whipstock are:

1. The necessity of a large number of round trips for the setting and operation of the tool.

2. The inaccuracies involved in the orientation of the tool face to correct the hole to a given direction.

3. The creation of sharp changes in direction, or dog-legs, which can cause serious problems in the latter stages of drilling.

With all of these disadvantages, whipstocks do not appear practicable for hole drilling in the prospective nuclear waste repository.

2.4.2 Knuckle Joints

The knuckle joint is a special type of drill support designed to deflect a borehole without using a whipstock. It is constructed with a spring-loaded, ball-type universal joint connected to the drill pipe, which allows the bit to drill at an angle to the axis of the drill string. Like the whipstock, the deflection must be oriented in the proper direction.

Due to its construction, its use would require a degree of annular space that likely will not be present in the type of drilling required in the prospective repository. Its use is primarily in oil and gas drilling and is limited to nondirectional sidetracking applications.

It cannot be reliably and accurately oriented to drill the continuation of a hole in a predetermined direction. Its inaccuracy would make it an unreasonable option for making possible corrections in repository holes.

2.4.3 Jet Bits

Jet bits operate on the principle of producing a deflection in a borehole by the jetting or washing action of a drilling fluid discharged at high pressure through a bit nozzle oriented in a specific direction. This jetting action is more effective in softer formations. Jet bits offer the ability to run a stiff or stabilized drilling assembly, and then to deflect or correct the direction of the borehole to any angle of inclination or azimuth direction without making a trip out of the hole. This, of course, would involve the use of an orientation method for the jet nozzle. Jet bits are a possibility in the control of deviation, provided adequate hydraulics are available and the geological formations are not extremely hard.

The requirement for large quantities of drilling fluids and the rock hardness to be encountered may limit its usefulness in the prospective nuclear waste repository.

2.4.4 Downhole Motors (DHM)

As the name implies, rotational power is localized at the bit in the hole. There are two types of downhole motors, the turbine motor, or turbodrill, and the positive displacement motor (PDM).

The turbine motor consists of a multistage, vane-type motor and stator section, a bearing section, a drive shaft, and a bit-rotating connecting joint called a "sub".

PDMs are low pressure screw-type pumps, run in reverse and consist of a dump valve, a motor assembly, connecting rod assembly, and a bearing assembly. Part of this tool's versatility is its ability to be used with compressed air for drilling when a liquid medium is not desirable. However, prolonged use of air can result in heating problems with resulting damage to the rubber-like material of the stator.

In directional drilling, whether in hole-straightening applications or in controlling the course of a borehole, the PDM is used in conjunction with a "bent sub" just above the motor. A bent sub is a short connecting joint in the drill string with the upper threads cut concentric with the axis of the sub body while the lower threads are cut to an axis inclined from one to three degrees in half-degree increments.

When incorporated into the drill assembly, this shaft offset angle creates a bend in the assembly, which imparts a lateral force to the drill bit. This lateral force can then be aimed in a predetermined direction.

Application of downhole motion can potentially result in accurate drilling results; however, the degree of accuracy will depend upon the ability to track the trajectory of the hole by directional surveys.

Downhole motors have the highest potential for use in the prospective repository of any equipment available. However, the cost would be high, and economic and engineering evaluations must be made to determine if the cost is justified.

2.5 HOLE SURVEY

Directional or corrective measures are futile without accurate knowledge of bit position. The proper deflection and change of direction of a hole can only be accomplished by accurate orientation of the deflection tool at the bottom of the hole. Tool face orientation requires precise information in the form of directional survey data from the hole.

The following are the most common methods used for surveying the borehole.

2.5.1 Magnetic Base Surveying

Vertical drilling deviation is described in terms of azimuth and angular direction from true vertical. Because physical length measurements are made along the path of the borehole, the coordnates for establishing position are the departure distance from the drilling rig center of rotation, angle of inclination of the bit, and azimuth direction in which the bit is heading. The path of departure, being a simple or complex curve, necessitates a number of continuing surveys as the hole progresses, or after-the-fact open hole survey. Ultimate accuracy depends upon the quantity of survey points, repetitive surveys, quality of instrumentation, operational and interpretive skills, and other interfering factors which may or may not be known at the time of survey. The data are reduced by spherical trigonometric hand calculations or by computer programs.

Horizontal drilling represents a more restricted opportunity for instrument selection and more difficult conditions for applying the tools. A vertical-tending hole readily accepts a plumb bob type tool to measure dip angle and a compass card for recording azimuth, all placed by gravity and retrieved by wire line and winch. The compass card seeks north while the plumb bob establishes a point on the compass card offset from center in a direction indicating the invert or low side of the hole, and at a distance from the card center indicating the inclination of the hole. Applying this tool in a horizontal hole, the compass card remains horizontal, and the plumb bob is suspended off the card. Although variations of this tool are available for flatter holes, placement requires either washing it in with water or air, or physically placing the instrument by shoving it down the bore with push rods. Retrieval is by wire line and winch.

Magnetic surveys require the use of nonmagnetic drill collars made of special nickel alloy, or of stainless steel, if the instrument is to be run inside the drill rods. This type of instrument can be run in open hole by removing the drill string from the hole.

Magnetic survey instruments are generally of the single-shot or multishot varieties, consisting of three basic units: timing device or a motion sensor unit, a camera section, and an angle-indicating unit. The timing device is used to operate the camera at predetermined times. The motion sensor can be used to replace the timer to give positive control as to when the camera is accuated. This is an electronic device that operates an electric lighting system in the camera just seconds after the motion of the survey tool has ceased. The camera is prefocused and loaded with film made of a special heat-resistant material. The angle-indicating unit combines a magnetic compass to measure azimuth and a plumb bob to measure the angle of inclination of the borehole from horizontal. In multishot-type surveys, a 10 mm film strip is generally utilized to take several photographs at many predetermined depths with film exposure controlled by a motion sensor or by taking a picture at given time intervals synchronized with a surface watch.

2.5.2 Gyroscopic Base Surveying

Gyroscopic surveys can be run without magnetic interference down the entire length of the drill string. The magnetic compass is replaced by a gyro compass controlled by a high-rpm electric rotor. The gyro single shot's primary purpose is to orient deflection tools in areas of magnetic influence, as well as to determine drifts (i.e., the inclination angles) and directions of holes. All gyro survey instruments also consist of a timing device, a camera section, and the sensitive gyro compass unit. After the warming-up procedures, the gyro unit is first oriented to a known direction at the collar of the hole, and the timing device is set to take a photograph, say, at 1-min intervals. The instrument is encased in a protective outer barrel and lowered by wire line to the survey stations in the borehole. Surveys are taken at predetermined intervals going into, and coming out of, the hole. Frequent 5-min drift checks are performed to determine the procession rate of the gyroscopic instrument at various positions in the borehole. These drift checks are later incorporated into corrections of the raw directional data to take into account the gyro procession.

The instrument is centralized along the axis of the hole, as readings are taken, by metal belly springs or rubber fingers attached to the outer barrel of the tool. Some surveyors perform a "new-centers" correction check by initially rotating the gyro instrument in the collar of the pilot hole to obtain several photographs. This indicates how well the centralizers are performing their function and results in a correction which is later applied to the whole set of raw survey data.

While magnetic-type survey tools are readily operable by drilling-machine operators (after a reasonable schooling process), gyroscopic tools tend to remain a specialty of contractors or as a service provided by the tool manufacturers. Recent developments have combined gyros with other instruments. At least one manufacturer intends to market in 1984 a surface readout tool employing a north-seeking type gyro combined with a rotating magnetometer. Rotating the magnetometer 180° during each shot tends to cancel errors. Lateral accuracy is reportedly 1:1000, with vertical accuracy at 0.5:1000 while in a horizontal mode and in a nonmagnetic environment.

Multiaxis gryo systems have greatly increased gyro surveying accuracy and reliability within the last few years. Cost and sophistication generally limit applications to high-capital ventures such as offshore drilling platforms and complex multiwell systems.

2.5.3 Reference Base Surveying

A third technique measures the curvature of the bore as related to a straight line and references this to a horizontal plane. A tubular arrangement in one type has a beam light source at one end which is essentially viewed or photographed from the other end. The beam displacement at the target determines the rate of curvature of the tubular housing. Another type has circular baffles along its bore and photographs their displacements as the housing bends. Each is referenced to a bubble level for the horizontal base. Both of these methods are unaffected by the magnetic environment and are easily interpreted. By multiple-point surveying and averaging techniques, they have been shown to have a desirable degree of accuracy.

Direct optical survey methods should be considered for straight and relatively short holes having proportionally large bores. In this method, a light-reflecting or laser-reflecting mirror is placed within the pipe and behind the bit. A flat mirror reflects the light on centerline. As the deviation grows, the reflection angle builds. Slightly curved mirrors exponentially adjust the reflection to prevent interception of the surrounding drill pipe inside diameter.

Atmospheric moisture and dust, which affect the accuracy, could be ventilated prior to such a survey exercise. However, as distance grows, it is highly improbable that reasonable drilling techniques would provide an adequate bore path, particularly at 600 ft. For short holes or initial surveys, this adaptation would be simple, expeditious, and inexpensive.

2.5.4 Survey Instrument Manufacturers

Some of the companies that make directional survey instruments or provide directional survey services, with headquarters' locations, are as follows:

Gyroscopic Base Survey Tools

1. Eastman Whipstock - Houston, Texas
2. Sperry-Sun - Houston, Texas
3. Humphrey Inc. - San Diego, California
4. Scientific Drilling Controls - Newport Beach, California
5. Kuster Company - Long Beach, California

Magnetic Base Survey Tools

1. Eastman Whipstock - Houston, Texas
2. Sperry-Sun - Houston, Texas
3. Totco - Glendale, California
4. Sverigesgeologiska - Lulea, Sweden

Reference Base Tools

1. Gryo Log Ltd. - Toronto, Canada

2. Atlas Copco - Stockholm, Sweden

2.6 DIRECTIONAL DRILLING EQUIPMENT MANUFACTURERS

The main source of information was from Robbins' files that are maintained on directional drilling equipment. Other sources of information were trade publications and manufacturer reference books.

Equipment that did not have the capability to drill low-angle holes 4 to 12-1/4 in. diameter to a depth of 400 to 600 ft were not included.

A list of the equipment manufacturers and specifications is shown in Table 1. This list is grouped by general equipment type and summarizes pertinent operating data.

2.7 CASE HISTORIES - HORIZONTAL/LOW-ANGLE HOLE DRILLING

An inquiry was conducted of mining and drilling contractors in the United States and abroad. The topic of the inquiry was horizontal or low-angle hole drilling with regard to the categories of:

a. equipment used

b. dip angle

c. length of hole

d. diameter of hole

e. rock type and condition

f. muck removal method

g. survey methods used

h. directional accuracy of the hole

The results are shown in Table 2. Only two of the projects made any attempts at directional control. One was by OCISA in Madrid, Spain. This was a 12-1/4 in. diameter raise bore at a 45° angle. The accuracy achieved was a deviation of 8-1/2 in. from the target at 656 ft.

The other was a water tunnel project in Norway. Deviation in the first hole was 5.6 ft sideways and 3.3 ft up. A second hole was drilled with deviations of 35 in. sideways and 11.5 in. up. Boring was done with a tri-cone bit.

All of the projects surveyed, with the exception of the J. S. Redpath project, used water or drilling fluids for muck removal. The J. S. Redpath project was in a salt formation and used compressed air for muck removal.

DISTRIBUTION LIST

B. C. Rusche (RW-1)
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Office of Geologic Repositories
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Washington, DC 20545

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Washington, D. C. 20545

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J. E. Shaheen (RW-44)
Institutional Relations Staff
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Forrestal Building
Washington, D.C. 20585

J. O. Neff
Salt Repository Project Office
U.S. Department of Energy
505 King Avenue
Columbus, OH 43201

D. C. Newton (RW-23)
Engineering & Licensing Division
Office of Geologic Repositories
U.S. Department of Energy
Washington, D.C. 20545

O. L. Olson, Project Manager
Basalt Waste Isolation Project Office
U.S. Department of Energy
Richland Operations Office
Post Office Box 550
Richland, WA 99352

D. L. Vieth, Director (4)
Waste Management Project Office
U.S. Department of Energy
Post Office Box 14100
Las Vegas, NV 89114

D. F. Miller, Director
Office of Public Affairs
U.S. Department of Energy
Post Office Box 14100
Las Vegas, NV 89114

D. A. Nowack (14)
Office of Public Affairs
U.S. Department of Energy
Post Office Box 14100
Las Vegas, NV 89114

B. W. Church, Director
Health Physics Division
U.S. Department of Energy
Post Office Box 14100
Las Vegas, NV 89114

Chief, Repository Projects Branch
Division of Waste Management
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

S. A. Mann, Manager
Crystalline Rock Project Office
U.S. Department of Energy
9800 South Cass Avenue
Argonne, IL 60439

K. Street, Jr.
Lawrence Livermore National Laboratory
Post Office Box 808
Mail Stop L-209
Livermore, CA 94550

L. D. Ramspott (3)
Technical Project Officer for NNWSI
Lawrence Livermore National Laboratory
P.O. Box 808
Mail Stop L-204
Livermore, CA 94550

D. C. Hoffman
Los Alamos National Laboratory
P.O. Box 1663
Mail Stop E-515
Los Alamos, NM 87545

D. T. Oakley (3)
Technical Project Officer for NNWSI
Los Alamos National Laboratory
P.O. Box 1663
Mail Stop F-671
Los Alamos, NM 87545

W. W. Dudley, Jr. (3)
Technical Project Officer for NNWSI
U.S. Geological Survey
Post Office Box 25046
418 Federal Center
Denver, CO 80225

NTS Section Leader
Repository Project Branch
Division of Waste Management
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

Document Control Center
Division of Waste Management
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

P. T. Prestholt
NRC Site Representative
1050 East Flamingo Road
Suite 319
Las Vegas, NV 89109

M. E. Spaeth
Technical Project Officer for NNWSI
Science Applications, Inc.
2769 South Highland Drive
Las Vegas, NV 89109

SAI-T&MSS Library (2)
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Las Vegas, NV 89109

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Lakewood, CO 80215

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Energy Support Division
Holmes & Narver, Inc.
Post Office Box 14340
Las Vegas, NV 89114

J. A. Cross, Manager
Las Vegas Branch
Fenix & Scisson, Inc.
Post Office Box 15408
Las Vegas, NV 89114

N. E. Carter
Battelle Columbus Laboratory
Office of Nuclear Waste Isolation
505 King Avenue
Columbus, OH 43201

V. M. Glanzman
U.S. Geological Survey
Post Office Box 25046
913 Federal Center
Denver, CO 80225

J. B. Wright
Technical Project Officer for NNWSI
Westinghouse Electric Corporation
Waste Technology Services Division
Nevada Operations
Post Office Box 708
Mail Stop 703
Mercury, NV 89023

ONWI Library (2)
Battelle Columbus Laboratory
Office of Nuclear Waste Isolation
505 King Avenue
Columbus, OH 43201

W. M. Hewitt, Program Manager
Roy F. Weston, Inc.
2301 Research Blvd., 3rd Floor
Rockville, MD 20850

H. D. Cunningham
General Manager
Reynolds Electrical &
Engineering Co., Inc.
P.O. Box 14400
Mail Stop 555
Las Vegas, NV 89114

T. Hay, Executive Assistant
Office of the Governor
State of Nevada
Capitol Complex
Carson City, NV 89710

R. R. Loux, Jr., Manager (8)
Nuclear Waste Project Office
State of Nevada
Capitol Complex
Carson City, NV 89710

C. H. Johnson
Nuclear Waste Project Office
State of Nevada
Capitol Complex
Carson City, NV 89710

John Fordham
Desert Research Institute
Water Resources Center
P.O. Box 60220
Reno, NV 89506

Dr. Martin Mifflin
Desert Research Institute
Water Resources Center
Suite 201
1500 East Tropicana Avenue
Las Vegas, NV 89109

James Friant (5)
The Robbins Co.
Box C8027
Kent, WA 98301-0427

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3151	W. L. Garner (3)
8024	M. A. Pound