AD743224

RESEARCH IN LONG HOLE EXPLORATORY DRILLING FOR RAPID EXCAVATION UNDERGROUND

Prepared For

U. S. BUREAU OF MINES

FINAL REPORT - PHASE I

Prepared by

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San Francisco, California 94111

Sponsored by Advanced Research Projects Agency
ARPA Order No. 1579, Amendment No. 2
Program Code 1F10

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April 1, 1972

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DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

Unclassified

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Jacobs Associates 500 Sansome Street San Francisco, California 94111	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP Unclassified

3. REPORT TITLE

RESEARCH IN LONG HOLE EXPLORATORY DRILLING FOR RAPID EXCAVATION UNDERGROUND

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Final Report

5. AUTHOR(S) (First name, middle initial, last name)

Thomas N. Williamson

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
April 10, 1972	31	10

8a. CONTRACT OR GRANT NO. H0210037 b. PROJECT NO. ARPA Order No. 1579 c. Ammendment No. 2 d. Program Code 1F10	9a. ORIGINATOR'S REPORT NUMBER(S) None 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) None

10. DISTRIBUTION STATEMENT

Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES None	12. SPONSORING MILITARY ACTIVITY Advanced Research Projects Agency- Department of Defense Washington D.C.

13. ABSTRACT

Research has led to a new concept generation for drilling a four inch diameter probe hole horizontally. This is to be used to probe ahead of mechanical tunnel boring machines to forewarn of dangers or to allow time for orderly change of tunneling methods or techniques. The method is designed to project the probe hole 1000 feet deep in moderately strong and high strength rock.

The equipment was purchased and or designed and manufactured. It was assembled in preparation for field tests in two or more quarries to optimize the design.

The first quarry test site was prepared.

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

Unclassified

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Rapid Underground Excavation						
Probe Hole Drilling						
Rotary Drilling						
Percussion Drilling						
Core Drilling						
Tunneling						
Rock Excavation						
Horizontal Drilling						

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2.0 CONTRACT DATA

The research was supported by the Advanced Research Projects Agency of the Department of Defense and was monitored by the Bureau of Mines under Contract No. H0210037

The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either express or implied, of The Advanced Research Projects Agency or the U. S. Government

Effective Date of Contract	:	February 26, 1971
Contract Expiration Date	:	February 26, 1972
Amount of Contract	:	$59,284.00

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Mr. T. N. Williamson (415) 434-1822

3.0 TECHNICAL REPORT SUMMARY

Under this Phase I of a planned three phase research project a novel horizontal rock drilling method was conceived and developed. Hardware was produced and assembled to provide tests of methods and development of criteria for long-horizontal probe drilling machines. The ultimate purpose of the holes to be drilled is to provide safer conditions by giving advanced knowledge of potential hazards in underground excavation, particularly in tunneling, and to assist in more economical advanced planning.

This Phase I is to provide a test drill concept, procure and assemble test drilling equipment and prepare an initial test site. Phase II will be to test the concept and arrive at a design criteria. Phase III will include design procurement and test of a prototype drill for underground use.

Specifically the goal of this Phase I of the research program is to develop a probe drill for rapid underground excavation for tunnel boring machines (TBM) working in moderately strong and high strength rock. Moderately strong rock (MSR) for this purpose has been defined as that with a uniaxial compressive strength of 10,000 to 20,000 psi. High strength rock (HSR) has been defined as that of 20,000 to 30,000 psi compressive strength. Of course there are a few tunnels driven in very high strength rock of above 30,000 psi and many soft ground tunnels in materials weaker than 10,000 psi. This research is not directed toward problems in these areas but may assist in the ultimate solution of probing in these stronger and weaker materials.

The current work developed a drill to make a hole 4 inches in diameter and 1000 feet deep. The drill is capable of occasional coring the formation as required. The instantaneous drilling rate for any drilling combination should be about triple that which can be achieved by todays TBMs. This means that the maximum production rate of the probe drill has as its goal a production of 90 feet per 8 hour shift in HSR and 168 feet per shift in MSR.

The drill is instrumented sufficiently to record data for selecting the best combination of thrust, RPM, and fluid or air flow rates and pressures. The ultimate drill must be compact enough to cause a very minimum of interference to the normal tunneling progress. It must be compatible with available power sources and should not cause any detrimental effect on the tunnel environment. The test drill components and methods were selected with this ultimate space and environment limitation in mind.

Until this research project, the two best ways to drill long holes horizontally in rock were wire line core drilling, where samples are required, or down hole percussion drills for full or open holes. The best shift production rate for wire line core drills is about 40 to 60 feet depending on rock hardness and other conditions. Down hole percussion drills are much faster on an instantaneous basis but the net production rate would have been even slower in deep holes. This is because to change to coring would require withdrawing of the tool and disconnecting each rod. This is very time consuming. It appeared that before the state of the art provided drills or methods with a production rate of not more than one third to one half that required.

A new method of handling 1000 feet of drill rod in a single piece was conceived. This is a method of storing the rod in a pipe on the tunnel floor or in a previously drilled hole behind the drill when the drill is set up in an alcove alongside the tunnel. This method provides a new concept in circulating fluid (air or water) through the storage pipe and into the open end of the drill rod stored in it. This eliminates the use of a traveling drilling hose and the swivel as well as the time consuming job of handling them and the individual pieces of pipe as drills are advanced or withdrawn. Drills can be withdrawn to change drilling methods or to replace worn out bits very rapidly by another device designed and built on this project. This is a rapid rod extractor with which two powered-counter rotating wheels are clamped to the rod and drive it in or out of the storage pipe or hole at the rate of 150 feet per minute.

The 35 H.P. rotary-hollow-spindle drill rig and tools and instruments were assembled at a shop in Burlingame, California. The first test site for "shake down" tests was arranged for and prepared at Granite Rock Company's quarry at Aromas California approximately 100 miles south of San Francisco.

4.0 INTRODUCTION

It has been recognized that rapid excavation techniques developing for underground tunneling, are creating a need to have much better methods of sampling materials ahead of boring machines. These same techniques might be used for pre-job estimating. Such pre-job information should provide much more intelligent bidding for tunnel work and, therefore, result in an ultimate savings to the public who must pay for the growing demands for increased public works underground.

Probe holes ahead of construction or in advance of tunnel boring machines could provide information on potential hazards of bad roof conditions, gas or water. Discovery of bad conditions in advance by probing will permit orderely preparation for these bad conditions. It will not be necessary to take a continuous core but short sections of core at some regular spacing, or at any obvious change in conditions indicated by the drill instrumentation, are desirable.

Generally there are two types of ground conditions for tunneling with many sub-types under these two broad classifications. The two broad classes are "hard rock" and "soft ground" tunnels. Rock tunnels usually are considered to include those which cannot be cut with drag bits. They require either rolling cutter bits on a boring machine or the use of explosives in conventional tunneling. There are two classes of rock tunnels and they are MSR and HSR as described in paragraph 3. This study is restricted to these types of rock tunnels as opposed to soft ground which usually require a shield and sometimes even air pressure to retain flowing ground.

It was recognized that one of the more difficult problems in probe hole drilling is going to be hole direction control. Tools to provide straight holes were included in the plans.

Insofar as was possible, commercially available drilling units and methods were used in the systems selected. This required a minimum extension of the art; although ideas were borrowed from several divergent disciplines (oil well drilling, mining and construction) and they were combined in a unique assembly. These innovations included new method of drill rod extraction and handling and a new method of fluid circulation which were introduced with the equipment and design provided by this Phase I effort.

5.0 TECHNICAL DISCUSSION

5.1 Problem Description

Until 1955 most tunnels in rock for public works and military installations were driven with use of explosives. This three-cycle operation, of drilling, blasting and loading, produced tunnels under good conditions at rates of 50 to 100 feet per three-shift day.

During the early part of the 1950 decade, a century of effort to provide a mechanical tunnel-boring machine began to bear fruit. By 1965 tunneling machines were beginning to show signs of success at five or more sites in this country and abroad. There was a clear indication that, where these machines could be used, the production rate could often double or triple that made by drilling and blasting. It was not uncommon for tunneling machines to make 200 and 300 feet per day and to sustain this over several days. About 60 machines have now been successful. More than half of the new tunnel jobs started today use boring machines or such machines are considered very seriously in their planning. (7)*

The machines are increasing their productive capacity and reliability in those types of rock for which they originally were successful. They are extending their application to stronger rock types for which they were not considered a few years ago. In the beginning, they were not considered seriously for HSR, due to slow penetration and primarily to high cutter costs. The maximum rock-strength limit has been raised from 20,000 psi a few years ago to at least 25,000 psi and there have been some claims of success of machines used in 35,000 psi strength rock. The early diameter range limits of 8 feet minimum and 20 feet maximum have been extended at both ends. The minimum length of two miles, to justify a machine was a result of capital expenditure outlay, and is no longer universally valid as more and more used machines become available, or machines can be projected for use on more than one job.

The rapid acceptance of machines and the developing need for more and more underground construction has introduced several problems. These problems include: material handling; ground support; guidance; and environmental protection. In addition to these problems both the owner and the contractor need vastly superior methods of predicting geological conditions. These improved prediction methods are required both in pre-job planning and as the job progresses. They are needed to show the extent and kind of ground support required. Prediction methods are needed to show potential hazards of prolific water flow or dangerous gas. Improved geological prediction methods for pre-job planning will provide more realistic bidding as well as better prices and fewer costly post-job claims resulting from badly-predicted conditions.

*NOTE - Numbers alone in parenthesis refer to list of references.

Precisely this project addresses itself to providing a drill which will sample, from a horizontal hole up to 1000 feet in depth. The drill could be used in pre-job planning by sampling from each available potential tunnel adit. Normally, however, it will be used in conjunction with a tunnel-boring machine during operation.

The sample borer must not interfere with, or should cause a minimum delay to, the boring machine. It should be capable of taking adequate samples at reasonable intervals along the length of the bore hole. It should be able to drill in damp or dry conditions.

The drill should be usable in a tunnel of 10 to 20 feet in diameter or larger. It would be acceptable to provide a system requiring alcoves in the side of the tunnel at about 1,000 foot longitudinal intervals but these should not be large nor should they require extensive labor to install.

Tentative specifications for the drill were set by the investigating team in discussions with the technical monitor. These were that it should have as a goal, generally, the following characteristics:

1. Drill a hole which would provide intermittent cores from which at least one inch cubes of rock could be cut.

2. Require no more than 6 foot by 6 foot lateral displacement in or alongside the tunnel with no dimensional limitation on setup space along the tunnel line.

3. Drill at double the current production rate of tunnel-boring machines under good conditions which will be assumed to be 90 feet of probe hole per day in HSR and 168 per day in MSR.

4. Be capable of taking 5-foot cores at the end of each 45 feet of full hole drilling which will provide 10 feet total cores per 100 feet of drill hole and produce those drilling rates described in (3) above; but when change in drilling rate or cuttings returns or other variable indicates a drastic change in geological conditions, the system will provide a means for more frequent core recovery at some reduction in drilling rate. This reduction in rate would be more or less proportional to the loss in production rate per shift caused to the tunnel-boring machine.

5. Not add significant amounts of dust, water, gas heat or noise to the tunnel environment.

6. Be adaptable to being powered by an electric motor but recognizing that the outdoor test machine can be powered by gasoline engines for preliminary open-air tests in quarries.

5.2 Difficulties Anticipated

5.2.1 Drilling Rate Difficulty

Small diameter core holes have been drilled horizontally to as great as 1900 foot depth. This was done at Pennsylvania Turnpike tunnel. There are no records of drilling speed on this job. Conversations with experienced core drillers (including one who worked on the above Turnpike job) indicate that deep holes, using current state of the art, are much slower than will be required for the tunneling machine probe. One of the principal reasons for the slowness is time lost in rod handling, in conventional drilling or in pumping in, and retrieving, and withdrawing wire line inner barrels in wire line drilling. Drilling rate in production is, therefore, one of the major difficulties.

5.2.2 Hole Direction Difficulty

It will be essential that the probe drill hole be straight in most cases. This means that any change in hole direction of more than a few feet in 1,000 feet will cause either inaccurate information or interference with the boring machine or both. This is much better direction control than underground exploration or blast hole drillers normally attempt with horizontal holes. Hole deviation is caused by changes in rock, gravity, action of (or reaction to) the bit and bending of drill rod. Adequate hole direction control may be very difficult to obtain.

5.2.3 Machine Space and Environment Difficulty

Mechanically-bored tunnels, for the most part, have been 10 to 20 feet in diameter. The probe drilling must start at the area near the face, which usually is quite crowded with haulage, ventilation or boring equipment. Crew members, while few in number when compared to conventional tunneling, are concentrated in this area. A very real problem, then, will be to make a drill which will use very little lateral space. It must not produce adverse effects on the tunnel environment by discharge of drill-generated dust, mud, heat, excessive noise or noxious gas, but these are believed to be controllable to acceptable limits with techniques being considered.

5.2.4 Cuttings Removal Difficulty

There is very little or practically no experience in cleaning cuttings from very deep horizontal holes by the use of air circulation. Effects of loss of fluid circulation to broken or pervious ground must be evaluated and possibly eliminated.

5.2.5 Cost Effect Difficulty

It is believed that the overall effect of this tunnel research will be in an ultimate reduction in tunnel cost through better planning, possible with advanced knowledge of conditions. Together with safety this is one of the major goals of the research as the public is the buyer of many tunnels. At the same time it is recognized that a new operation may result and the cost of that additional operation should be minimized by the research if possible. This means that the capital equipment cost, labor requirements and supplies must be reasonably low. The system should not delay the main tunnel driving effort.

5.2.6 Data Reliability Difficulty

The data retrieved by the probe drill must be complete and accurate enough to predict severe problems such as broken rock, gas or water. Broken rock could cause collapse of the probe hole and loss of tools. Poor core recovery or loss of circulation of drilling fluid also could result.

Rock may be so badly broken that it will not support itself even in a small bore hole. If such a condition exists one of the reasons for the probe hole is satisfied. This is determination of very bad ground existance. This may not answer the needed information on gas or water but even their potential may be indicated by such ground.

Water could cause hazards to personnel or to some tools such as in-hole percussion drills. It could create some problems at the drill site in the tunnel if it issues from the hole in high volume pressure or temperature.

Gas, such as methane, could create explosive problems in or out of the hole being bored or in sufficient volumes could cause axphyxiation to those near the hole.

Gas or water pressures, volumes and their specific sources will be difficult to measure or locate. The measurement may require the application of hole packers such as those which have been developed by the Bureau of Mines for this purpose in methane. (10)

6.0 DRILL METHODS CONSIDERED

6.1 Drill Methods - General

Proven drill methods, as well as the so-called "novel" or "exotic" methods (1) were tabulated and analyzed. This analysis included the preparation of a matrix of drilling methods with values listed for each of the important parameters. A practical analysis of the potential capability of each method, for the problem as discussed in Section 5, was used in the final selection. (Table 1 and 2)

This section of the report briefly reviews the drill method considerations and the conclusions that were made. (2) (3) (4) (5) (6) & (8).

Drill Method Selection

DRILL METHOD	Diamond		Rolling Cutter	Percussion			Turbine	In-hole Motor	Thermal	Water Jets
	Core	Plug		Reg.	Rotary	In-Hole				
PARAMETER										
A- Thrust Needs	100	80	10	50	50	90	50	50	100	100
B- Hole Size	100	100	40	100	60	70	50	80	90	60
C- Depth Capability	100	100	100	30	10	90	100	100	80	90
D- Power Needs	50	40	90	30	30	40	30	30	50	50
E- Coring Ability	100	0	20	20	10	40	50	50	0	0
F- Pen. Rate HSR**	70	60	70	90	100	100	80	80	80	40
G- Pen.Rate MSR*	50	50	90	90	70	70	80	80	40	80
H- Eqpt. Compactness	80	80	40	90	70	80	80	80	60	60
I- Skill Required	70	70	70	80	60	60	40	40	50	40
J- Economics	80	70	90	40	40	70	50	60	40	40
K- Direction Stability	60	60	90	40	40	70	70	70	80	80
L- Safety	100	100	100	100	100	100	100	100	40	50
M- Direction Control	60	60	80	50	50	60	90	90	60	80
N- Adaptability to Rock Changes	30	90	100	100	90	100	80	80	50	60
O- Operation Delays	60	100	100	100	100	100	100	100	100	100
P- State of Technology	90	90	100	100	60	70	60	70	60	50
GRAND TOTAL	1260	1150	1170	1110	940	1210	1110	1160	960	980
Total Coring MSR*	1190	NA	1100	1020	740	1110	1030	1080	NA	NA
Total Coring HSR**	1210	NA	1080	1020	870	1140	1030	1080	NA	NA
Total Full Hole MSR*	1090	1090	1080	1000	820	1070	980	1020	880	940
Total Full Hole HSR**	1110	1100	1060	1000	860	1200	980	1020	920	900

* Medium Strength Rock

** Hard Strength Rock

NOTE: Rated 0-100 with 100 best

Table 1

DRILL CHOICE (FROM MATRIX, TAB. 1)

	DRILLING METHOD							
	CORING				FULL-HOLE			
	Medium Rock		Hard Rock		Medium Rock		Hard Rock	
	Method	Score	Method	Score	Method	Score	Method	Score
1	Diamond Core	1190	Diamond Core	1210	Diamond Core	1090	In-Hole Perc.	1200
2	In-Hole Perc.	1110	In-Hole Perc.	1140	Diamond Plug	1090	Diamond Core	1110
3	Rolling Cutter	1100	In-Hole Motor	1080	Rolling Cutter	1080	Diamond Plug	1100
4	In-Hole Motor	1080	Rolling Cutter	1080	In-Hole Perc.	1070	Rolling Cutter	1060
5	Turbine	1030	Turbine	1030	In-Hole Motor	1020	In-Hole Motor	1020
6	Reg. Perc.	1020	Reg. Perc.	1020	Reg. Perc.	1000	Reg. Perc.	1000
7	Rotary Perc.	740	Rotary Perc.	870	Turbine	980	Turbine	980
8	Diamond Plug	NA	Diamond Plug	NA	Water Jets	940	Thermal	920
9	Thermal	NA	Thermal	NA	Thermal	880	Water Jets	900
10	Water Jets	NA	Water Jets	NA	Rotary Perc.	820	Rotary Perc.	860

Table 2

6.2 Diamond Rotary Drilling

Detailed information on horizontal diamond drilling of long holes is just about nonexistent in the literature. Information or advice solicited from those experienced in the field (and experience in deep horizontal hole drilling is limited) indicated a wide range of probable production rates. These drillers also varied widely in estimate of ability to control hole direction or had to be very vague as written records are not available.

Some diamond drilling proponents made assurances that the best way to get production with diamond bits was with the core-type bit. They were almost unanimous in recommending wire-line coring techniques even though cores would not be required all the way. Their reason was that, in their opinion, coring is two to three times as fast as full hole drilling and bits are much cheaper. The wireline technique is required because rod handling for other types of coring is extremely slow (until the development of techniques first tried on this project).

Unfortunately it was very difficult to get any shift production rate estimating figures from the printed literature. Several Bureau of Mines publications gave good information on instantaneous rates, theoretical horsepower, etc. It is hoped that the proposed field work on this project will give future investigators a foundation of data from which probe drilling production rate forecasts can be made for diamond rotary drilling under different conditions.

At best it appears that diamond drilling, in its fastest form, will not be fast enough. Other methods had to be studied. It was recognized that diamond core drilling probably is the only drilling method to get satisfactory rock samples in a probe hole. The method chosen for "speed" or production drilling, therefore, must be compatible with diamond rotary drilling.

In choosing the size of diamond core drill bits and rods, four very important considerations were:

1. Speed of drilling

2. Core of usable size (from which one inch cube could be cut)

3. Getting a rod large enough to provide the required torque in the horizontal holes 1,000 feet deep. This size of rod had to pass drilling fluid (inside and out) for different drilling methods at reasonable pressure losses.

Based on experience and recommendations of several persons knowledgeable in this field, the "B" size wireline rod was chosen for the coring intervals and as a satisfactory size for other drilling methods.

6.3 Rotary (Rolling Cutter) Drilling

The potential of rolling cutter bit drilling and requirements for such a drill have been defined quite well in the literature. It is known that these bits perform much better in diameters double the 3 to 5 inch range under consideration for this study. This performance increases with size increase in a more or less direct line ratio of hole sizes. In open-pit quarries, for example, bit economy may be improved by 50% or more by increasing from a 6-1/4 inch bit to a 9 inch diameter bit.

Unfortunately while the large-size holes may be drilled cheaper with rolling cutter bits (and sometimes faster for an overall average drilling rate from sharp to dull bit) they also require a much larger drill rig because of the high thrust requirement.

The higher cost of the larger rig might be justified for this work. On the other hand, it is quite within reason to expect that a rig to drill an economical hole, with rolling cutter bits, will be too large to work within the confines of a 12 to 20 foot diameter bored tunnel and still permit boring operations to proceed. In a research project such as this all methods which appear to have a chance must be proven or disproven with documented field results.

It has been decided that a 4-1/4 inch rolling cutter bit will be tried. Rolling cutter bits are made for casing sizes and the standard bit sizes in this range in inches are: 3-7/8; 4-1/4; 4-3/4; 5-5/8; 6-1/4; etc. The size chosen, therefore, may not be an even inch or half-inch diameter as can be selected for other drilling methods.

For rolling cutter bits of 4-1/4 inch size, thrust of 4,000 to 5,000 pounds per inch of bit diameter is recommended for hard rock. Above 6-3/4 inch diameter, this thrust requirement may be increased to 6,000 pounds per inch of diameter. These bits should be rotated at 40 to 60 rpm.

When using water or light mud, in rotary drilling vertical holes, the fluid circulation should be enough to provide an annulus rising velocity of about 100 to 125 feet per minute. When using air or gas, 3,000 to 5,000 feet per minute vertical annulus velocity is recommended. There is no really good published data available on fluid (gas or liquid) requirements for drilling horizontal holes in rock. Some laboratory experiments indicate that much higher velocities, or about three times as much as in a vertical pipe are required to transport cuttings in a horizontal pipe. Field results, however, indicate that much less than this increase in ratio is required in a small hole, which includes a rotating drill rod. Presumably the revolving rod stirs up the cuttings and keeps them in suspension, so that a lower velocity than that theoretically indicated may be adequate.

It is recognized that any drill rig provided for this service must be small. It is doubtful that such a small rig can be provided, from those commercially available, which will produce 20,000-pound thrust required for a 4-inch hole. A drill of such capacity and size might be developed if research indicates that it is needed.

The Japanese are working on a drill which is similar and at the same time very dissimilar. (9) Their goal is a drill for much deeper (15,000 feet) capability. Their ground is much softer (less than 10,000 psi). They are not coring but only checking water inflow. Their 400 HP rig is about 10 times as powerful as that proposed in this study and requires a chamber 149 feet long, 6 feet high and 27 feet wide, 50% higher and 5 times as wide and 5 times as long as the chamber required for the drill being designed in the program.

6.4 Percussion Drilling

Percussion is the fastest and best method to drill holes of less than 5-inch diameter in all types of moderately-hard and hard rock. Many laboratory tests have shown that hard rock can be drilled by percussion drills at instantaneous penetration rates of two to three feet per minute. This can be misleading as production figures must be discounted from the high figures projected from instantaneous rates produced under laboratory conditions. Contractors figure production in the order of one foot per minute rather than the laboratory indicated potential of three feet per minute. It does not really matter whether the rock is MSR or HSR in potential production drilling rates, according to the practical experts in this field.

Depth of hole is important to percussion drilling. The traditional percussion drills, which pound on one end of the steel with the bit on the other end, start losing effectiveness in holes of beyond 100-foot depth and would be useless in holes of 500 feet or more, or even beyond 200 feet.

Fortunately a down-hole percussion drill recently has been developed in the size range required for this project. This 3.5-inch-diameter by 4-foot-long tool will drill a 4 or 4.5 inch-diameter hole. Its penetration rate is virtually unaffected by depths up to the 1,000 foot depth of this project.

Manufacturers of down-hole drills estimate 30 feet per hour in MSR and 15 to 20 feet per hour in HSR. Such penetration rates are approximately double those for tunnel-boring machines in these kinds of rock and, therefore, would be a satisfactory solution to this project.

The 3.5 inch percussion tool requires 300 cfm of 100 psi air to operate but may need more to clean a horizontal hole.

Percussion drills have another advantage and that is, unlike rolling cutter bits, they require very little thrust. As a matter of fact too much thrust may be detrimental. High thrust is going to be difficult for the last 500 feet of the 1,000 foot horizontal holes. The percussion drills are compatible with diamond drilling in low thrust requirement. The two methods are not compatible in RRM ranges as percussion drills need 15 to 20 rpm, whereas diamond drilling may require 300 to as high as 800 rpm.

There is some question as to whether air will be as good as water for removal of cuttings in a horizontal hole. If this research proves that water or mud is required, then existing percussion tools will not work. Much time and money has been spent trying to develop a mud-driven percussion drill. Most of this research has been by oil companies and their suppliers. The activity slowed down considerably about 1955 when it became apparent that the sintered tungsten carbide insert bit had solved, to an acceptable level, the hard rock drilling problem in oil wells. If it were found that such a drill, using water, were required it might be developed by picking up some of those abandoned research projects. Those who were active in the field included: Hughes Tool Company, Shell Oil, Gulf Oil, Southwest Research, Batelle Memorial Institute, and independent inventors such as Bassinger and Bodine. It should be pointed out that most of these efforts were discouraging and even with costs of $500,000, research tools seldom lasted longer than 25 hours.

6.5 Turbine Drilling

Turbines and in-hole positive-displacement motors were considered. Mud turbines are accepted tools and used for non-routine jobs in oil wells such as hole straightening or hole deflecting. Turbines are not made in small enough diameters to be of use in this project.

In-hole solid displacement mud motors (which also run on air) serve the same purpose as turbines, are used for the same application, and are made in 3.5 inch (or smaller) diameter. The best-known in-hole fluid positive displacement motor is the Dyna-Drill which is a Moyno pump modified to be a drill motor.

One advantage of an in-hole motor would be that it would eliminate one piece of equipment in the tunnel and that is the part of the drill required to rotate the drill rod. Another advantage is that it would lend itself to being adapted to hole-deflection tools better than a system which has a revolving drill stem. A third possible advantage is that it would reduce wear on the drill rod.

Some disadvantages of the in-hole drill are:

1. It might require a high pressure and volume mud system or several hundred gallons per minute at more than 500 psi.

2. The stationary (nonrevolving) drill stem might not keep cuttings in suspension for transport. If the rods must be rotated for cuttings return, the in-hole motor does no good in hole direction.

3. Maintenance costs are reported to be very high on the in-hole motors.

4. The motors must produce higher rotary speed to the tools than could be accepted by some of the candidate drill methods such as percussion drills for hard rock.

6.6 Novel ("Exotic") Drill Methods

All so-called novel or "exotic" drill methods were passed over for this project and the reasons are given briefly below. (1)

Rock-destroying methods, depending on thermal shock or evaporation, include the heat sources such as Kersone torches, lasers, and electron beams. None of these were selected because of one or more of the following reasons:

1. There is a variation in effect of different rock to such shock. Some respond well and some badly.

2. These methods produce bad effects on the tunnel environment of either heat or noxious gases in most cases.

3. Thermal methods are not conducive to sampling or coring techniques.

4. Thermally-produced holes are notoriously bad for having rough or undulating walls and this would add to the anticipated problem of cuttings removal in horizontal holes.

5. Thermal methods, other than the kerosene torch method, will require considerable research and development far beyond the scope of this project.

Impingement of solid pellets was not selected as a novel method, because research is not far enough advanced for use in this study.

High-pressure water jets are being studied and may be useful some day. None of the tools currently in research will be at a level of development required for field testing by the time they are required for this project. It is unlikely that they will be good for coring.

No ultra-sonic drills are anticipated to be ready within one or two years for evaluation of this project.

There is a possibility that future research beyond the scope of this project, may develop new methods of coring or extend the capability of some existing methods to use in this field. For example, during the 1960 decade, considerable laboratory work was done trying to develop a drill for astronauts to use on the moon. Such unusual approaches as percussion drills use for coring were tried.

6.7 Drill Method Conclusions

After a careful analysis of the possibilities, the following three methods were chosen for detailed analysis in the project:

1. Rolling cutter bits of 4.25 inch diameter and air or water circulation will be tried, varying RPM, thrust and water flow rates.

2. Diamond coring will be tried, varying thrust RPM, and fluid rates. This will be with "B" size rods, barrels and bits.

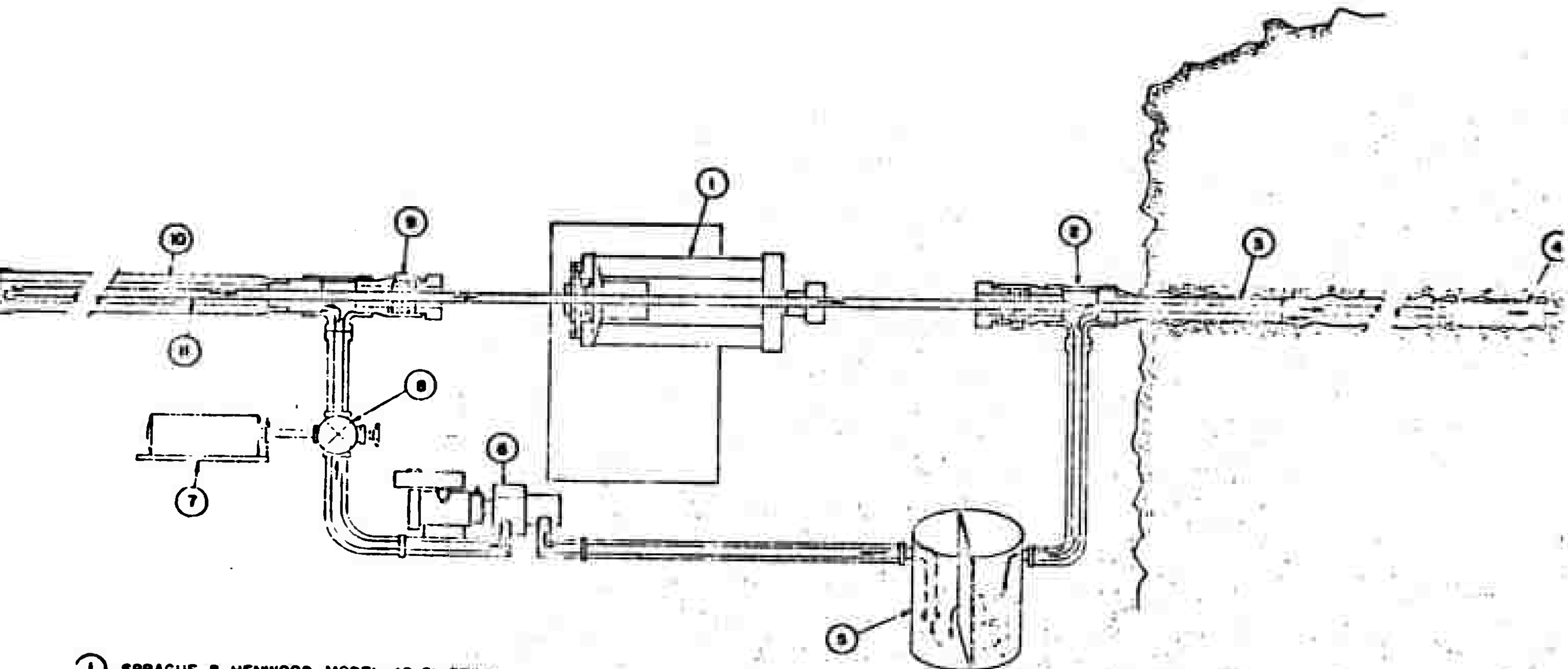
3. A down-hole percussion drill will be tried, varying RPM and thrust.

Generally speaking the range of the variables will be selected as the test proceeds. It if becomes obvious that any drilling technique will not work in the rock under test, then with data to substantiate this conclusion, the testers may abandon any process. It would be wasteful to run the full gammut of variables, if complete failure of the method can be projected from available data at any time. Such failures, if they occur, will be documented.

Several methods were considered for drilling the horizontal holes, particularly for handling the drill rod. It was recognized that it may be essential to drill these holes either very rapidly on week ends or off shifts; on the other hand, it may be desirable to do them to one side of the tunnel so as not to interfere with the tunnel-boring machine.

The rather new method of storing the drill rods - in a storage pipe strung out behind the drilling machine - was decided upon. In this case it was decided to store the "B" type drill rod in an "N" sized casing. This 1000' of casing would be strung out behind the drilling machine on the floor of a quarry test site; but in a tunnel it might be the hole behind the machine. This hole would have been drilled previously, to probe ahead of the boring machine. A cap will be put on the rear end of the storage pipe; a conventional stuffing box with a 90° Tee will be put on the forward end of the storage casing. Air or water will be pumped into the Tee and will enter the open rearward end of the stored drill rod in the storage casing. It will then pass forward through the drill to cool and clean the bit and carry the cuttings back out. (Figures 1 & 2)

A casing will be set into the surface hole to be drilled. This short piece of 5 inch diameter casing will have a Victaulic quick-opening connector for the stuffing box. This will permit its removal so that large tools can be inserted ahead of the stuffing box.



1. SPRAGUE & HENWOOD MODEL 40-CL DRILL
2. STUFFING BOX - LONGYEAR NO. 17393
3. HW CASING 5'LONG, 4"I.D., 4 1/2"O.D.
4. IN-HOLE PERCUSSION DRILL-MISSION B-32-10
5. SEPARATING BOX-CUTTINGS, WET OR DRY
6. PUMP (GASOLINE ENGINE DRIVEN) APPROX. 30 GPM
7. AIR COMPRESSOR - 360 CFM - 125 PSI
8. TWO-WAY VALVE
9. STUFFING BOX - SEE (2)
10. NW CASING 1000' LONG, 3"I.D., 3 1/2 O.D.
11. BW ROD 1100' LONG, 1 13/16"I.D., 2 1/8" O.D.

GROUND STORAGE OF DRILL ROD

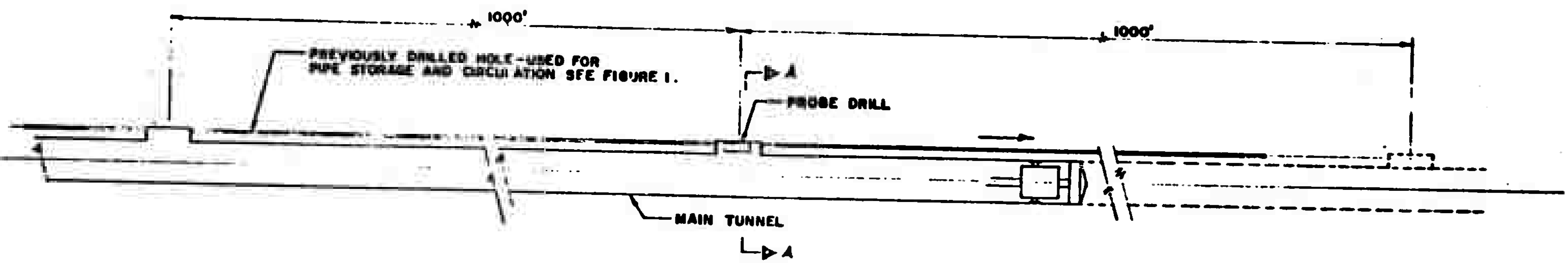
FOR

U.S. BUREAU OF MINES, ARPA

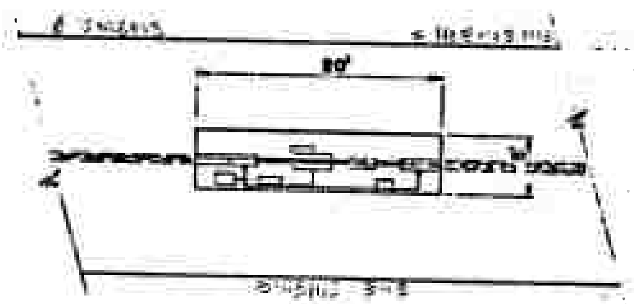
NOTES:

1. EQUIPMENT SPECIFIED IS TENTATIVE SELECTION ONLY - FINAL SELECTION TO BE MADE LATER.
2. PERCUSSION DRILL CAN BE REPLACED AS REQUIRED WITH DOUBLE TUBE SWIVAL TYPE CORE BARREL - 5' LONG - LONGYEAR BV NO 26672
3. RAPID ROD RETRACTOR BETWEEN DRILL 1 AND STUFFING BOX 2 - NOT SHOWN DRIVE WILL BE BY OPPOSED WHEELS, NOW IN DESIGN.

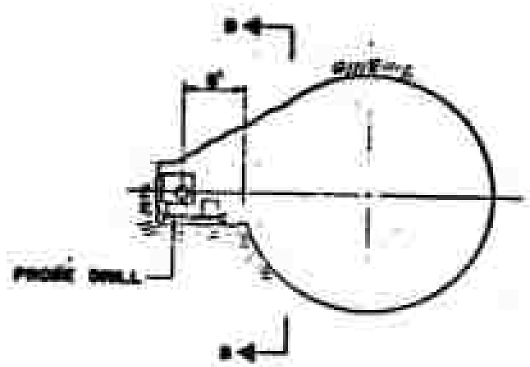
FIGURE 1



PROBE DRILL ARRANGEMENT FOR U.S. BUREAU OF MINES, ARPA



SECTION B-B



SECTION A-A

FIGURE 2

Return air or water will discharge from the Tee of the forward stuffing box into a hose for discharge into the mud pit or dust collector.

A drilling machine which applies thrust by gripping the drill rod and rotating it while it pushes it forward was selected. This hollow-spindle machine was specified to have a hydraulic-drive motor so that accurate torque figures might be recorded or computed during this test. The hydraulic motor also provides for the possibility of an infinitely variable rotary speed. (Figure 3)

It was recognized that a rapid method of withdrawing the drill rod from the hole would be required. A rod extractor was designed and built. This hydraulically-driven tool pulls the drill rod from the hole or re-inserts it in a hole at a rate of almost 150 feet per minute. It accomplishes this by gripping the drill rod between two counter-driven rotating wheels, the rims of which are shaped to the approximate circular shape of the drill rod. (Figures 4, 5 & 6)

Competitive prices were obtained on all major equipment items specified. The major suppliers of the principal equipment are shown in table 3.

7.0 INSTRUMENTATION

The difficulty of instrumenting field drilling tests was fully recognized from the beginning. In addition to the many variations in the drilling process, experience has shown that nature can present so many variations in rock conditions that instrumentation is very complex. Drilling researchers must add to these problems, the problems of dirt and frequent weather difficulties. It was felt, however, that effort must be made to instrument and record as much data with mechanical means as possible. Instrumentation and recording data for field drilling and excavation problems must - and will - be improved.

It was decided that an effort will be made to record seven variables. These are:

A. RPM

B. Penetration Rate

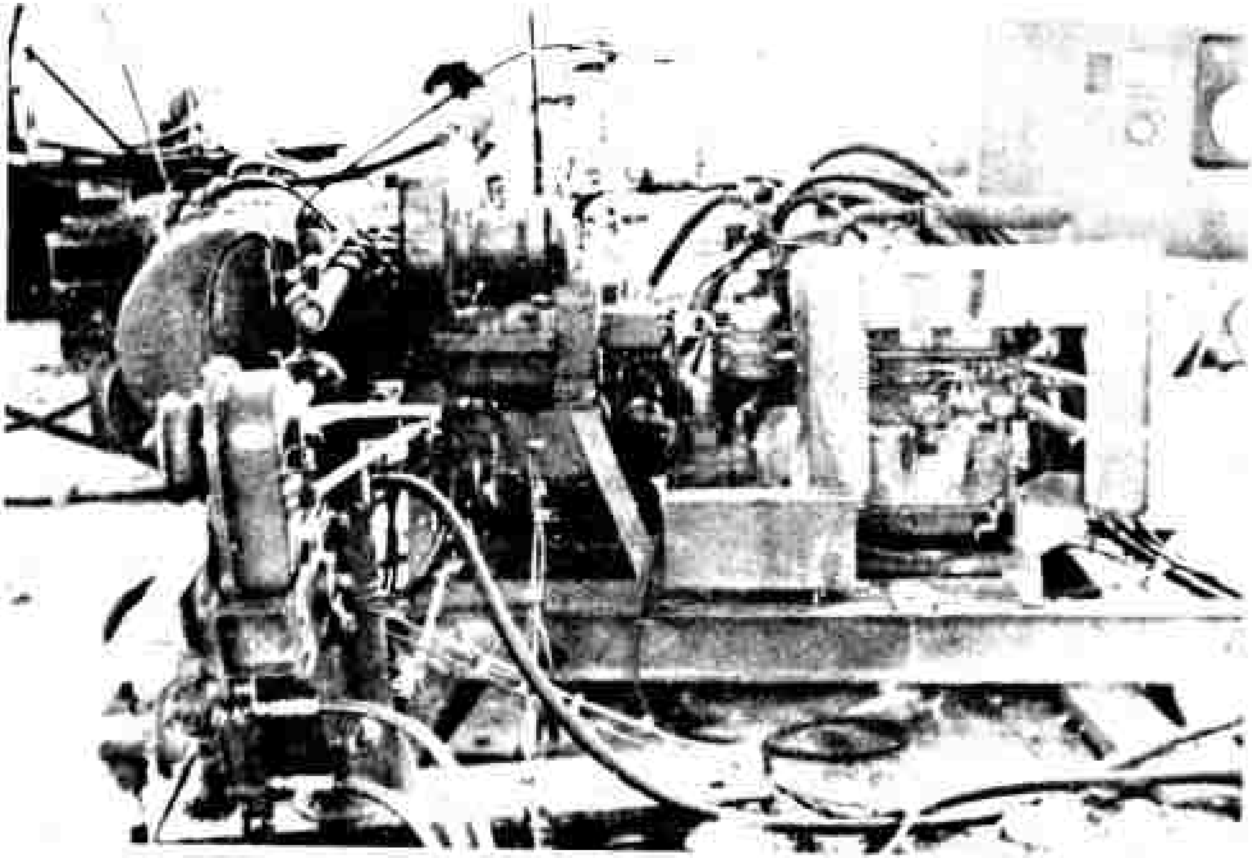
C. Hydraulic Motor Pressure

D. Hydraulic Motor Fluid Volume

E. Mud Volume (where applicable)

F. Mud Pressure

G. Thrust



40 HOUR - HOLLOW SPINDLE DRILL RIG ROD

EXTRACTOR LEFT FOREGROUND

Fig. 3

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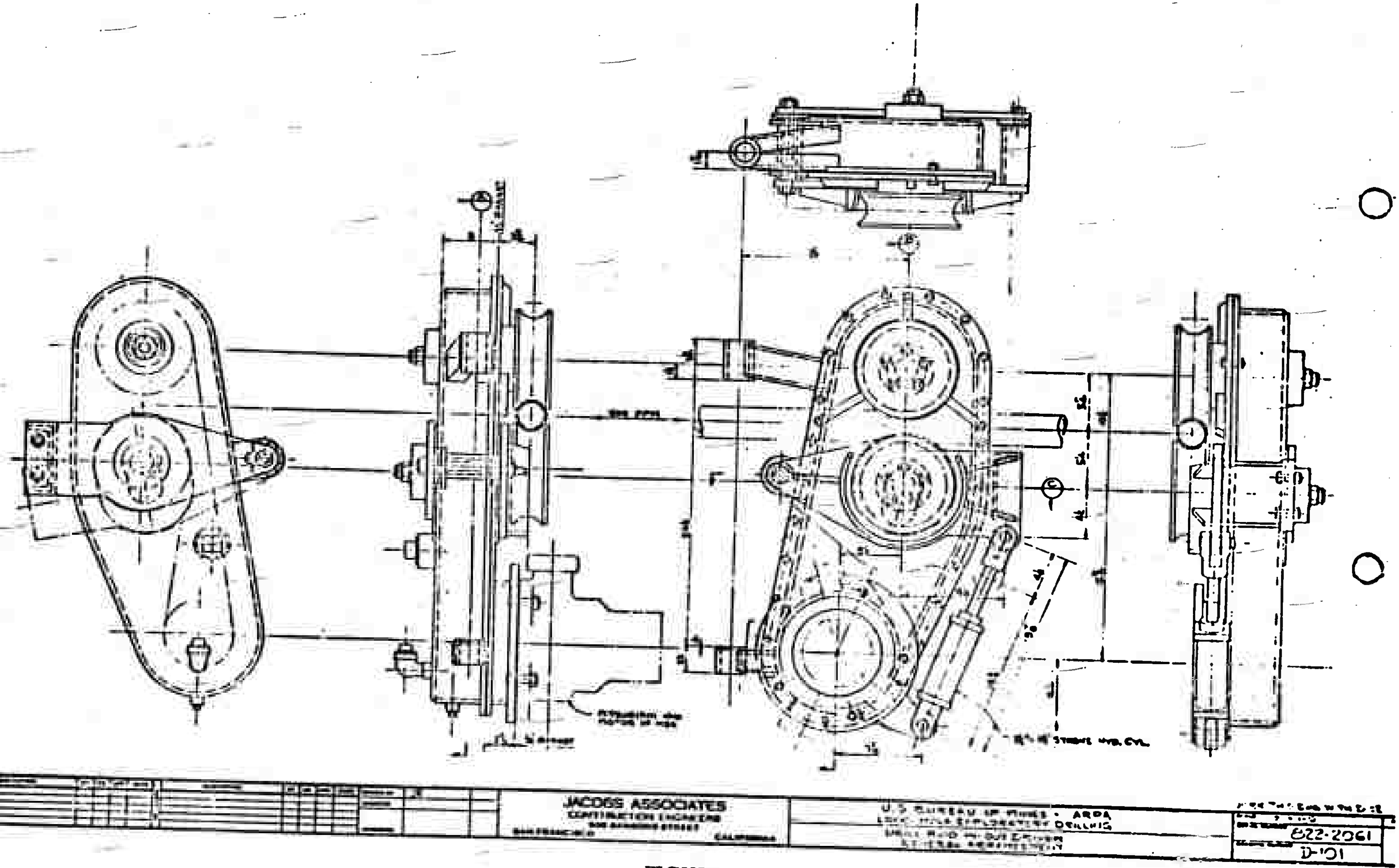

JACOBS ASSOCIATES
CONSTRUCTION ENGINEERS
SAN FRANCISCO
CALIFORNIA
U.S. BUREAU OF MINES - ARPA
822-2061
D-101

FIGURE 4

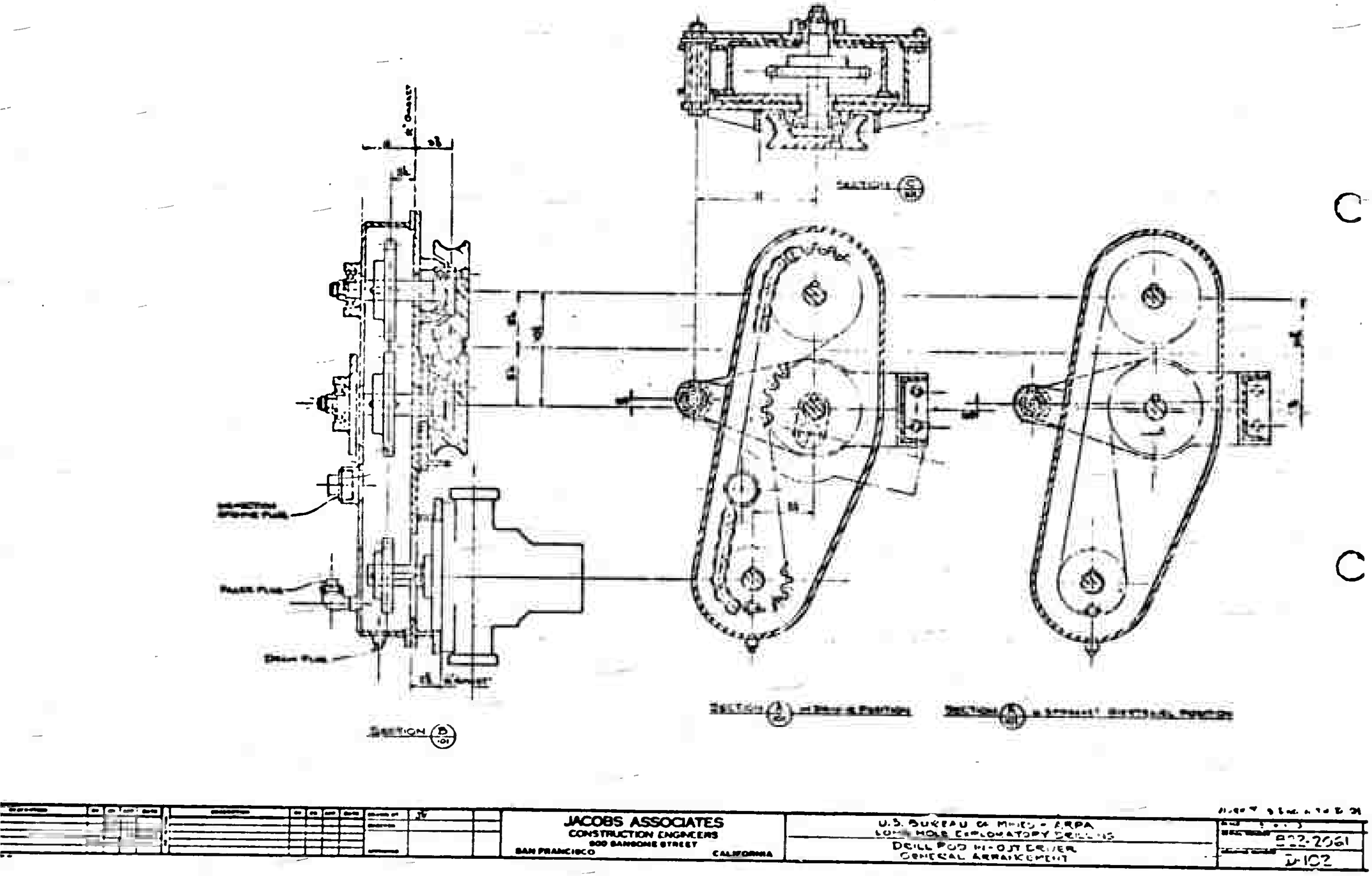
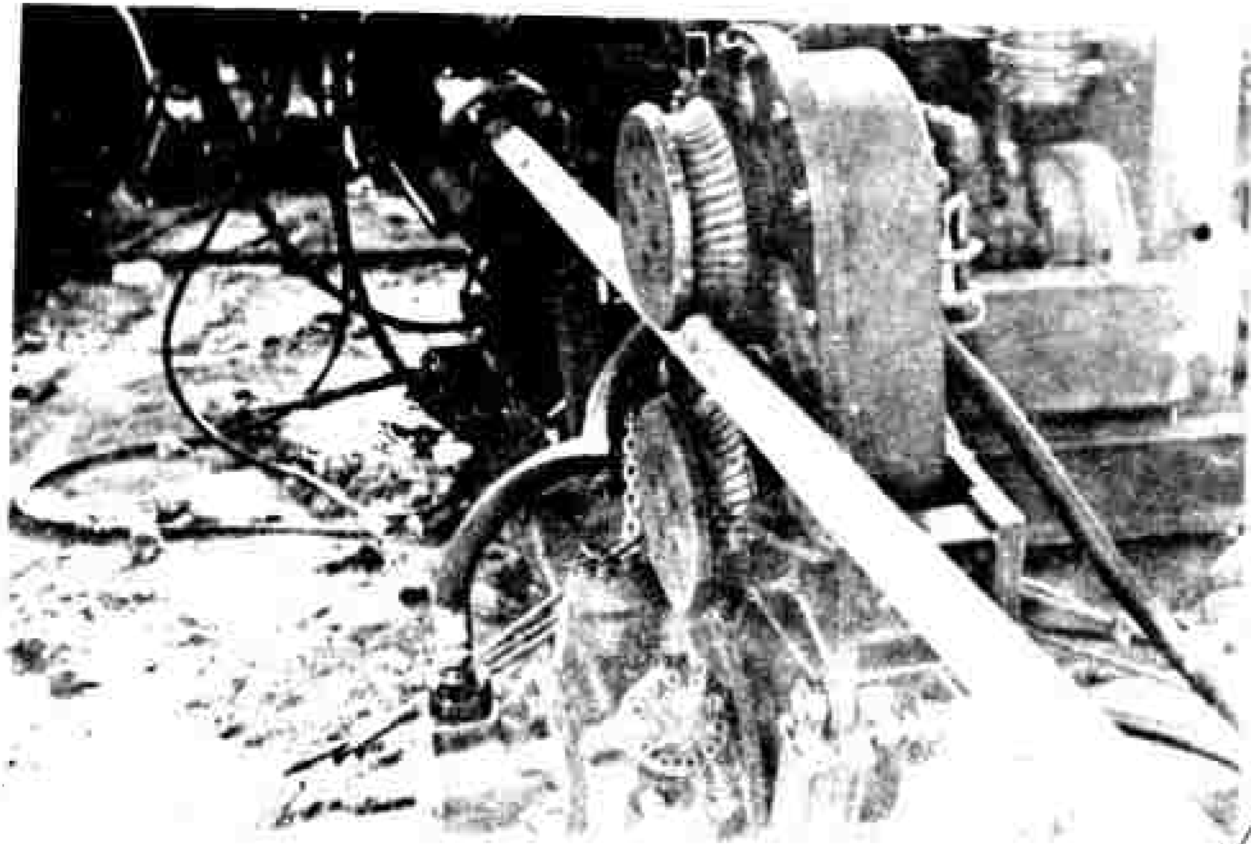

SECTION B
SECTION A
JACOBS ASSOCIATES
CONSTRUCTION ENGINEERS
500 SANSOME STREET
SAN FRANCISCO
CALIFORNIA
U.S. BUREAU OF MINES - ARPA
DRILL POD
GENERAL ARRANGEMENT
D-102

FIGURE 5



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ROD EXTRACTOR AND HYDRAULIC MOTOR

WITH ROD - DISENGAGED

Fig. 6

The three pressure recording (C, F & G) will be recorded on a single circular chart on an American Pressure Gauge.

The penetration rate and RPM will be shown by the influence on an Airpax magnetic pickup through a response from a rack gear for a penetration rate and a circular gear for the rotating speed. These will send their signals into a Rustrak recorder.

The mud gallons per minute and hydraulic fluid gallons per minute are also recorded from a signal given by a flow meter.

The Rustrak recorders are run by two 12-volt automobile batteries. The American Pressure Gauge recorder is a windup clock.

8.0 TEST SITE

Several test sites were examined or considered in all parts of the U.S. The contract called for appraisal of the equipment in two kinds of rock. Briefly, these rock classes are MSR and HSR previously defined. After reviewing several test sites for rock, weather, labor and travel conditions, two general areas were selected for closer study. These were: California and the Virginia and West Virginia or Central Appalachian areas.

California had the principal advantage of being close to the home office of the investigators and, therefore, would require less travel expense, and fewer administrative problems caused by distance. It had the disadvantage of having very few active rock quarries, however, in good solid homogenous rock. Most of the large California aggregate producers are near the coastal metropolitan areas and either get their material from a gravel deposit or from rock which has been rather badly shattered by recent earthquake movements. California had the disadvantage of high union labor wage rates and possible restrictive practices which could cause some delays or higher costs to a research test program.

What appeared to be a good hard rock test site was selected at Aromas, California. This was a Granite Rock Company's quarry. It is about 100 miles south of San Francisco. Early advice was that although the rock was broken, they had rather good experience in not losing holes because of circulation problems. It was also shown by tests to be very high strength rock and is highly rated for aggregate. Mr. John Green, Manager and his staff at Aromas were most helpful in getting set-up.

Very generous offers for field testing rights also were made by several quarry operators in the Virginia area. These included an offer of help from Mr. James Hill of Superior Stone Company; Mr. Charles Luck of Luck Industries in Virginia; and an offer of a site at an underground limestone quarry in Fort Springs, West Virginia by Mr. William Ruby of Acme Limestone Company. In California, Mr. Orville Johnson at Kaiser's Clayton quarry felt that he could arrange for us to test at an upper level there. At the latter site, the ground space conditions were not as good for a test layout as were those at Aromas. Test site pictures are shown in Figures 7 & 8.

AERIAL VIEW OF DRILL RIG IN QUARRY SHOWING ROD RUNNING FROM HOLE AT LOWER LEFT, THROUGH RIG TO STORAGE PIPE AT UPPER RIGHT COMPRESSOR AND WATER TANKS IN LEFT CENTER

Fig. 7

AERIAL VIEW OF 1000 FEET OF PIPE ON QUARRY
FOR STORING DRILL ROD

Fig. 8

PRINCIPAL EQUIPMENT

SOURCE

EQUIPMENT	MODEL	MANUFACTURER
Drill Rig	40CL	Sprague & Henwood
Water Pump	(35 GPM)	Longyear
Drill Rod	BQU	Longyear
Casing	NW	Longyear
Hoist	750	Sprague & Henwood
Percussion Drill	DHD14	Ingersoll Rand
Rod Extractor	-	Jacobs
Core Barrel	BQU	Longyear
Recorders	-	Rustrak
Magnetic Pickup	-	AirPax
Stuffing Boxes	B Rod	Longyear
Pressure Gage	-	American

TABLE 3

9.0 EQUIPMENT ASSEMBLY

The equipment was assembled at a marshalling area leased for this purpose at Burlingame, California.

The Sprague and Henwood 40 CL Skid-mounted 40 hp drill rig is the basic unit. This is a specially-modified hollow spindle drill rig, which means that the drill rod is fed through the rig, being gripped, rotated and fed by an automatic chuck. A special feature is that it has a hydraulic drive inserted between the Ford gasoline engine and the transmission. This permits selection of an infinite range of rotary speeds. More importantly, it provides a means of computing torque or horsepower through recording hydraulic pressures and volumes used by the rotary drive. (Fig. 5)

The same hydraulic pump, which drives the rotary head, provides pressure for thrust through a separate circuit. It is used also to run the hydraulic motor on the rapid rod extractor. (See Figure 4, 5 & 6)

A wire line hoist was selected from Sprague and Henwood. Their Model 750 is to be used for any wire line core recovery tests which are planned to be run for data gathering and comparative purposes and for fishing for lost tools.

An E. J. Longyear BQU wire-line core barrel which is 5 feet long was selected. This included the complete assembly of outer and inner barrel and overshot. The reamer shell and bits will be ordered as consumable supplies during Phase II.

One thousand feet of Longyear "B" type wire-line drill rod was purchased. Longyear also furnished 1000 feet of "N" sized casing and two "B" rod stuffing boxes and reducers for them from the "N" casing.

Longyear furnished the mud pump. This gasoline-engine-driven Beam pump has a 5 speed transmission. It produces 35 GPM at 500 psi and is driven by a gasoline engine.

An Ingersoll-Rand DHD 14 down hole percussion drill was purchased. This 3-1/2 inch diameter tool requires air at about 300CFM at 100 psi.

The rapid rod extractor was designed by Jacobs and manufactured by Renstrom Gear Co. It is powered by an M5A Mitsubishi hydraulic Motor.

Air compressors will be rented for field tests.

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