COO-2677-8
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THE DESIGN OF A WATER JET DRILL FOR DEVELOPMENT OF GEOTHERMAL RESOURCES

Annual
Progress Report

for period June 1, 1976 - May 31, 1977

CONTRACT No. EY 76 S 02 2677.M001

Prepared for
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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DISCLAIMER

ABSTRACT

In the second year of this contract research has been expanded to the drilling of crystalline rock. Advance rates of 40 inches per minute have been achieved at 16,000 psi, 10 gpm flow rate in a 30,000 psi compressive strength rock using the water alone as the drilling mechanism. The quality of the hole achieved as the jet drilled a variety of rock was found to vary and a Hydromechanical drilling bit, combining high pressure water jets with roller cones, has been developed. A field drilling unit has been tested and modified to allow the drilling of holes to 3-1/2 inch diameter using the Hydromechanical drill. Preliminary work on the development of a cavitation test for rock is also included.

Acknowledgment

The nozzles were constructed by Mr. James Blaine and much of the research has been carried out by Mr. Blaine, Mr. A. Krause and Mr. R. Robison, with the assistance of graduate and undergraduate students. The cavitation tests have been run under the supervision of Mr. B. Hale. It is a pleasure to record for this assistance.

Introduction

This report describes research carried out during the second year of Contract ERDA EY 76 S 02 2677 M.001, investigating the use of high pressure water jets as a means of improving the drilling rates for geothermal development.

During the course of this second year two factors have caused a re-evaluation of the direction of the research and led to some modification of the program planned. The first was the acceptance of a practical limit on the rate at which deep holes could be drilled on the order of 2-300 ft/hr, based on the logistics of feeding pipe into the hole. Because this rate had been greatly exceeded in the sandstone rock tested in the first year of the program, efforts to improve drilling rates beyond this level were discontinued and the effort concentrated instead on increasing the diameter of the hole drilled. The second factor influencing the program has been the developed ability to successfully drill Missouri Red Granite (compressive strength approximately 30,000 psi) with a jet nozzle operating at a driving pressure of 15,500 psi. This pressure is approaching the levels which have been used in field drilling tests of jet drills by commercial oil companies and therefore has reduced the need for cavitation assistance to drilling. The intention of the cavitation assist was to weaken the rock and thus lower the jet pressure required for drilling. Although jet pressures are now approaching viable levels, practical considerations require that as low a jet pressure as possible be used in the program, so the cavitation work is still continuing, although at a slightly reduced level of emphasis. The format of the research has, however, continued in the same divisions as has previously been reported (Figure 1) and the program will therefore be broken into these subdivisions for the purposes of the report which follows.

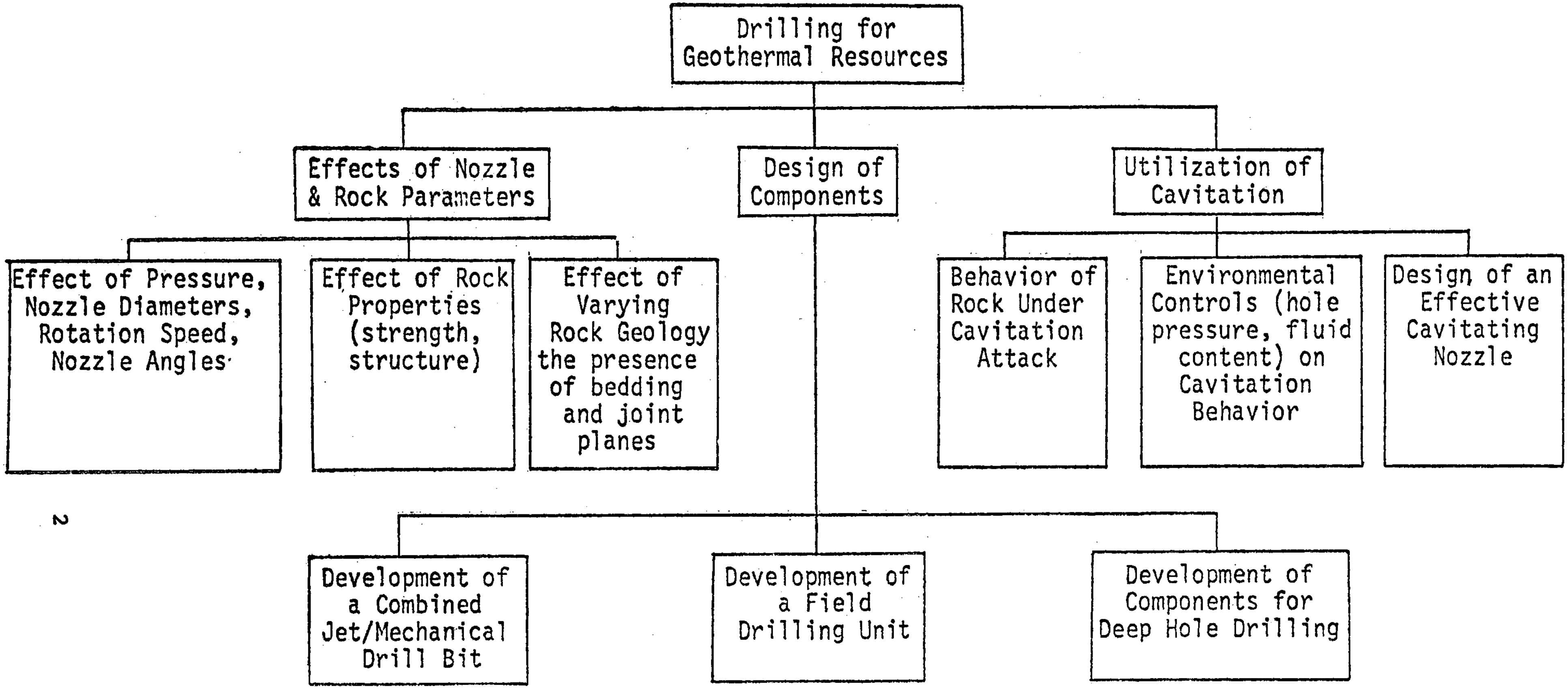


Figure 1. Current Program Elements Contract ERDA:EY 76 S 02 2677.000.

Effects of Nozzle and Rock Parameters

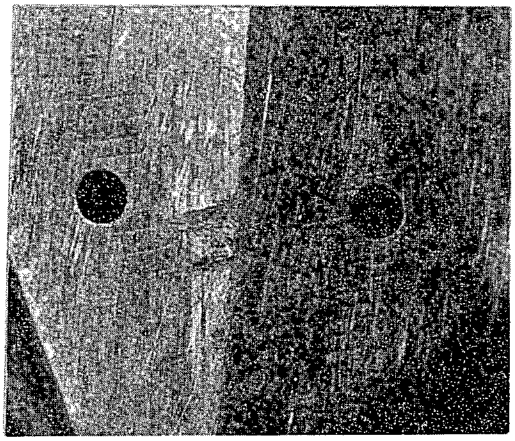
i) The Effect of Pressure, Nozzle Diameters, Rotation Speed and Nozzle Angle

The major results in this area have been described in earlier reports (COO-2677-6 and COO-2677-7) and summarized in two papers, one previously submitted with report COO-2677-7 and one herewith attached.

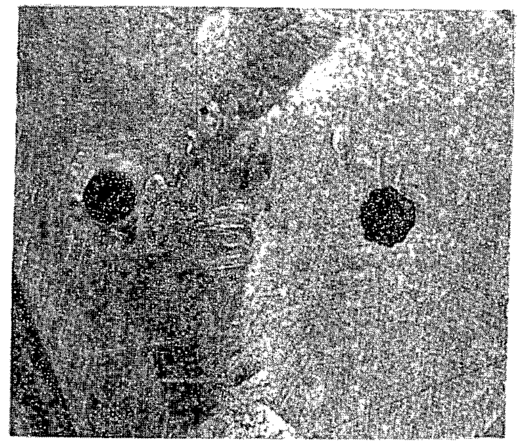
The research has identified that the nozzle design must be tailored for the rock type being drilled in order to obtain optimum performance and that while a dual orifice design has proved significantly better in drilling granular rock (with advance rates achieved of over 280 inches/minute) this is not the case with crystalline rock where a single orifice of equivalent flow rate and pressure has proved to give superior performance (advance rate of 40 inches/minute in Missouri red granite).

One problem that has been identified in the research is the lack of a low cost nozzle with a suitably long life for the conditions likely to be encountered. Contact with the rock is not a normal occurrence for the nozzles, and they are therefore better able to withstand wear while drilling in very abrasive rock than conventional bits. However, internal erosion on the throat section of the conventional brass nozzles normally used will cause unacceptable nozzle failure within 30 minutes at 10,000 psi and within 5 minutes (Figure 2) at 22,000 psi. To counter this problem a thin electroless nickel plating has been applied to the nozzle surface at low cost (approximately $1 per nozzle) and has proven capable of withstanding the erosive forces at the pressures currently under test (Figure 2b). This solution has required a small design change in the equipment and has proven a satisfactory way of providing nozzles for laboratory data.

In conjunction with another ongoing research contract funded by the U.S. Bureau of Mines (H0252037) a potentially more satisfactory solution for long life nozzles is being sought through use of either tungsten carbide or electroformed nickel.

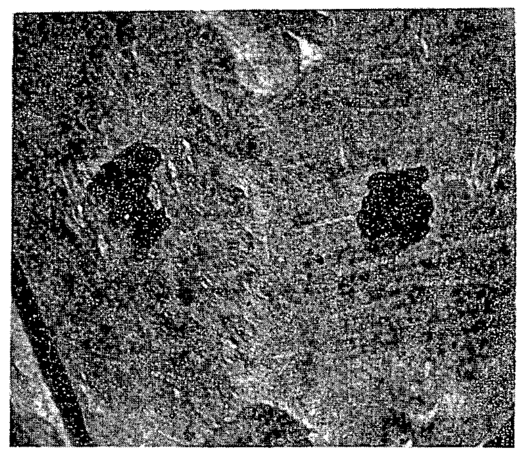


i) Before test



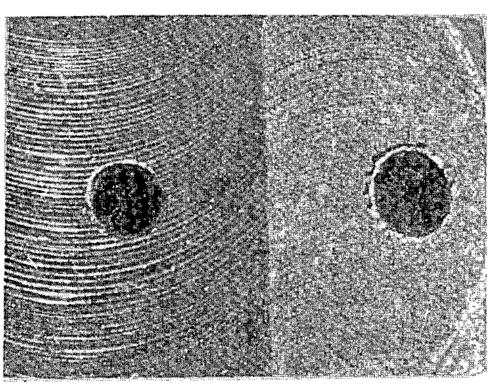
ii) After 5 minutes

iii) After 10 minutes

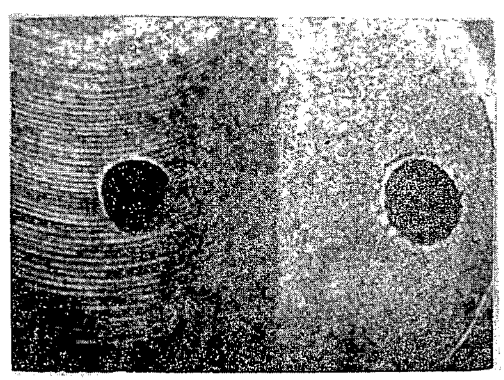


iv) After 25 minutes

2(a). Unplated brass nozzle run at 22 ksi



i) Before test



ii) After 25 minutes

2(b). Plated brass nozzle run at 22 ksi

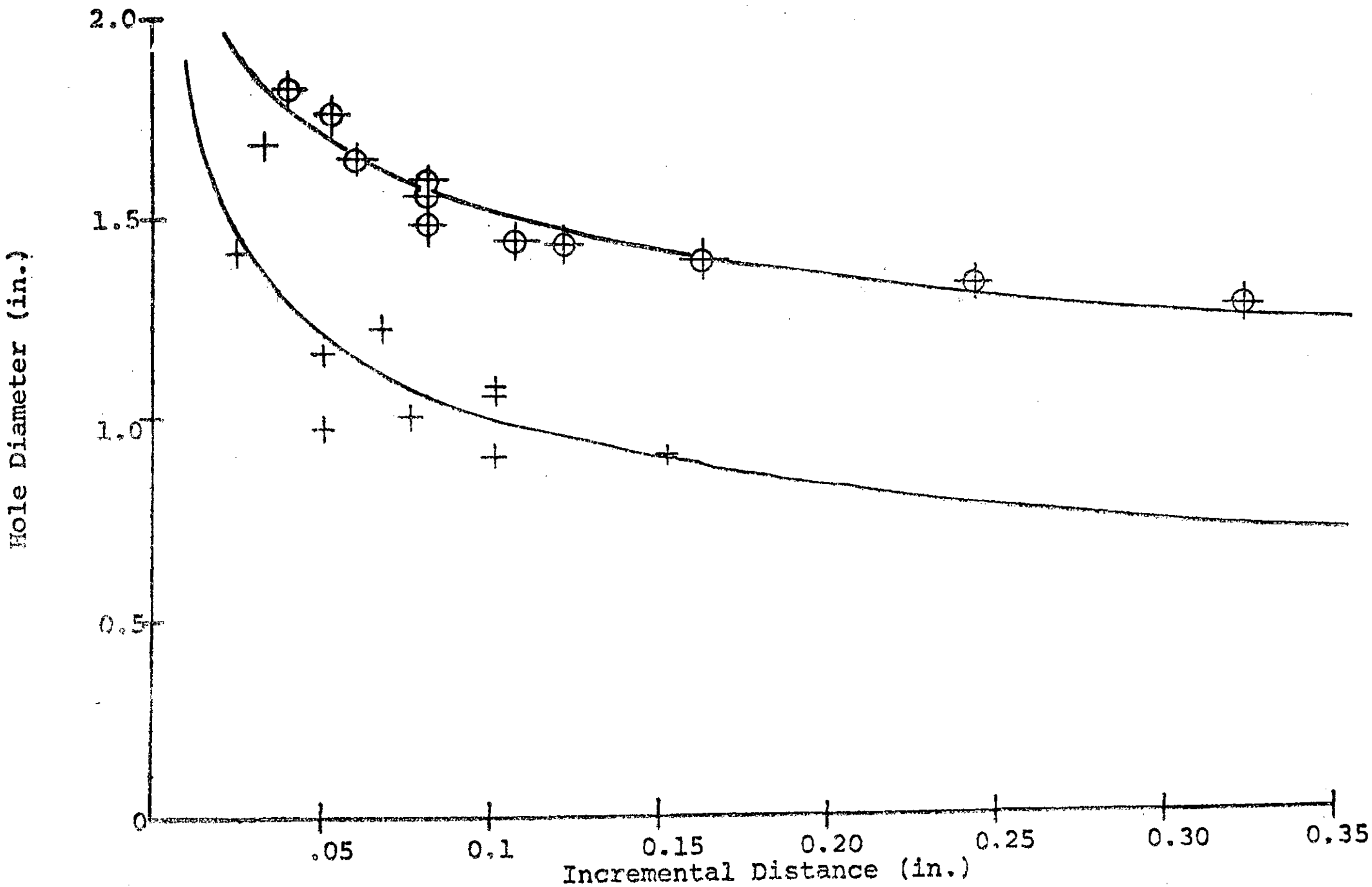
This program was undertaken following an investigation of the use of welded steel nozzles (COO-2677-2) which indicated that a satisfactory joint between the nozzle and the pipe could not be attained.

Rotational speed has been determined to have little effect on drilling rate except at low advance rates and high rpm where consecutive jet passes on the jet cut hole profile either touch or overlap, a secondary parameter, incremental feed distance per revolution is therefore the controlling parameter (Figure 3) unless there is a great change in rotational speed, in which case hole diameter will be reduced by the increased lateral speed of the jet over the rock. This will probably not, however, be a factor with the geothermal bit under development since the standard rotational speed of 50-60 rpm falls considerably below the level where this will occur.

ii) Effect of Rock Properties

Little progress has been made in this area at the present time. It has previously been demonstrated that compressive strength of the rock is not a factor in the ability of the jet to cut rock (COO-2677-2). Studies of the effects of confining pressure and borehole back pressure on drilling rate have shown that there is a sharp reduction in drilling rate as the pressure, from whichever source, rises to 1,000 psi but that the effect diminishes above that level. A change in cutting jet pressure of equal magnitude did not affect the cutting effectiveness of the jet to nearly the same extent and the sensitivity of the jet cutting to applied pressure would therefore appear to be related to a change in rock characteristics. This sensitivity changes with rock type and while a 44 percent decrease in hole diameter occurred with a 500 psi confining pressure where the sample was Berea sandstone, there was a 12 percent reduction in diameter for equivalent confinement where the sample was Missouri granite. Four rock types have been tested under this program with varying confining pressure and a series of physical property

Figure 3. The Effect of Incremental Distance on Hole Diameter for
a) sandstone drilled with a 22-1/2° nozzle at 10,000 psi
b) limestone drilled with a 30° nozzle at 20,000 psi



tests to determine which properties undergo equivalent change will be carried out during the months when field activity is closed by the weather.

iii) Effect of Varying Rock Geology

When a rock is tested in the laboratory the sample chosen is generally the most homogeneous, flaw-free piece which can be prepared. In consequence a mistaken idea of the response of the rock to attack can often arise since where the material lies in situ it is often bisected by joints, bedding planes, material of varying strength and under varying strata pressures.

In part because of data obtained from the tests described above but mainly because of the progression of the equipment from the laboratory to the field, the sensitivity of the jet drill performance to host rock geology was therefore the object of a small study. The results of the first part of this study (Figure 4) illustrate the problem likely to arise in field trials. A second set of trials were scheduled for the field rig but had to be postponed because of equipment problems, followed by the onset of winter.

The subject will form part of the study to be carried out in the lead mine trials proposed for this summer. The matter has, however, already been partially solved by the addition of a reaming bit to the nozzle (see below) and also by the intent to make the drill thrust sensitive rather than feed rate sensitive during the next phase of the field drilling unit trials.

The field trials will be carried out at a depth of approximately 1000 ft and will be located in the side of an entry. The ground will be, therefore, under varying tectonic stress due to the overburden and the stress concentration factor due to the presence of the opening. The effect of stress on drilling rate will thus be directly discernable as the drill advances away from the opening. A second series of trials is planned in the same area, but destressing the test site before running the trials for comparison purposes.

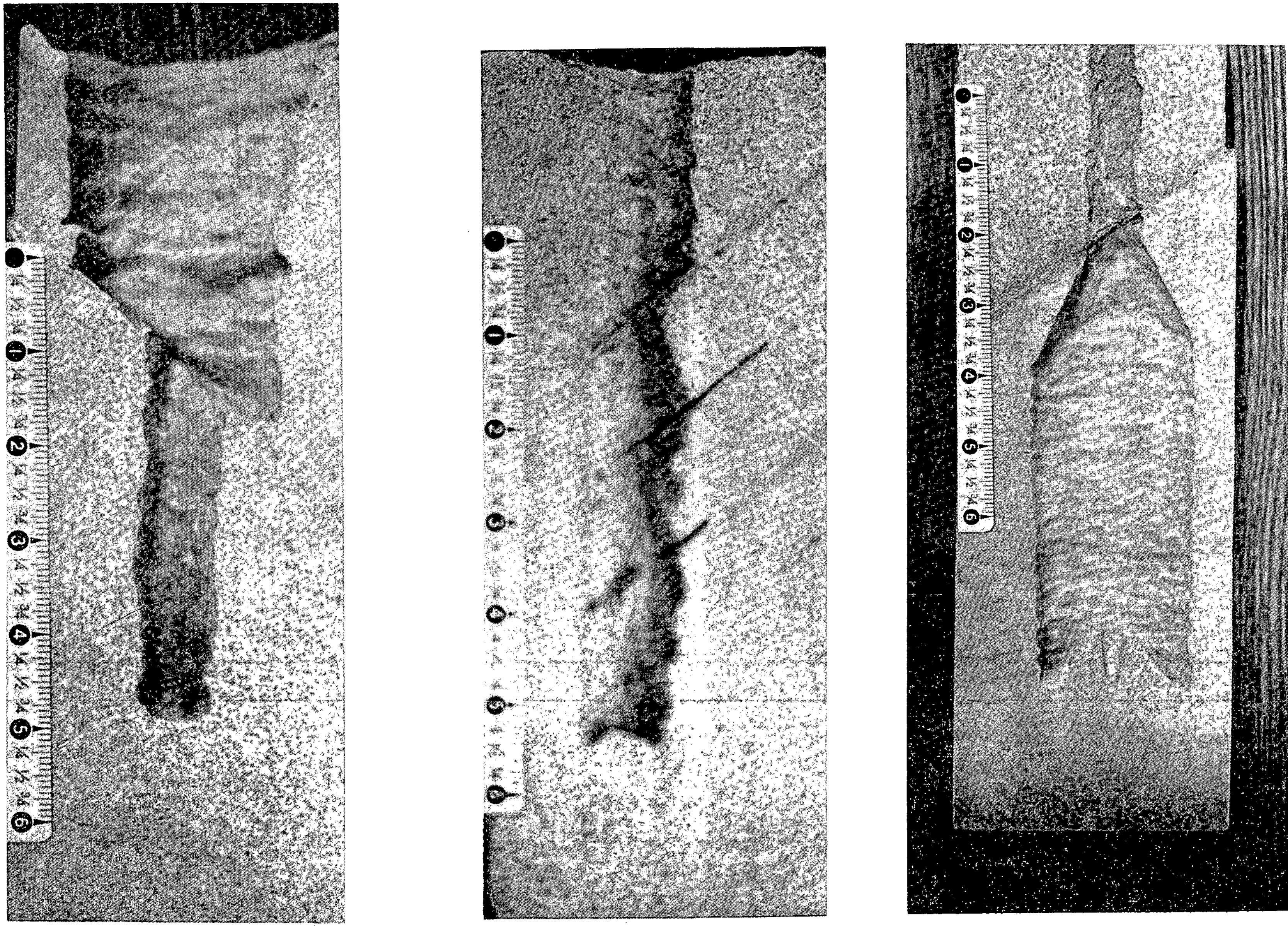


Fig. 4. Water jet drill holes through a) a "hard-soft" rock interface, b) a "soft-hard" interface, c) a rock with thin, hard inclusions.

Utilization of Cavitation

i) Behaviour of Rock under Cavitation Attack

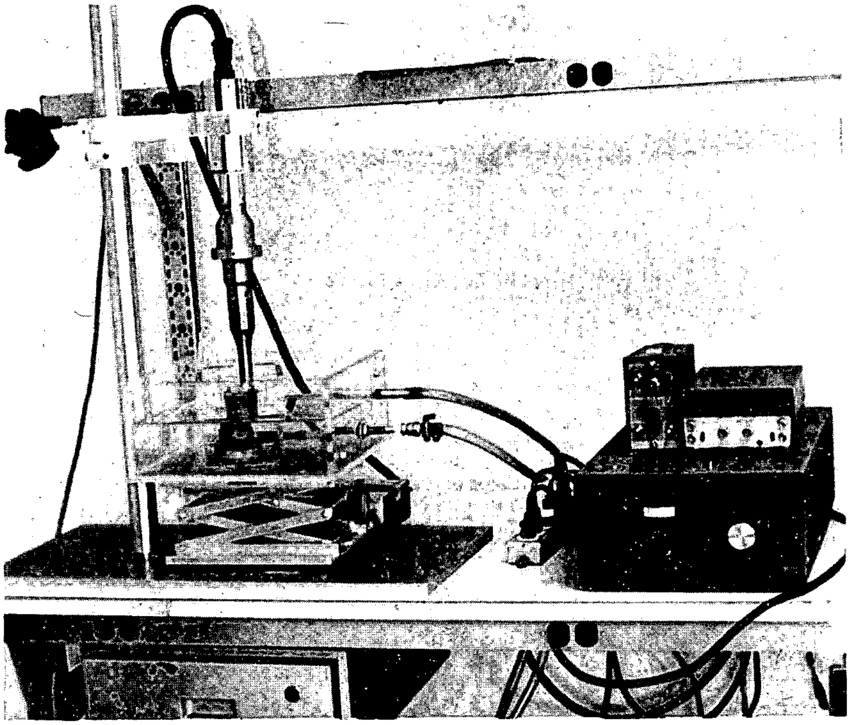
A method of determining cavitation erosion resistance for metals has been developed by ASTM Committee G-2 (Standard G32-72, p. 724, Part 10 of the Annual Standards, 1975). This method uses a vibratory horn to oscillate a specimen of the material in a bath of liquid. It was originally intended that this test would be used to determine the cavitation resistance of each rock type used and, in this way also, perhaps, determine a parameter of cuttability.

The procedure as outlined in the standard is not amenable to the testing of rock samples. Because of machining difficulties it is necessary to glue the samples onto a platen attached to the horn and the various bonding agents tested all failed within a short period of time after the beginning of the test.

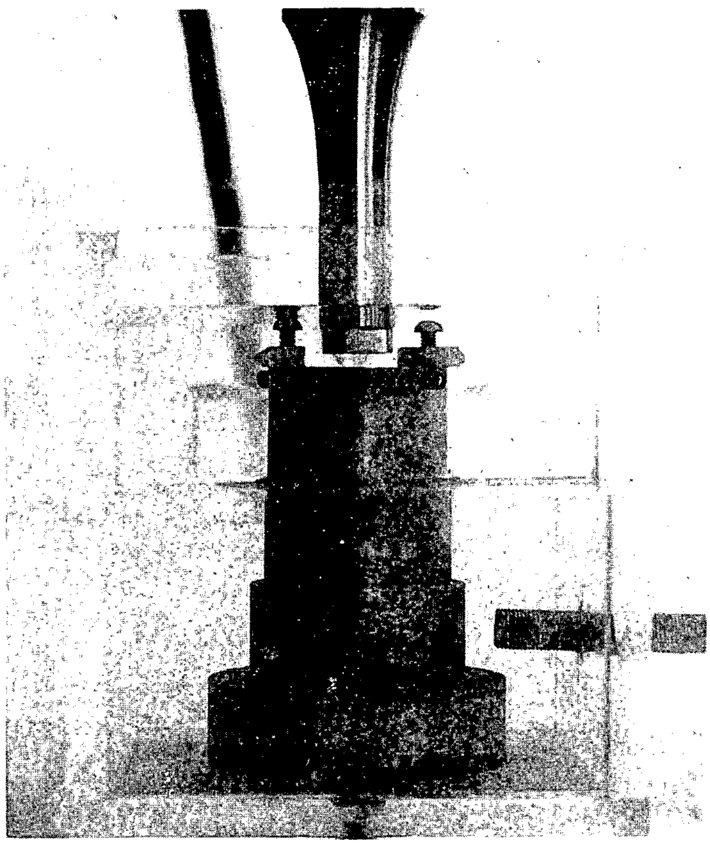
Persistent power failure of the power supply to the vibratory horn caused it to be returned to the supplier. During its absence the test procedure was changed to the "stationary specimen" type of cavitation test, for which, at the present, no standard exists.

The advice of ASTM G-2 members was sought and a modified test-rig (Figure 5) has been developed. Initially a central hole was located in the sample to allow a flow of water to enter the cavitation zone to remove debris and cool the surfaces. Observation of the tests has, however, indicated that there is sufficient turbulence in the area to solve both problems and the hole drilling has therefore been stopped.

At the present time a standardized test procedure is being developed seeking to correlate static specimen damage with that obtained by the conventional ASTM test using metal samples and once this has been obtained a wide suite of rocks, specimens from which have already been prepared, will be tested.



i) Overall view



ii) Detail showing horn tip

iii) Detail showing specimen with hole in the holder

Figure 5. Cavitation Testing Equipment

Standardized handling procedures to measure the mass loss in the rock samples are also being developed. Because the tests are made under water, and the specimens rapidly give up water when exposed to less than 100 percent humidity the current solution, to standardize humidity and weigh the samples after 24 hours in air, may later require modification.

Drawings have been obtained for the Lichtarowicz flow cavitation testing rig. This will be constructed during the Fall and correlations between data obtained from this procedure will be correlated with that using the vibratory horn.

A paper discussing the development of the stationary specimen test has been submitted for presentation at the 4th International Symposium on Jet Cutting Technology in 1978.

ii) Environmental Controls on Cavitation Behaviour

The major effort in this area will take place during the third year of the contract. During the preliminary work with the cavitation test rig it was noted that a specimen which has been strongly stressed will erode more readily under cavitation attack.

iii) Design of an Effective Cavitating Nozzle

The major effort in this area will take place during the third year of the contract. This program has been deferred because of the ability of jets at 16,000 psi to effectively drill granite at the maximum speed required (200 ft/hr). The task has serendipitously been simplified since the problems associated with inducing cavitation in a dual orifice nozzle would be much greater than those attached to cavitating flow from what has proven to be the superior single orifice nozzle.

Design of Components

i) Development of a Combined Jet/Mechanical Drill Bit

A number of factors have led to the development of the combined Hydro-mechanical drill bit. Several of these have been referred to above and in earlier reports; the lack of a smooth profile where the advance rate and rotational speed are mismatched and the change in hole diameter as the drill passes through varying rock and stress conditions are, for example, major factors. The major reason for the move to the combined system was outlined when the initial proposal on this contract was submitted. The water jet action, particularly in granular rock, is extremely localized and, while deep slots may be cut by the jets, the intervening kerf, although very weak, will be removed by the jet only if directly attacked. For this reason the use of a mechanical device to break these ribs will minimize the energy required in rock breakage.

The particular orientation of the jet nozzles and the bit has been chosen to take advantage of both systems of drilling (Figure 6). A high pressure drilling nozzle, dual orifice and of the design which proved most effective in the earliest testing (COO-2677-1) is used to drill an access hole ahead of the main assembly. Test data indicate that the advance rates achievable with this nozzle will exceed the rate achievable with the main bit assembly and thus a central hole will be created ahead of the bit. This will relieve some of the stress on the rock under the bit teeth, and thus make the rock easier to drill. However, its main purpose is to provide a path for the nozzle body to advance into ahead of the main bit unit. The nozzle body contains four additional orifices (for a 4 roller bit) which direct the jet flow along the line of contact on which the cone teeth reach the bottom of their penetration on each advance.

The intention of this modification is two-fold. South African investigators have found that adding water jets to drag bits allows a doubling in the "bite" of the bit for equivalent applied force (Ref. 1). This can be explained if one considers the sequence of events which occur as a bit tooth penetrates rock or as a drag bit advances. (Ref. 2).

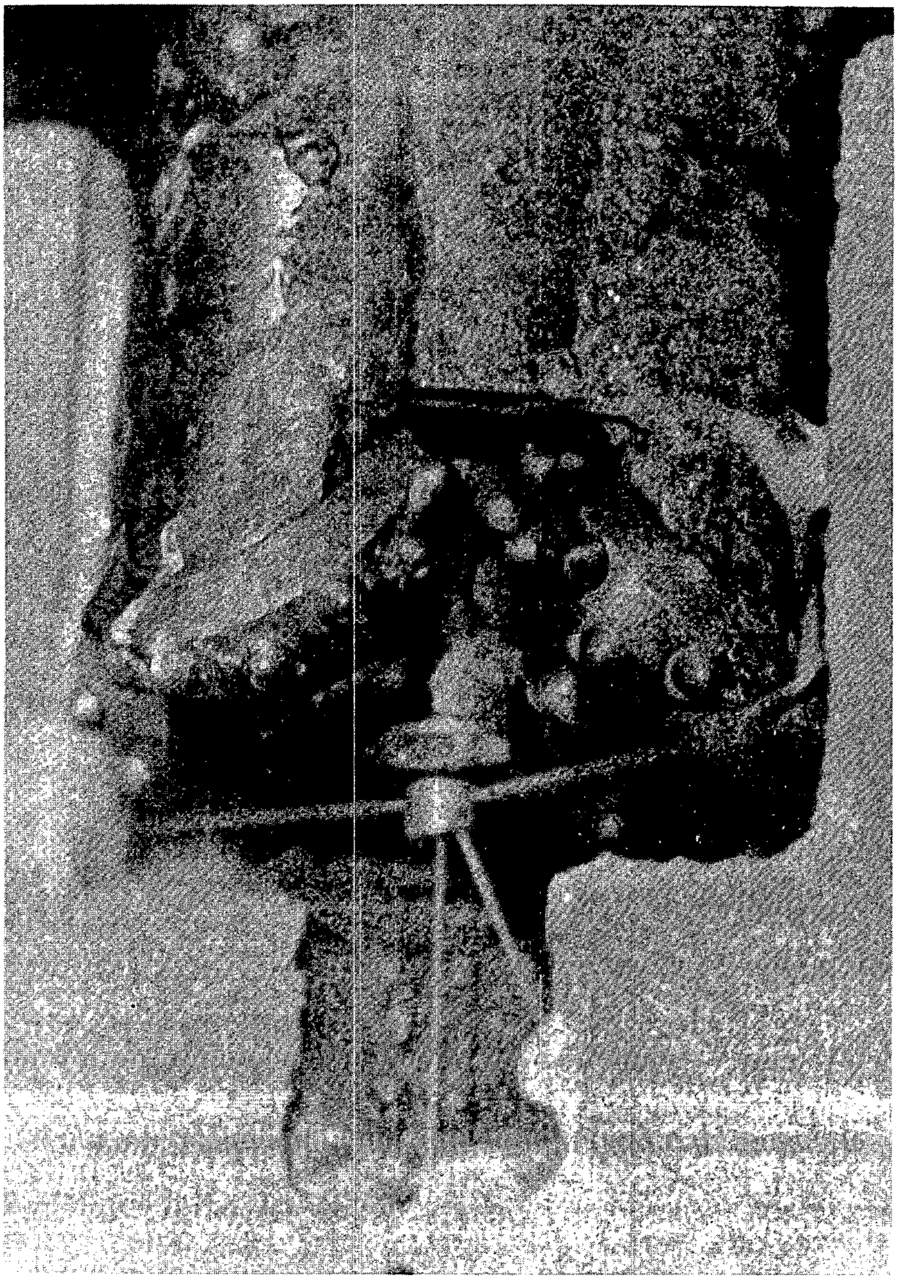


Fig. 6t View of jet head and roller drill bit (backed away from the rock and at reduced pressure and without 2 lateral jets to allow the photograph).

As the bit penetrates the rock (Figure 7) it first crushes a zone ahead of itself, creating a plastic zone which behaves as a fluid. As the bit continues to advance the pressure exerted by the bit generates a hydrostatic force in the plastic zone and high lateral forces are generated along the line of contact with the solid rock. These forces ultimately cause further crack growth which migrates up to the surface, creating a chip which is then expelled from the crater. Much of the energy which is exerted by the bit goes into the crushed zone of rock and is distributed around the contact surface so that only a fraction of it will be used for the secondary crack growth and chip formation.

Conversely when the water jet action is combined with the mechanical bit the water will remove the crushed rock as it is created, thus the force on the bit will not be dissipated as it advances and the wear created by pushing the bit through a tightly packed zone of crushed rock will also be reduced. In this manner the bit will be able to achieve a greater penetration for a given thrust. A secondary advantage is that as the bit penetrates the material not only does it crack under the bit but lateral cracks are also created. The water jet has been found capable of exploiting cracked material at a much greater rate and at lower pressures than where the material is solid, so that the jet will remove some of the cracked, but not crushed, material from the bit path as it advances.

This theoretical evaluation of the benefits of combining the two systems has been tested in the laboratory. Because of the low flow rate available with the equipment in the laboratory (10 gpm) the hole was drilled in two stages. Firstly, the central access hole was drilled in the sample (because of the 10,000 psi limitation on pressure with the pump used the holes in dolomite and marble were drilled with a diamond core bit, the limestone was drilled by jet). Tests were carried out varying the speed of rotation and

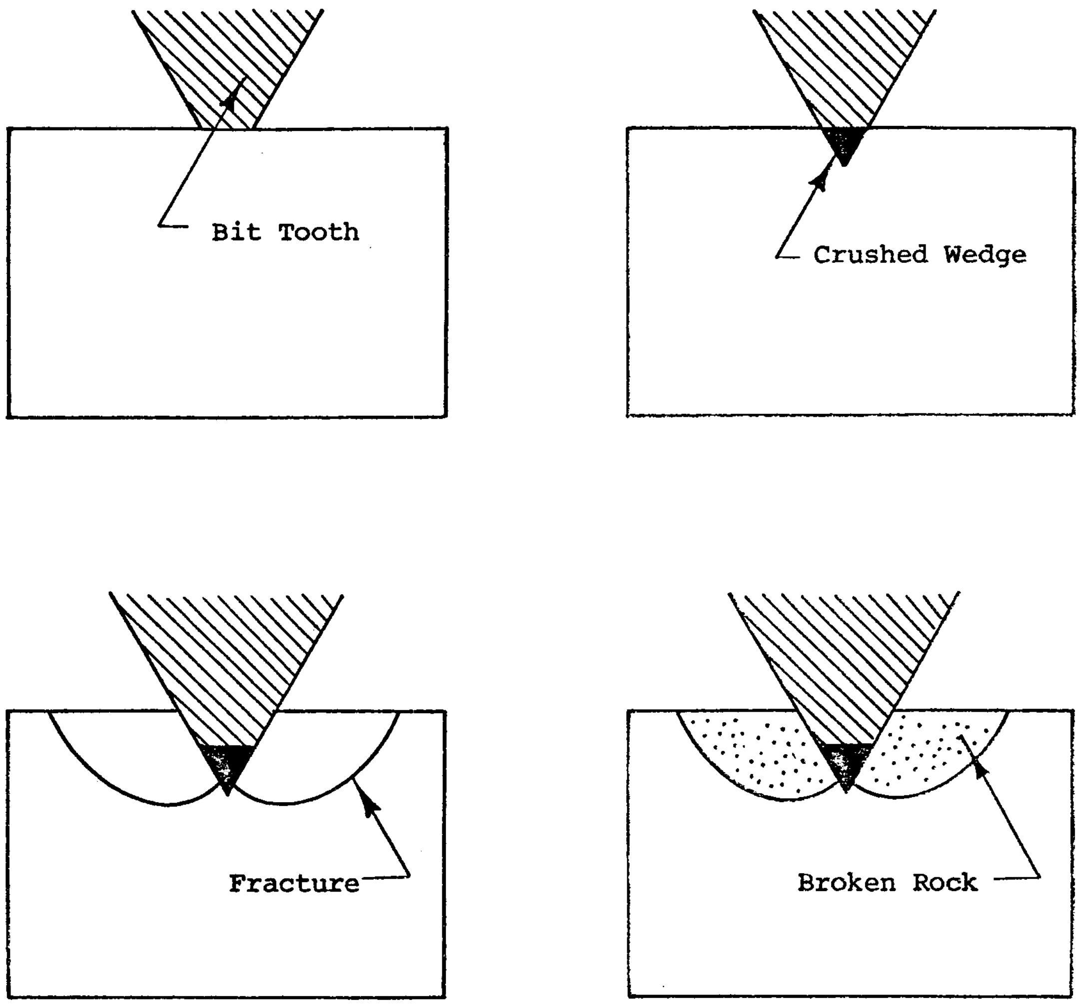


Figure 7. Crater Formation Mechanism. (After Ref. 2)

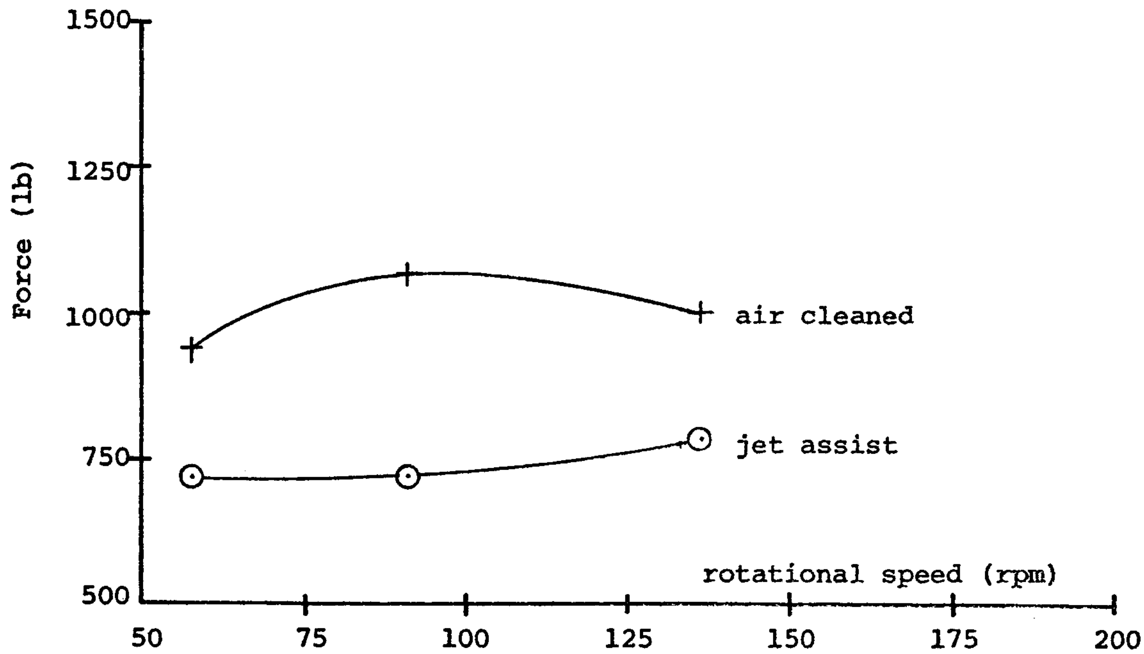
the advance per revolution of the bit in a nine level factorial experiment as identified in the results (Table 1). Tests were carried out in two modes, drilling with no jets but using compressed air to clean the hole, and drilling with water jets located under the drill bits. The results from tests in three rocks are appended (Figures 8-10) and can be interpreted to give the following conclusions. Firstly, that where the flow rate is sufficient and the jet pressure adequate that the addition of a water jet assembly to a drill bit will either reduce the force required by 20-30 percent or allow an increase in advance rate of 40 percent in advance rate for equivalent thrust.

(Note:These results have been criticized by Worden as being at such low loading rates that chip formation does not occur - examination of debris from a test indicate that chipping was occurring under the bit).

Where the assembly was tested in limestone both the above conditions held but when tests were carried out in dolomite and marble, two rocks which are very difficult for the jet to drill unassisted, disparate results have been obtained.

The bit advance rate is controlled by two parameters which are set before the test, the rotational speed of the bit, and the advance of the bit for every revolution it makes (the incremental distance). While both factors affect jet performance the range of rotational speeds is such that it has relatively little effect on the limestone results, for the dolomite there is a discernable optimum speed of around 60 rpm, while forces for the marble increase with bit speed. The reason for this is also related to the data on the results of varying incremental distance where, in all cases, load increased as the "bite" of the bit was incremented.

The reason conjectured for these results is that the jet volume and pressure is insufficient at the higher rotational speeds and incremental



i) Effect of Rotational Speed

ii) Effect of Incremental Distance

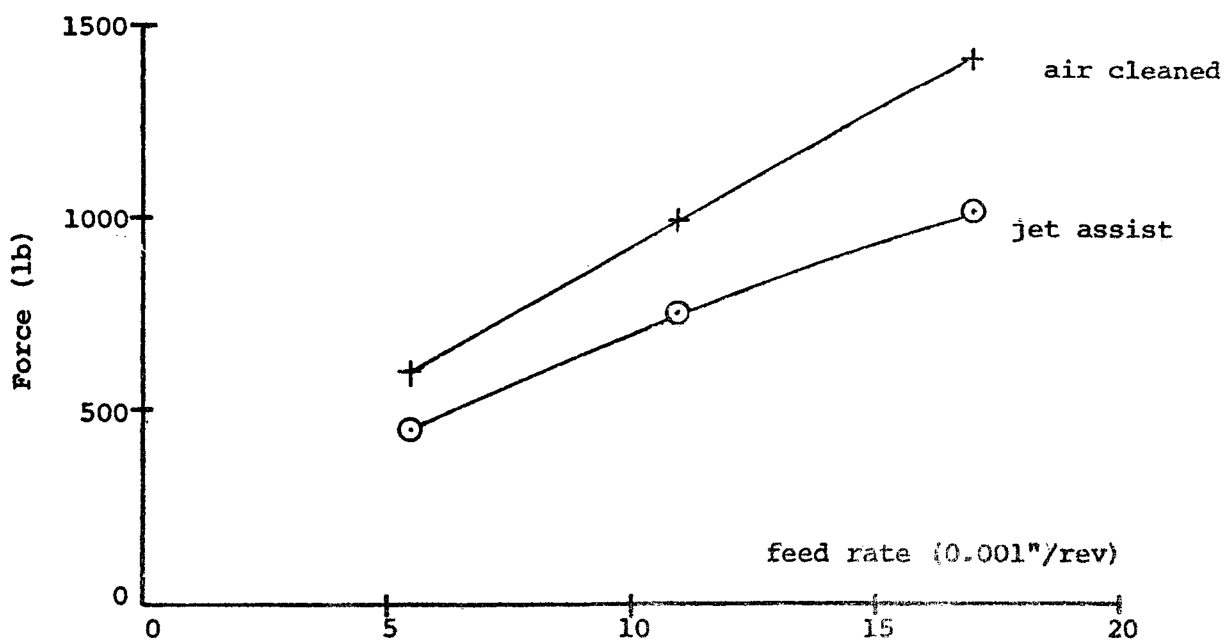
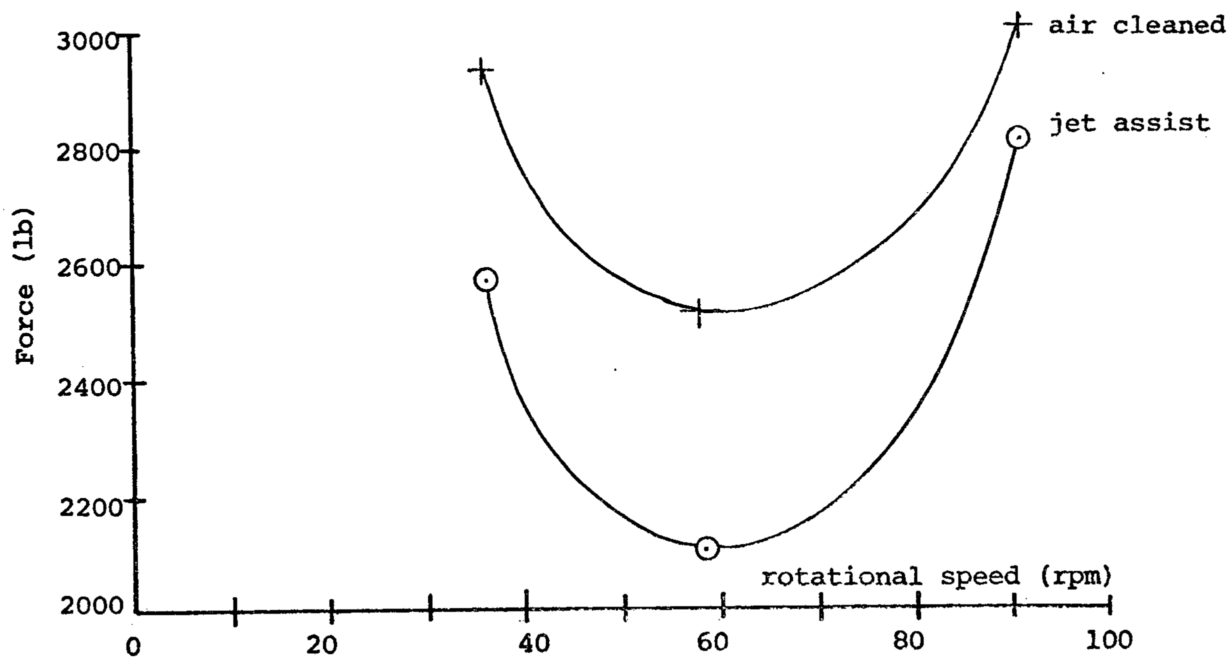


Figure 8. The Effect of High Pressure Cutting on Bit Load in Indiana Limestone



i) Effect of Rotational Speed

ii) Effect of Incremental Distance

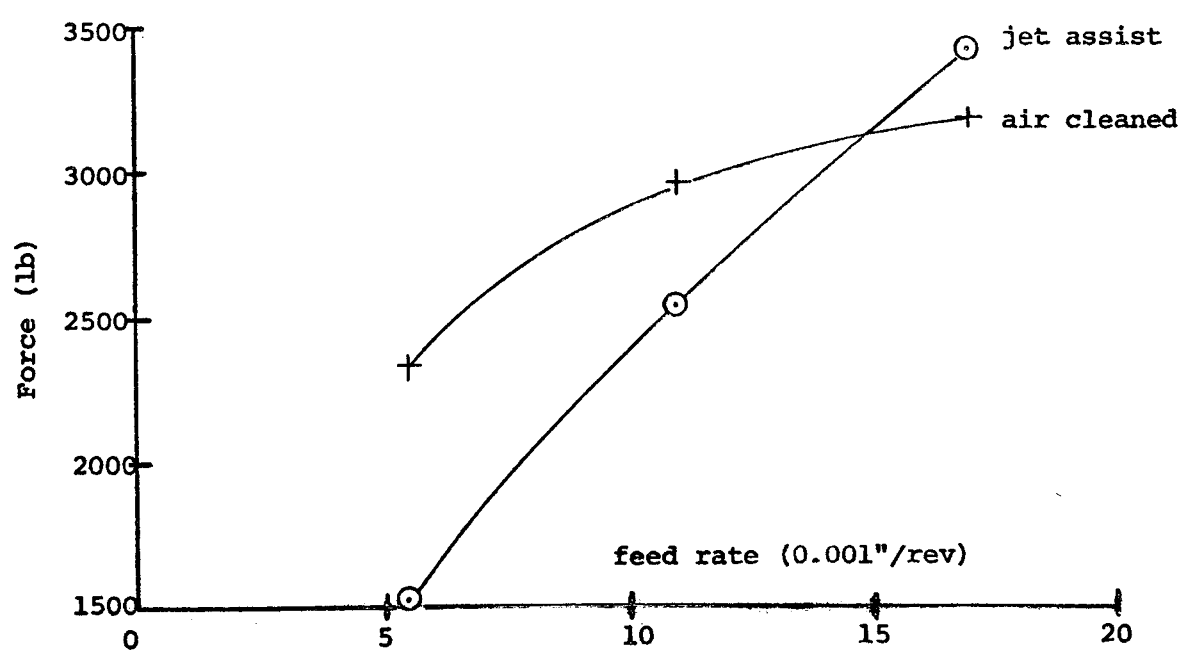
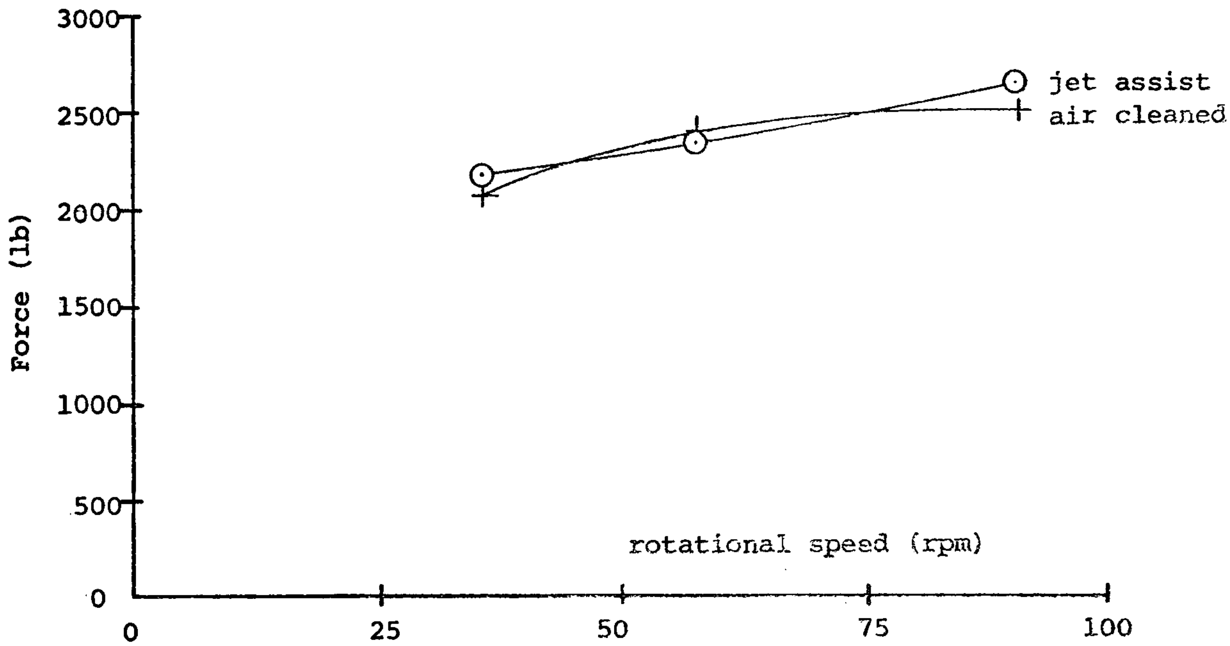


Fig. 9. The Effect of High Pressure Cutting on Bit Load in Dolomite.



i) Effect of Rotational Speed

ii) Effect of Incremental Distance

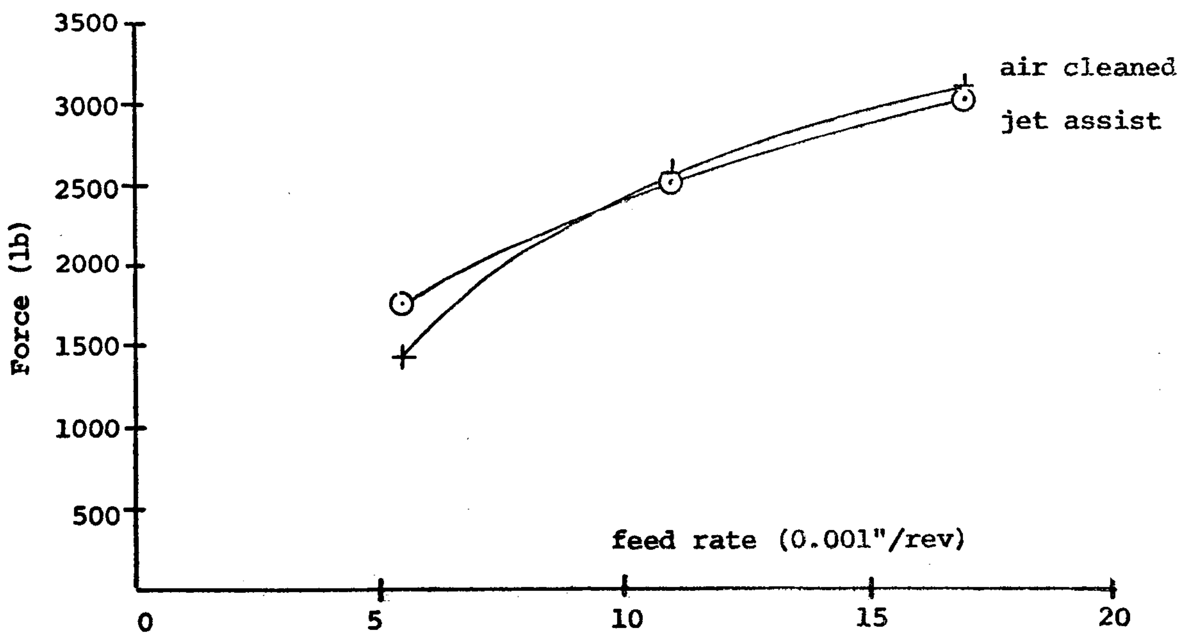


Fig. 10. The Effect of High Pressure Cutting on Bit Load in Tennessee Marble

Table 1. Load required to drive a 3-7/8" bit through rock with, and without, jet assistance. Load values are in lbs.

	Feed Rate (in./rev.)	Dry RPM 36	Dry RPM 58	Dry RPM 91	Dry RPM 136	With Jets RPM 36	With Jets RPM 58	With Jets RPM 91	With Jets RPM 136
Limestone	5.5	---	550	600	650	---	400	500	450
	11	1175	1025	1100	850	---	750	750	750
	17	1400	1250	1500	1500	---	1000	900	1150
Dolomite	5.5	2500	2000	2500	---	1100	1500	2000	---
	11	3100	2650	3100	---	3000	1800	2800	---
	17	3200	2900	3400	---	3600	3000	3600	---
Marble	5.5	1000	1550	1670	1970	1500	1760	1890	1890
	11	2500	2400	2600	---	2400	2310	2310	2800
	17	2700	3200	3200	---	2600	2960	2960	3340

Figure 11. Hydromechanical Drilling Unit

distances for the jet to cut out to the peripheral cutters of the bit. The result is that the hole is no longer being properly cleaned, since air is not used in the jet assist runs, and there is a force buildup due to the buildup of debris in the hole. This can be seen from the increased gradient of the jet curve relative to the dry curve for the dolomite as feed rate is increased. The very slight change for the marble is probably because of the different geological structure of the material but will also be because the jet is insufficiently powered to assist the bit.

These trials will be rerun with higher flow rates/pressures on the jets in order to verify these explanations during the summer.

ii) Development of a Field Drilling Unit

The initial field test unit was essentially completed (Figure 11) in the summer of 1976. A conventional SIMCO drill stand and hydraulic power unit were modified to accept high pressure tubing in place of the regular drill pipe. A 150 hp (15-25,000 psi) Flow Equipment intensifier and corresponding power pack provided the high pressure water. This unit underwent proof trials in the area surrounding Rolla in the Fall. Dolomite was drilled at 36 in./min and limestone and granite samples were drilled at 12 in./min. Extensive tests were planned for the portable unit. However, problems developed with the Dennison hydrulic pump which operates the intensifier and several shaft failures occurred before the problem was corrected.

With winter approaching, it was decided to remove the intensifier and power pack from the portable unit and install the intensifier and accumulator remotely in the laboratory so that testing could continue. The laboratory drill stand and specimen chamber were then used with the intensifier for high pressure tests during the winter.

The increasing flow requirement demonstrated by the results of the laboratory tests described above have led to the use of a large flow rate pump on the rig for the tests which are planned for this summer. A Kobe size 4J pump on loan from the Bureau of Mines will initially be used until other equipment becomes available and this is capable of a 25 gpm supply at 10,000 psi. Ultimately to drill in the harder granites a modified plunger and liner 4J pump will be manifolded with the Flow intensifier to give a combined flow of 24.5 gpm at 18,000 psi.

The field drill unit has been modified for use with the Hydromechanical bit and the necessary drill steel has been obtained to drill test holes down 200 ft. Monitoring equipment to measure rotational speed and bit load have been added to the rig. The testing in the field will compare the results from the Hydromechanical bit with those obtained under equivalent conditions using a tricone bit of equivalent size which has been supplied to us by Gruner-Williams.

<u>Development of Components for Deep Hole Drilling</u>

The first stage in the development of the Hydromechanical bit from the laboratory to ultimate application in industry will be the trials described above where units will be tested at depths to 200 ft. Discussions have been initiated with Maurer Engineering on potential problems which may arise in the progression of the bit to field application and two problems have, to date, been evaluated. The first relates to the transport of the necessary high pressure fluid from the surface to the drilling piece. Equipment has been used by oil company investigators who have drilled at jet pressures up to 15,000 psi at depths up to 6000 ft (Ref. 3). It is currently believed that if the system operating pressure can be brought down below this level that equipment will be available.

The second matter relates to the removal of drill fragments from the hole. Experimental results cited above show that the current flow is sometimes inadequate for complete cleaning and transportation purposes and while

Bureau of Mines research (Ref. 4) has shown that a flow of 25 gpm is sufficient to clean a hole 2000 ft long drilled at 3-1/2 inches diameter in coal, this concern has motivated an ongoing investigation into the practicality of using compressed air as a lifting device.

Planned Program for the Third Year of the Contract

As the research project has developed so the program has changed from that originally proposed. The program proposed during the second year was modified due to a problem with the field equipment and development has therefore been concentrated in the laboratory rather than in field testing as had originally been intended. This bias will be countered in the third year of the research. The development of the program is built around the elemental structure (Figure 1) as follows:

1. Nozzle-Rock Interaction

   a. The effects of nozzle and rock parameters.

At the present time, the effect of change in nozzle geometry on drilling rate has been established for both granular and crystalline rock. This program will be continued in the third year under tests in the traixial test chamber in order to determine the effect of back pressure and confining pressure on the geometric relationships established. For example, test results indicate that an increase in back pressure of 500 psi or an equivalent increase in the confining pressure on the rock is sufficient to cut the effectiveness of the jet cutting in granular rock. This phenomenon will be further examined and a method for solution to this problem in order to improve drilling rates will be sought. The preliminary data indicates that this effect is related to the nozzle diameter and the smaller the nozzle diameter the greater the effect. Therefore, it may be necessary to change the nozzle geometry in order to cope with this problem.

b. The effect of varying rock geology and the presence of bedding and joint planes.

It has been found that for an unassisted water jet drill, at a constant feed rate, the diameter of the hole is a function of rock geology and is also sensitive to the change in orientation of the beds relative to the drilling bit. Experiments will be carried out both in the laboratory and in the field to verify that a combination of a mechanical and water jet drilling head is able to cope with a varying geometric relationship to the geology without any variation in hole linearity or diameter.

2. Utilization of Cavitation

a. The behavior of rock under cavitation attack.

A standard test is being developed based on the ASTM acoustic test and compared with the Lichtarowicz Flow cavitation test extended and if necessary modified to cope with rock samples; data will be collected on the susceptibility of rocks to cavitation impact. Based on this test a wide suite of rocks will be tested and this data will form part of a Master's thesis.

b. Environmental controls on cavitation behavior.

The effect of confining pressure and hole back pressure on cavitation effectiveness will be monitored and the potential advantage to the use of a shroud such as that developed by Sandia as a means of improving the cavitation effect around a submerged jet will be tested within the triaxial chamber.

c. Design of an effective cavitating nozzle

Tests will continue in the modification of a cavitating nozzle with the shroud to include any possible benefit that might be obtained by aspirating fragments from the broken surface into the jet stream.

3. Design of Components

a. The development of a combined jet-mechanical drill bit.

The combined system as currently developed at UMR will be field tested and modified as necessary. The investigators will work with Maurer Engineering and Smith Tool in order to develop this nozzle design based on a simple modification of existing drill bits and take greater advantage of the existing state of the art in drill bit manufacturing, thus to more readily transfer the technology developed under this program into the state of the art. Comparison will be made between the Hydromechanical drill bit and the standard tricone bit performance.

b. Development of a field drilling unit.

This unit is now ready for application and will be used in testing the Hydromechanical drilling bit in a suite of rocks.

c. Development of components for deep-hole drilling.

As the program develops further so it may become necessary to modify the existing equipment in order to more successfully drill to greater than 200 ft.

4. Theoretical Modeling of the Program of the Drilling Rate Achieved with a Water Jet-Mechanical Drill Bit

During the second contract year basic relationships between advance rate and jet parameters were investigated. This relationship will be further researched in the third contract year to cover the behavior of a water jet-mechanical drill bit combined system.

Based on the equation which will be derived it will be possible to predict the horsepower required and the penetration effectiveness that will be achieved in drilling with this new system, in both granular and crystalline rock.

5. Contacts with Industry

a. Close cooperation is being developed between the University of Missouri and Smith Tool in order to transfer the technology to industry and also to gain valuable information from industry on the practical problems involved in the construction of drilling bits for deep-hole drilling. Further information is being shared with Maurer Engineering and advice is being sought from Maurer Engineering on the problems associated with deep-hole drilling with this system proposed. Concurrently, the information will be disseminated to the industry both through personal visits and through presentations at the technical meetings.

b. Work is proceeding on a research agreement with St. Joe Minerals Corporation for a study to be carried out drilling in sandstone and dolomite in an underground lead mine. It is intended that the sandstone testing be carried out this summer at a pressure of 10,000 psi, and that, subsequent to determining the required pressure to drill the dolomite that the rig be modified and drilling tests be carried out in the dolomite during the winter months.

Publications

1. "Preliminary Experimentation on the Design of a Water Jet Drilling Device," 3rd Int. Symp. Jet Cutting Technology, May 1976. Previously submitted to ERDA with COO-2677-1.

2. A paper was presented, without publication, at the 30th Annual Petroleum Mechanical Engineering Conference, ASME, in Tulsa, September 1975, "High Pressure Water Jet Erosion and Rock Breakage." At the present time, no formal text for this paper has been prepared for publication.

3. A review paper was given at the Research Workshop on Water Jet Cutting Technology held in Rolla, November 1975, "Experimentation in the Field of Water Jet Cutting." Six copies of these Proceedings were sent to ERDA, with report COO-2677-2.

4. A paper entitled "Environmental Effects on a Water Jet Drill" was presented at the 31st Annual Petroleum Mechanical Engineering Conference, ASME, in Mexico City, September 1976. This was submitted to ERDA with COO-2677-6.

5. A paper entitled "Hydromechanical Drilling of Holes Larger than One Inch in Diameter" has been accepted for presentation at the 32nd Annual Petroleum Mechanical Engineering Conference, ASME, in Houston Texas, September 1977. This was submitted to ERDA with COO-2677-7.

6. A paper entitled "Water Jet Drilling in Sandstone and Granite" has been accepted for the 18th Symposium on Rock Mechanics, Keystone, Colorado, June 1977. It is herewith appended.

7. Three papers on a) the underground drilling tests, b) the surface tests of the Hydromechanical bit, and c) a standardized cavitation test for rock, have been submitted for the 4th International Jet Cutting Symposium in Canterbury, UK in April 1978.

Time Allocated

1. Principal Investigator: Dr. David A. Summers

Dr. Summers spend 50 percent time on this contract during the summer months and 25 percent time during the academic year.

2. Co-Investigator:

During the summer months in 1976 Dr. Dwight W. Bushnell spent 100 percent of his time on this contract prior to leaving the University. He was replaced by Dr. Terry Lehnhoff who has spent 25 percent time during the academic year in continuing this assistance.

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WATER JET DRILLING IN SANDSTONE AND GRANITE

By

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ABSTRACT

Under contract to the U.S. Energy Research and Development Administration the University of Missouri-Rolla is developing a high pressure water jet drilling device. This paper describes some of the preliminary work in the laboratory and discusses changes in drilling parameters required for sandstone and granite. A modified drill bit to improve penetration using a combined water jet and roller cone bit is described and preliminary data on the results discussed.

INTRODUCTION

In order to gain access to the geothermal reserves present in this country, it is necessary that an access hole be drilled. In many situations the economic cost and speed of drilling will determine in large measure whether or not a reserve can be considered as a valuable resource. In this regard the University of Missouri-Rolla has been under contract to the Energy Research and Development Administration for the last two years to investigate the high speed drilling of rock using high pressure water jets as the main cutting mechanism. The ultimate objective in the program is to drill at high speeds through granitic and other igneous rocks with initial portions of the program being carried out in Berea sandstone and other sedimentary rocks in order that the parameters controlling the penetration ability of the rock can be more clearly established. Sandstone was used because the softer the rock, the greater the cutting ability with change in parameters and thus a more easy quantification of performance can be obtained. One problem has emerged from the research results which relates to working with soft granular material relative to igneous rock, the ultimate target of this research, and that is that there is a difference in penetration mechanism and the way in which the water jet removes material from granular rock as opposed to crystalline material. This phenomenon has become more apparent as the emphasis of the research has changed from the preliminary parameterization of the jet cutting ability toward its application in cutting granite.

RESULTS FROM CUTTING BEREA SANDSTONE

In the preliminary research on sedimentary rock the effect of rotational speed, advance rate, jet pressure, and nozzle angle were all examined (1). The results of the program indicate that advance rates of up to 300 inches per minute can be attained (Figure 1) in sandstone at a hole diameter of approximately 1 inch. While this has application in the roof bolt drilling operation for mining, it has little practical application for deep hole drilling since there is a limit to the speed at which holes can be created. This limit is imposed by the speed at which pipe can be fed into the hole and the limit currently runs at approximately 200 to 300 feet per hour. For this reason test procedures have since been adapted to change the feed rate to a maximum of approximately 60 inches per minute (300 feet per hour). This rate is used in the experiments which follow. The sandstone and the granular rock tested is relatively permeable and it has been found advantageous to drill this type of rock with a dual orifice water jet (Figure 2) in which one of the orifices is directed straight forward while the other is inclined out at an angle sufficient to cut to the required hole diameter. While this works extremely well for the sedimentary rock, in part perhaps because the infusion of the rock ahead of the nozzle by the leading jet weakens it sufficiently that the reaming jet is able to cut more effectively, such is not the case in crystalline material. The granular material is removed on a grain by grain basis and the jet cutting action is extremely localized under the impact point. The presence of the grain boundaries serves to arrest any cracks which initiate in and around the cutting location, and for this reason the jet will cut very narrow slots not much wider than the jet diameter itself and this must be taken into account when relating advance rate and rotational speed. The reason for this is that the jet which reams the hole will only cut the jet diameter each revolution; and where the advance rate is greater than the jet diameter per revolution, the hole will no longer become smooth but rather ribs will be created on the sides of the hole which will eventually work in towards the center interfering with the passage of the drilling bit. Where these ribs are small they can easily be broken by the main jet assembly but this causes abrasion of the drilling tool when no mechanical cutter is incorporated in the system and provides a limit to the jet performance. Where the feed rate is less than the jet diameter then there is a noticeable increase in hole diameter (Figure 3).

CUTTING OF CRYSTALLINE ROCK

Crystalline rock in general does not have the large number of voids and the high permeability of the Berea sandstone used in the earlier part of the test. Thus the trials which were carried out in Missouri Red Granite (which has a compressive strength of approximately 30,000 psi) using the same nozzle design as that which had given very promising results in the sandstone did not give the same benefit in the granite. On the contrary it was found that by use of a single larger diameter orifice rather than using two orifices from the nozzle with the ensuing jet angled to drill the peripheral hole that this would, at the same time as giving a better advance rate, remove the central core to a sufficient degree that the nozzle would not interfere with it. The improvement in performance by going from a dual to a single orifice nozzle in the crystalline rock is the converse of the experience which was found in the granular material. This design has been used in a series of tests to parameterize the performance of jet cutting granite and test results have been carried out to advance rates of the order of 40 inches per minute (Table 1).

APPLICATION OF TECHNOLOGY

The object of the research is not merely to obtain a means of drilling small diameter holes faster. While such a development has benefit, nevertheless the major application of this program lies in the geothermal energy area where access holes between 4 and 9 inches in diameter are required. While water jet cutting in crystalline material will result in some removal of the material between adjacent cuts to a much larger distance (up to 3/4 in., 2) rather than the one or two nozzle diameter thickness which will be removed by jet action between adjacent cuts in granular rock, nevertheless as the jets cut through rock of different resistance to jet action so the hole diameter will vary and the quality of the surface cut. Such a variation in hole diameter and hole quality is not acceptable in a situation where pipe casing may have to be installed to protect the hole; and further, the use of water jets to completely remove all the rock at these diameters would require more energy than necessary since the ribs cut between adjacent slots are very weak and, therefore, easily removed by mechanical action. Conversely, where a rock is drilled under bit tooth or carbide insert cone penetration, the rock is broken and crushed creating a plastic zone under the bit tooth which distributes the stress applied through the tooth reducing its performance during the penetration process.

In order to improve upon the drilling ability of both systems, a combined design was proposed taking advantage of the strengths of each cutting mechanism. Thus, high pressure water jets are directed through the center of the drill bit (Figure 4) to drill a central access hole ahead of the roller cones. A roller cone bit is then used to ream this 1 inch diameter hole to the required diameter. However, by itself the roller cone would suffer from the creation of plastic zones under the teeth and thus a reduction in the effective penetration rate. For this reason high pressure jets are directed along the contact line between the drilling bit and the rock surface. Thus, as the rock is crushed under the bit this will immediately be removed by the high pressure jet. This reduces the load on the bit for a given penetration rate while at the same time increasing the penetration ability of the tool itself. Research in South Africa along similar lines using single drag bit cutters (3) has shown that an advance rate of at least twice that of the system without high pressure jets can be achieved and that bit life can be improved by an order of magnitude.

A bit has been constructed incorporating these modifications and is currently undergoing preliminary testing. At the present time the flow rate through the nozzle system is such that the two jet actions, drilling the advance hole and assisting the roller cone bits, cannot be performed simultaneously as the bit advances. The program, therefore, has been to drill the leading hole first and then to change the nozzle on the bit and, so that the jets are directed across the roller cones, the bit is then advanced into the rock drilling into the required diameter.

At the present time only the initial tests in Indiana limestone have been carried out to determine baseload conditions for the system and to provide some initial parameters for evaluation. In drilling these small 6 inch cubes of limestone the equipment layout is as follows (Figure 5). The drill bit is located on a free sliding platform on the front of the lathe mounted ahead of the load cell. The rock sample is chucked into the lathe and as the lathe rotates so the drill bit is advanced under controlled conditions to drill the required hole (Figure 6). The loads are monitored by a strip chart recorder from the strain gaged load cell and subsequently analyzed. The data which has been achieved from the test to date are shown (Table 2). Preliminary conclusions from this series of tests are that using the water jet reduces the force required to cut the rock while at the same time allowing greater advance rates to be achieved than could be achieved without jet assistance. (It was found, for example, that without jet assistance the forces required to advance the bit at 136 rpm and a feed rate of 5.5 thousand per revolution were too great for the lathe assembly. However, this speed and feed could be achieved with the jet assist). It should also be borne in mind that under these test conditions the bit is not chipping the rock but merely crushing the material under the teeth, and is therefore not operating under optimum conditions.

FUTURE WORK

It is intended that the experiments in the laboratory be continued to determine the optimum position for the jets relative to the roller cones. A larger combined nozzle will then be constructed and this will be attached to a mobile drilling platform. This rig will be taken to the field to determine under operating conditions and with drilling runs initially of 10 feet the performance of the modified drilling bit in rocks ranging from local sandstone through dolomite to the Missouri Red Granite. In passing it should be mentioned that the drilling rates that have been achieved to date have been achieved at jet pressures in the order of 10,000 to 15,000 psi and this pressure range has been used in the field by Maurer (4) in drilling to depths of 6,000 feet. We therefore feel that this technology has a strong potential for application in the field within the not too distant future.

ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

1. Hole diameter for two nozzles and two rotation speeds as a function of advance rate.

2. Nozzle design used for advance rate studies.

3. The effect of incremental distance on hole diameter for a) sandstone drilled with a 22-1/2 degree nozzle at 10,000 psi, b) limestone drilled with a 30 degree nozzle at 20,000 psi.

4. Water jet mechanical drill bit. (Two jets have been removed to assist the photographer).

5. Equipment layout showing the location of the load cell behind the bit.

6. Specimen configuration showing the pilot hole.

Table 1

Nozzle performance effects on drilling diameter in Missouri Red Granite. Pressure 15.5 ksi.

Nozzle Angle	Advance Rate (in/min) 10	20	30	40	Flow Rate (gpm)
	Hole Diameter (in.)				
10°	1.1	.76	.65	-	9.16
15°	.78	.70	.68	.57	9.09
20°	1.25	.65	.60	.60	8.82

Table 2

The effects on drill bit load where jet assist is applied to a 3-3/4" diameter coring bit.

Advance Rate (0.001 in./rpm)	Without assist rpm 58	91	136	With assist rpm 58	91	136	342	536
	Applied Load on Bit (lb)							
5.5	550	600	650	400	500	450	750	600
11	1175	1100	850	750	750	750	-	1000
17	1400	1250	1500	1000	900	1150	-	1100
20	-	-	-	-	-	-	-	1650

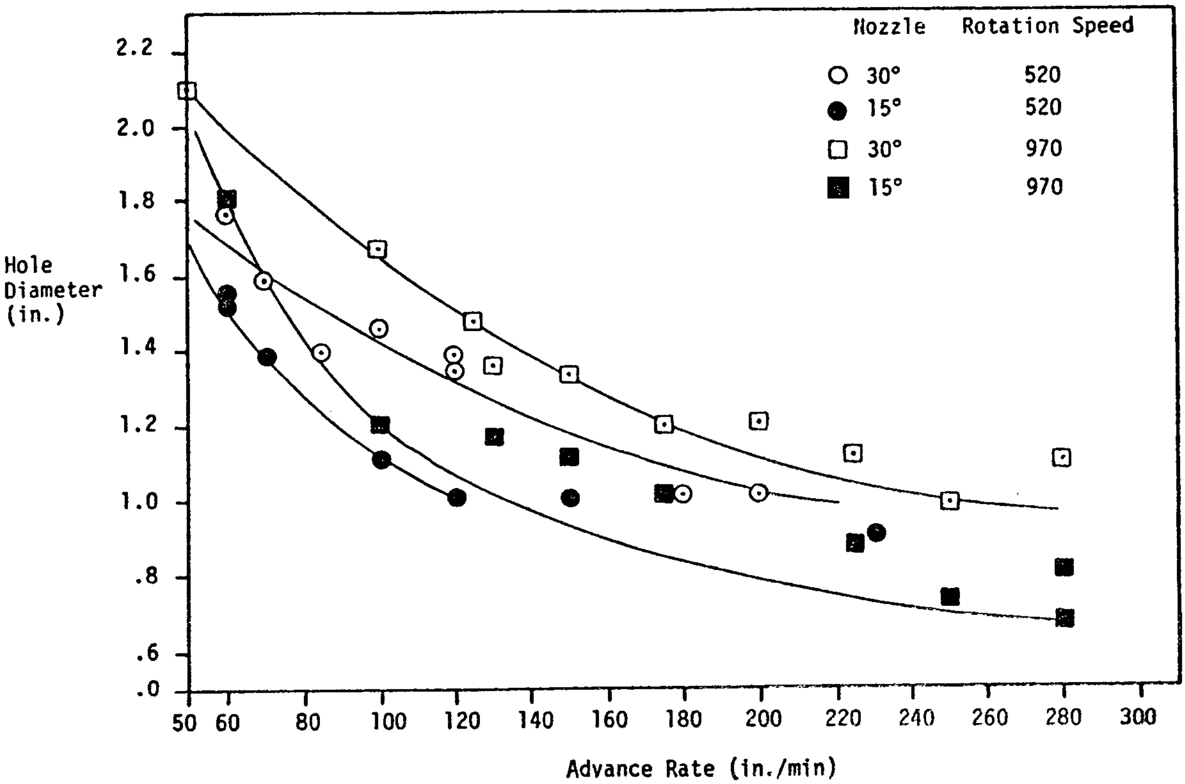
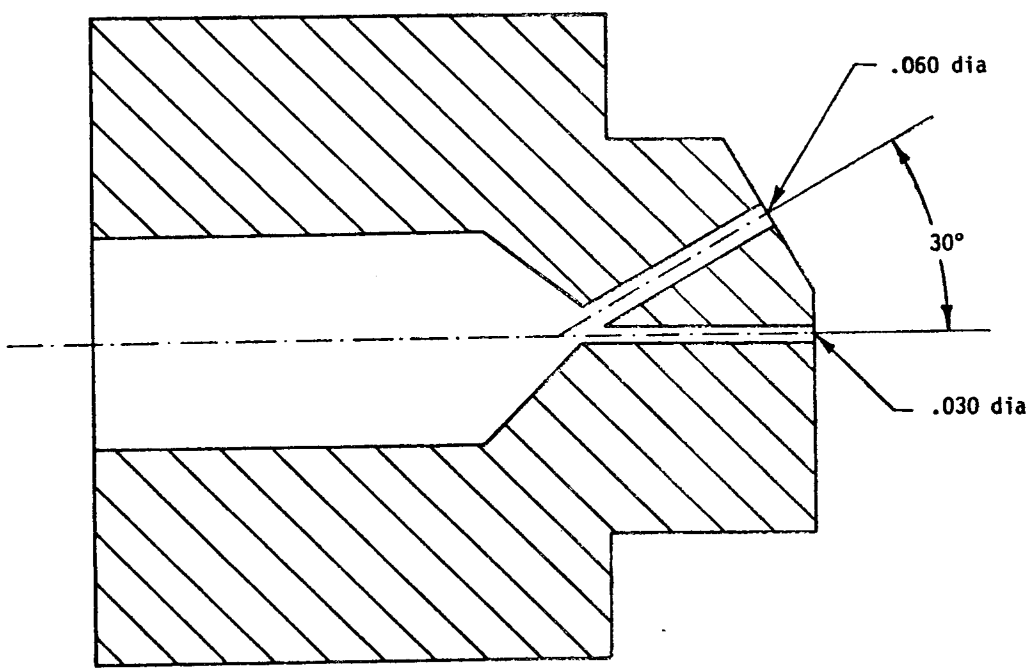


Figure 1



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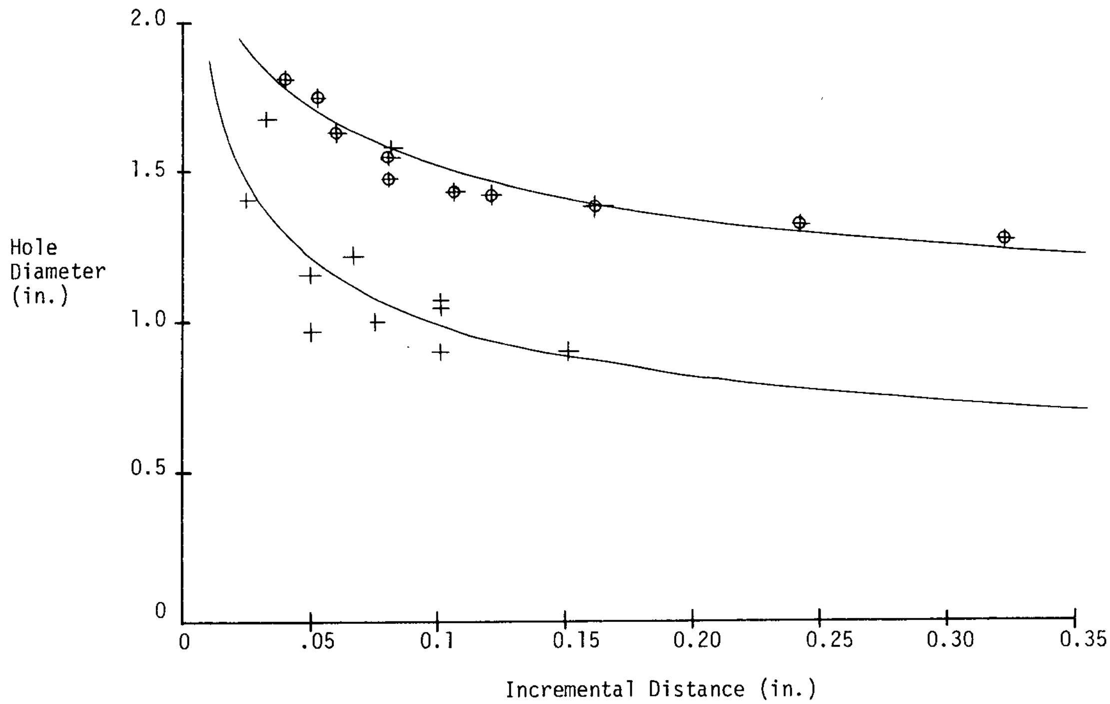

Figure 3

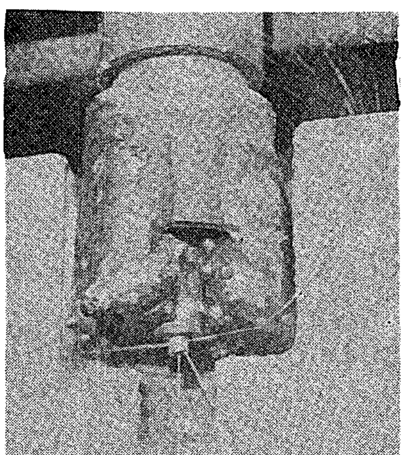

Figure 4

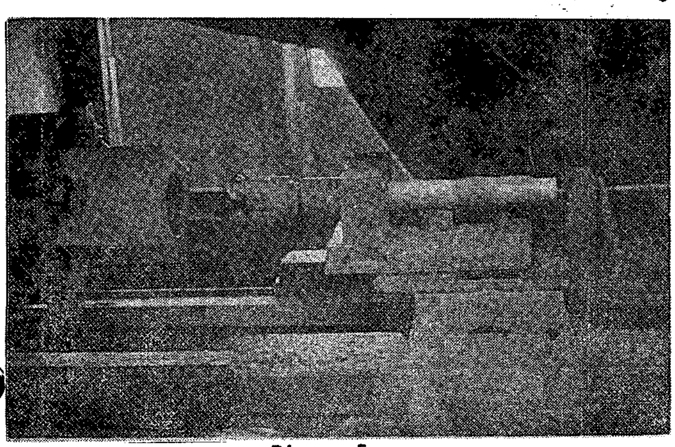

Figure 5

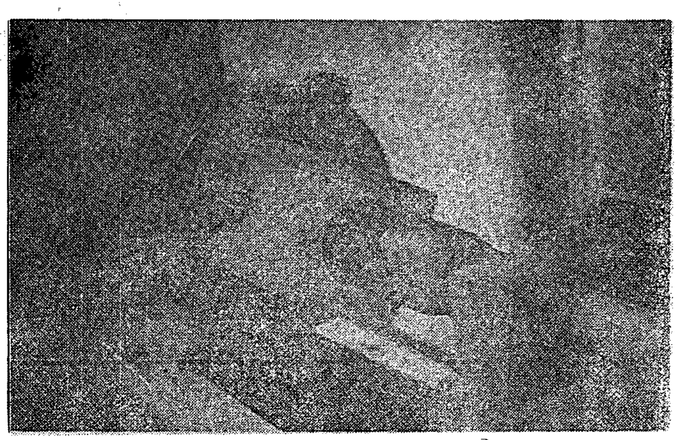

Figure 6