MASTER

THE DESIGN OF A WATER JET DRILL FOR DEVELOPMENT OF GEOTHERMAL RESOURCES

Progress Report
for Period June 1, 1975 - January 15, 1976

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January 1976

Prepared For
THE U. S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
UNDER CONTRACT NO. E(11-1)-2677

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ABSTRACT

The initial experimentation leading to the design of a water jet drilling device is described. The effect of change in nozzle design on cutting rate is illustrated. An improved nozzle design giving advance rates of over 200 ft/hr is described. Preliminary experimentation using cavitating jet flows is illustrated. The effect of feed rate, rotational speed, and anisotropy are also described.

Introduction

On June 1, 1975, a contract was entered into between the Energy Research and Development Administration and the University of Missouri-Rolla. The scope of work for that contract called for

- 1) Evaluation of the increase in jet pressure on drilling rate, under rock and borehole fluid pressure,
- 2) Analysis of the effects of additives on jet cutting performance,
- 3) Analysis of the effect of jet cavitation on jet drilling rate,
- 4) Evaluation of a nozzle drilling bit,
- 5) Demonstration in the field of the design applicability.

Of these tasks it was proposed that numbers 4 & 5 be completed in a second year of funding with the proposed program being as shown in Figure A.

At the present time the program is sensibly on schedule with work progressing on effective nozzle design at the same time that the triaxial chamber modifications are being completed ready to begin the test program. The equipment for the field test rig is being assembled, and the main pump will be shipped during January.

A paper describing the initial experiments which were carried out on nozzle design is appended, and this describes the first tests with the equipment to determine the effects of pressure nozzle angle and rotational speed on the jet performance. Since this paper was written, further research has been carried out, and this is described below.

Figure A. Original Work Plan

Experimental Results

The major emphasis of the research until this point has centered on the geometry of the cutting nozzle. Twenty-two nozzle geometries have been tested in a program to find the best combination of nozzle shape and size (Table 1).

Hole diameter was chosen as the measure of jet effectiveness, since the complexity, time and specimens required precluded using advance rate as the measure. Nevertheless, occasional tests were carried out to relate the hole diameter to the feed rate. In the first of these (Table 2) a 3-level, 2-factor fractional experiment was carried out to relate hole diameter and feed rate. Exponential relationships of the form

$$y = Ax^B$$

and

$$y = Ae^{Bx}$$

were computed and plotted (Figures 1 & 2).

It was interesting to note that in both cases the curves for 40, 80, and 120 rpm coincided at a feed rate of approximately 2 in/minute. This was the rate at which the earlier experiment (attached) was carried out and in which no effect of rotational speed on hole diameter was evident.

In the first experiment single orifice nozzles had been used to drill holes at a constant feed rate. The central core left under the nozzle had on three occasions contacted the nozzle, very rapidly eroding the soft brass. In order to stop this a small (0.02 inch) orifice was drilled through the center of the nozzle (type 1). The result was a dramatic increase in the diameter of the hole achieved which translated into an

Table 1. Nozzle geometries, test parameters and results of initial nozzle design program.

Type	Pressure (ksi)	RPM	Feed Rate in./min	Hole Diameter (in.) Length (in.)	Remarks
10	80	0	3/4 x 5 in.	10 t = 2 min
	10	80	0	5/8 x 5 in.
10	80	0	3/4 x 4 in.	11 t = 2 min
10	80	0	3/4 x 3 in.	12 t = 2 min
10 10 10 10 10 10 10 10 10 10 10 10 10 10	40 40 40 80 80 80 120 120 120 120 120 120 120 120	2.5 5 10 2.5 5 10 2.5 5 10 15 18	3 in. dia 21. in. dia 1.3 in. dia 3.4 in. dia 1.9 in. dia 1.7 in. dia 3.0 in. dia 1.65 in. dia 2.4 in. dia 1.8 in. dia 1.5 in. dia	1

Type	Pressure (ksi)	RPM	Feed Rate in/min	Hole Diame- ter (in.)	Remarks
10	80	5 in.	2-3/4 in.	17
	10	80	10 in.	1-5/8 in.	
	10	80	24 in.	1-1/4 in.
10	80	5 in.	2-1/4 in.	16
10	80	2.5 in.	2-1/4 in.	21c
10	80	2.5 in.	3 in.	21a

Type	Pressure (ksi)	RPM	Feed Rate (in/min)	Hole Diameter (in.) Length (in.)	Remarks
10	80	0	0.5 x 4 in.	6 t = 2 min
	10	0	0	0.5 x 7.5 in.	split after 10 sec
	10	80	0		split after 10 sec
	10	120	0		split after 10 sec
10	80	0	3/4 in. x 3.5	7 t = 2 min
10	80	0	0.5 x 4.5 in.	8 t = 2 min
10	80	0	5/8 x 3	9 t = 2 min

Type	Pressure (ksi)	RPM	Feed Rate (in./min)	Hole Diameter (in.)	Remarks
6	80	2.5	2-1/4 in.	3
	8	80	2.5	2-3/4 in.	
	10	80	2.5	3-1/4 in.
6,000	80	2.5	1-3/8 in.	19
	8,000	80	2.5	1-7/8 in.	
	10,000	80	2.5	2-1/4 in.
10	120	0	7 in.	13 split after 25 sec
10	120	0	2.5 in.	14
10	120	0	3 in.	15 split after 15 sec

Type	Pressure (ksi)	RPM	Feed Rate in/min	Hole Diameter (in.)	Remarks
10	80	16 in.	2 in.	21b
10	120	25 in.	3-5/8 in.	20
10	80	25 in.	2.5 in.	4
10 10 10	80 80 80	16 in. 10 in. 5 in.	2 in. 2.5 in.	18

Type	Pressure (ksi)	RPM	Feed Rate (in./min)	Hole Diameter (in.)	Remarks
10	80	2.5	3 in.	2
10 10 10 10 10	120 120 120 120 120	2.5 10 24 32 42	2.5 in. 2.5 in. 2 in. 1-3/4 in. 1.5 in.	22

Table 2. Hole diameter measured as nozzle rotational speed and feed rate are varied.

10,000 psi			
40 rpm	80 rpm	120 rpm	feed rate in./min
3.0	3.4	3.0	2.5
2.1	1.9	1.65*	5.0
1.3	1.7	2.1	10.0
		1.8	15.0
		1.5	18.0

* result dropped from analysis

hole diameter values are in inches

Figure 1. Variation in hole diameter with feed rate in the form $y = Ae^{Bx}$.

Figure 2. Variation in hole diameter with feed rate in the form $y = Ax^B$.

ability to drill the Berea sandstone at a rate of 15 in/min. At a traverse rate of 2"/minute the addition of this 25% flow rate increased the volume of rock removed by 750%.

This led to a comparative study to determine if increasing the size of the central hole, while retaining the same size for the angled hole would be advantageous (type 2). In the event this did not work as well. This is because the flow was preferentially now going straight ahead of the nozzle rather than flowing through the side hole. In a second comparison a single orifice equal size to the combined 2 nozzle diameters was constructed (type 3) with the jet angled to cross the center of the hole. It was found this gave an equivalent diameter to that achieved with the dual jet (type 1). This is an area which will be investigated further.

A dual conic with each nozzle at 30° to the axis and with a smaller central hole (type 4) was tested and did not show significant improvement in results.

A series of tests was therefore initiated looking at the effect of varying the characteristic of the forward pointing jets. In the first series of nozzles (type 6 to 12) dual jets were inclined to intersect within the block. The series was initiated after the first trial (type 6) resulted in the test sample splitting in half after 10 seconds. The experiment was repeated with the bedding in the perpendicular direction, and the sample again split along the bedding plane. The result was repeated under different conditions, and the series of tests then initiated. At the large intersection angles the sample did not split, but tension cracks were clear in the walls and below the crater. There was also evidence of the augmented jet created when the two jets intersect (Figs. 3 & 4).

Figure 3. 1 ft long, 6-in. diameter Berea sandstone block split after 10 seconds by a type 6 nozzle.

Figure 4. Sectioned side of a cavity cut by a converging jet pair showing tensile cracks generated around the cavity.

Figure 5. Result of an eccentric rotation of the nozzle about the feed axis, showing fragment size (at A & B).

The experiments were repeated with twin jets directed parallel to one another (types 13-15), and in two cases the sample split after a short time interval.

The indication was, therefore, that a dual jet directed ahead of the jet might be advantageous in giving a better hole cutting and perhaps in breaking the rock. For the first of these tests (type 16) a converging pair of jets was used with an equal sized hole for reaming. Although this gave a satisfactory performance, it was not as great as anticipated, and again it is considered that this is because the forward pointing nozzles were of equivalent size to the reaming orifice. Where the forward jets were reduced in size (type 17) a much improved performance was obtained. The small almost horizontal orifice did not, however, appear to contribute to the improved cutting rate.

When the angled jet was directed to the side of the hole and parallel jets directed forward, a high drilling rate was achieved, but the anticipated variation in hole diameter with advance rate was not obtained. This phenomena is still under investigation.

Two other approaches, using a fan array of equal sized orifices (type 19 & 20) and an eccentric rotation (type 21 a,b,c) were also tested. The array did not give an equivalent performance to large less numerous jets, although with the five 0.03 inch orifices (type 20) the largest hole diameter was achieved. Putting the nozzle on an eccentric gave an increase in the attainable advance rate, where the eccentricity of rotation was small, but the fragment sizes were relatively large (Figure 5).

The performance of the multiple array (type 20) was contrasted with a two orifice jet system of equivalent flow rate at three advance rates (type 22), and the superiority of this simpler system was demonstrated.

The conclusion at the present time is, therefore, that a dual orifice jet with a vertical jet of half the diameter of the inclined or reaming jet appears to hold promise as a basic system upon which to develop the jet drilling system. Using this system with a 0.03 - 0.06 in. orifice combination (type 22), a drilling rate of 210 ft/hr has been achieved (Fig. 6), some 2,100 percent greater than that of a single orifice 0.04 in. in diameter with an increase of less than 300 percent in flow volume.

The advantage to using converging or twin parallel jets in disrupting the central core of the hole and the optimum relationship between the two orifices for a type 22 nozzle need study, and this will be carried out as this year's program develops. The advantage to a slight eccentricity of the nozzle axis has, serendipitously, been observed and this also will be investigated.

A small preliminary investigation of the phenomena associated with jet cavitation has also been begun in preparation for a study to be developed later this year. To date the study examined the effect of standoff distance on jet performance when a 10,000 psi, 0.04 in. jet was submerged and directed onto a Missouri granite target. A 2 in. standoff gave the best result with no target damage at 0.5 in. or 3 in. The exact nature of the target surface after jet attack is currently being studied microscopically (Fig. 7). A 10,000 psi jet is directed at a submerged polished natural quartz surface (normally undamaged at this pressure). The cracks generated by cavitation bubble collapse can be clearly seen. It is these flaws, then exploited by the main jet pressure, which increase jet penetration rate.

Figure 6. Section through a hole drilled at 210 ft/hr feed rate at 10,000 psi by a type 22 nozzle.

Figure 7. Polished quartz surface after cavitation jet impact (outside the main impact point) showing surface micro-pits and fracture cavities. (x 128)

Planned Program for the Remainder of this Contract Term

1. A detailed analysis leading to an optimal nozzle design will be carried out, based on the results obtained to date.
2. Three rocks (Berea sandstone, Indiana limestone, and Holston limestone) will be tested in the now modified triaxial test chamber to examine the effect of back pressure, rock confining pressure, and jet parameter on the drilling rate. A type 22 nozzle will be used for part of this study, and the resulting hole diameter will be used as the measure of effect.
3. Sixteen of the tests of the above series will be repeated using varying concentrations of commercial polymeric additives (Polyox, Nalco 625, Revert, Polyhall 654, and the Alfonic 1214-60) to determine if additives substantially improve cutting performance.
4. The cavitation study will be continued and probes inserted into nozzles to determine if this improves rock cutting ability. Preliminary indications are that there may be a minimum size below which the jet disrupts rather than cavitates when a probe is inserted. Cavitation is not anticipated to improve the cutting of granular materials as much as the cutting of brittle crystalline material.
5. The components of the field rig will be composited and preliminary field tests will be carried out to provide a data base, drilling in Missouri dolomite and Missouri granite.

The program initially proposed for this contract term is currently on schedule. It is anticipated that the first year program as identified will be completed in the specified time.

Publications

1. At the present time only one refereed paper has been submitted for presentation.

"Preliminary Experimentation on the Design of a Water Jet Drilling Device," 3rd Int. Symp. Jet Cutting Technology, May 1976, and this is appended.

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;" this is in editing and six copies will be forwarded to ERDA upon completion.

4. A paper is being prepared for the Rapid Excavation and Tunneling Conference in Las Vegas in June. This will be submitted to ERDA when accepted.

5. A paper is in preparation for the 31st Annual Petroleum Mechanical Engineering Conference, ASME in Mexico City, September 1976. This will be submitted to ERDA when accepted.

Time Allocated

1. Principal Investigator Dr. David A. Summers

Dr. Summers spent 50 percent time on this contract during the summer months and 25 percent time during the academic year. This 25 percent time commitment will be continued for the remainder of this contract term.

2. Co-Investigator Dr. Dwight J. Bushnell

Dr. Bushnell spent 100 percent time on this contract during the summer months and 25 percent time during the academic year. This 25 percent time commitment will be continued for the remainder of this contract term.

Acknowledgement

Most of the nozzle experiments were carried out by Dr. M. Mazurkiewicz with the assistance of Mr. J. Blaine, who constructed the nozzles. Mr. C. Grisham built the test frame. We are grateful.

APPENDIX

PRELIMINARY EXPERIMENTATION OF THE DESIGN OF THE WATER
JET DRILLING DEVICE

by

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Summary:

The present demand for new and novel drilling and excavation techniques has given added emphasis to the already popular mechanisms of jet cutting. This paper presents some preliminary results of jet drilling in Berea sandstone while varying nozzle design, jet pressure, and jet rotation speed. Of primary interest is the volume of rock removed for a given nozzle design and given pressure. The volume of rock removed was seen to increase as the pressure and nozzle angle increased. These preliminary tests were all run with a constant drilling rate of 3 m/hr. However, a single test was run after a semi-optimum nozzle was selected and an advance rate of 23 m/hr was achieved.

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1. Sectioned pipe and hole showing nozzle geometry for a jet drilling head.
2. General view of drilling test stand.
3. Sample configuration for a drilling test.
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5. Nozzle geometry for the test series.
6. Hole drilled with a 10 deg nozzle, rotating at 80 rpm, 55 MN/m² jet at 1 mm nozzle diameter.
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9. Nozzle series shown after completion of the test program.

Introduction

There is a continuous and growing need for energy around the world, particularly as the available petroleum resources are reduced and other demands are made for the product. For example, one ton of grain requires five tons of oil to produce, in the form of fertilizers as well as power (Ref. 1). Concurrently there are warnings of the practical limits of the uranium supply, counted on to fuel a major portion of this nation's energy requirements in the last quarter of this century (Ref. 2). Additionally, if the supply of coal currently required for 1985 is to be delivered, an average of over one new mine opening each month will be required (Ref. 3).

All potential energy resources must therefore be exploited if the energy crunch is to be reduced to an uncomfortable squeeze. Almost all these resources are underground and require at the very least access drillholes to prove the deposit and, in the case of petroleum and geothermal deposits, to allow utilization of the resource. Particularly for geothermal heating of homes, little further plant is required, so that, if a rapid and economical method of drilling the access holes were available, at least the spectre of freezing could be held in abeyance.

Currently approximately 90 percent of the holes drilled to explore for petroleum resources are dry (Ref. 4). While there is also a need to determine the geothermal gradient in many areas of the world to determine the feasibility of installing geothermal fields, the cost of boreholes under normal oil well drilling techniques is increasing, and the cost of lining such holes with steel casing increases, and availability of pipe decreases with increase in the diameter of the hole. It has been anticipated that a large savings could be made if the boreholes could be drilled at a smaller diameter.

In order to increase the speed of drilling and at the same time reduce the number of times that the drill head must be replaced during the drill operation (a procedure which may take up to 24 hours in a deep hole location), a method of drilling using high pressure water jets for excavation has been proposed and is currently being developed at the University of Missouri-Rolla. The use of high pressure water jets as the main method of rock excavation will reduce the number of times the drilling head must be replaced and has been shown to increase drilling speed (Ref. 4). In the current program three aspects of a water jet drilling head are being examined. The first is a modification of the geometry of the cutting nozzles; the second is the use of cavitation within the jet flow as a means of increasing drilling rate, particularly in crystalline rock; and the third is the use of long molecular chain polymers to improve jet structure and stability and therefore to improve drilling rate.

Dr. Maurer has shown in field experimentation that water jet drilling can improve the penetration rate of conventional drills by a factor of up to five in vertical hole drilling, and by a factor of fifteen where directional drilling is involved (Ref. 5). The design location of the jets used in his research, however, involved jets directed forward from the main drilling bit and with the nozzle housing located within the drill bit assembly. Water jets have the advantage that within the nozzle chamber the pressure of the jet is hydrostatic, and jets can therefore be directed at any required angle from the chamber and still effectively cut rock. Thus, water jets can be used not only to drill ahead of the drilling nozzle, but also to the side (Fig. 1). Preliminary experimentation therefore is centering on the evaluation of a combination dual orifice nozzle, one of which would cut an access hole ahead of the nozzle assembly and a second nozzle which would then ream the borehole to the required diameter. The first portion of the program is described herein and included the development of a test frame for this program and an experiment carried out to determine the effect of changing the cutting parameters on the effectiveness of the lead nozzle in cutting the access hole.

Construction of the Test Chamber

The program which is to be carried out to examine jet cutting parameters requires that the nozzle be rotated and advanced into the rock samples. It was originally anticipated that the initial tests would drill a hole approximately two inches in diameter, and it was considered that a six-inch diameter rock sample would therefore be of sufficient size for the test program. One-foot long samples would then give a sufficient length of drilling time for an initial evaluation of the effectiveness of the particular cutting parameters of each individual test. The research program as well as incorporating the test parameters described above, would also investigate the effects of confining pressure of the rock and back pressure within the borehole. In order to accommodate these latter two test parameters it was intended to use a triaxial test chamber suitably modified. The research equipment must therefore be able to incorporate this triaxial test chamber within a test frame. In the initial evaluation of the test design it was decided that a better control of the system initially within the laboratory could be achieved if the triaxial chamber was raised and lowered while the nozzle supply point was rotated. The test stand (Fig. 2) was therefore designed under these conditions. In the experimental program described herein where the initial design parameters of the nozzle were determined, the triaxial chamber was not used, and samples were located within a surrounding plexiglas shield to contain the water flow (Fig. 3). It was found necessary to anchor the rock sample during these experiments since, where lateral jets were used, the force transmitted

Figure 1. Sectioned pipe and hole showing nozzle geometry for a jet drilling head.

Figure 2. General view of drilling test stand.

Figure 3. Sample configuration for a drilling test.

by the jet to the rock sample was sufficient to topple the sample were no constraint imposed. Slow water flow to the nozzle was supplied by a 46 kw high pressure pump which has previously been described, and the flow was transmitted to the nozzle through a Harwood high pressure coupling.* A direct drive to the nozzle was then achieved through a 40 to 1 reduction gearing from a variable speed d.c. motor. The platform upon which the rock was mounted could be raised and lowered by a winch also driven by a variable speed d.c. motor (Fig. 4). The speed of rotation and the speed of advance of the sample were both controlled from a central panel.

Experimental Design

In order to evaluate the requirements of the preliminary excavating nozzle a factorial experiment with 27 data points was carried out on Berea sandstone. Three test parameters were examined in this program: the effect of nozzle inclination, jet pressure, and nozzle rotation speed. Three nozzle inclinations were developed based on a chosen nozzle geometry (Fig. 5), with the angle subtended by the jet with the drilling axis being 10 deg, 20 deg, and 30 deg. Three jet pressures, 41.4 MN/m², 55.2 MN/m², and 69 MN/m², were developed in the jet, and the rotational speeds were at 40 rpm, 80 rpm, and 118 rpm. The sample was in each case advanced at a constant speed of 5 cm per minute, and the nozzle orifice in all cases was 1 mm.

Experimental Procedure

Samples of Berea sandstone were prepared 30 cm long and, with the exception of the first few samples which were square, 15 cm in diameter. The sample was located in the test frame and clamped in place. The protective plexiglas shield was lowered and secured and the sample platform raised until the nozzle standoff distance was 8.9 cm for the 10 deg and 20 deg nozzles and 7.6 cm for the 30 deg nozzle. The smaller standoff distance in the final case was to ensure that the jet action remained within the surface of the sample. The initial standoff was provided to ensure that an opening was cut into the rock sufficiently wide at the surface that the nozzle body and holder could enter the rock. This initial distance also allowed time to correctly adjust the sample feed rate before the nozzle entered the hole.

* The use of proprietary products described in this experimentation are used for descriptive purposes only and should not be construed as an endorsement of these products by either the University of Missouri-Rolla or the Energy Research and Development Administration.

Figure 4. Motor drive to elevate test platform.

Figure 5. Nozzle geometry for the test series.

The nozzle drive was initiated and the jet brought up to pressure and stabilized before the feed mechanism was engaged. Pressure stabilization was improved by a large dampening chamber located between the supply pump and the swivel coupling. The experiment was continued until such time as either (a) the nozzle jammed within the rock sample or (b) the nozzle had penetrated 19.05 cm into the rock. At this point the drive mechanisms and pump were simultaneously shut down; then the sample platform was lowered and the sample withdrawn and replaced prior to the next test. The sample order was randomized for the first nozzle series (10 deg), and this order was repeated for the remaining two nozzle series. The rock samples were then sectioned longitudinally, photographed, and the dimensions of the cavity recorded.

Experimental Results

Three of the experimental runs were stopped because the nozzle contacted the central cone. It was, however, noted that there was a slight angle to the pipestem. While the 10 deg and 30 deg nozzles were located so that the jet force cancelled this bend and the pipe rotated concentrically, this was not the case with the 20 deg nozzle. This was located so that the reactive force exaggerated the eccentricity, and an estimated 2.5 mm wobble occurred in the feed. This may explain why the cone did not hit the nozzle on that test series.

Observation of the process indicated that the jet rebounded strongly until the nozzle had penetrated between three and four inches into the sample, beyond which the hole was filled with fluid and the water escaped over the surface of the sample under no apparent pressure.

Examination of the samples indicated that the passage of the nozzle caused secondary erosion of the hole. This was most evident in a 10 deg nozzle, 80 rpm at 55 MN/m² (Fig. 6), where the change can be clearly seen. It is curious that the damage occurs above the leading edge of the nozzle holder, suggesting that increasing turbulence and perhaps cavitation as the fluid leaves the rock/holder annulus is causing further damage.

Because of the limited number of data points obtained (Table 1) only simple data analysis is possible. Two criteria of performance were taken--cone height, since this gave the distance at which the jet was cutting, and hole diameter. The feed rate was kept constant and thus hole volume was a direct function of the square of hole diameter (DIAM). A regression equation computed for this in terms of jet pressure (P MN/m²) and the nozzle inclination to the hole axis (NA) gave an equation

$$DIAM^2 = -2.74 + .8846 P \sin N. A. + .00295 P^2$$

with a regression coefficient of 0.90. The data indicated no variation in hole diameter with rotational speed; however, this

Figure 6. Hole drilled with a 10 deg nozzle, rotating at 80 rpm, 55 MN/m^2 jet a 1 mm nozzle diameter.

Table 1. Borehole Diameters for Initial Study.

Nozzle diameter	1.02 mm	Feed rate 3.05 m/hr
Holder diameter	3 cm	(5.09 furlongs/fortnight)

Rotational Speed (rpm)	Nozzle Angle								
	10°			20°			30°		
	Pressure (MN/m ²)			Pressure (MN/m ²)			Pressure (MN/m ²)		
	40	80	120	40	80	120	40	80	120
41	3.43	3.05	3.30	3.56	3.81	3.43	5.33	4.06	4.83
55	3.56	3.80	4.19	4.83	4.57	4.70	5.08	5.33	5.21
69	4.32	4.83	4.32	6.10	5.84	5.59	6.10	6.73	6.86

Diameter values in cm

may have been due to the limited range of speeds examined and the close relation between the diameter of the nozzle retaining device (3.1 cm) and the average hole diameter (4.7 cm).

The experiment was conducted with the jets cutting across the bedding plane for most samples. Differential cutting of the sandstone where the jets cut along the bedding (Fig. 7) indicated that the jet removes more rock in this mode than along the bedding, confirming results reported earlier in Barre Granite (Ref. 6).

In developmental research following this experiment the effect of advance rate is being examined. Initial data showing that this reduces hole diameter are illustrated in Figure 8.

As could be anticipated, there was no detectable wear on the nozzles except where the cone was intercepted (Fig. 9).

As an ancillary to the experimentation and in verification of the concept proposed as a basis of the project, it is worth recording that an initial test was carried out with an 11 deg incline nozzle to determine the shape of the orifice cut. This nozzle grounded on the sides of the orifice within an advance of 5 cm into the rock sample. A second orifice was then drilled into the nozzle at an angle of 90 deg to the first nozzle. Using this secondary reaming nozzle a hole larger than 5 cm in diameter throughout was drilled through a one-foot sample of the rock at the rate of 14 m per hour. The hole geometry was very irregular, however, and much work remains to be done in order that nozzle geometry be optimized to improve drilling rate and to improve the alignment and condition of the holes excavated.

Acknowledgments

This work was carried out under the Energy Research and Development Administration contract ERDA E(11-1) 2677. Mr. Morris Skalka was technical project officer on this program. The authors are grateful for the support given to this project and the encouragement of Mr. Skalka in the program. The research was carried out with the assistance of the following students: Mr. Ahmud El-Saie, Mr. Boon Tan, Mr. P. G. Manusmare, and Mr. J. Donham. The pressure manifold was designed by Dr. M. Mazurkiewicz. The equipment was built by Mr. Charles Grisham, and the nozzles were constructed by Mr. James Blaine. The authors are grateful to the above-mentioned gentlemen.

Figure 7. Sample drilled across the bedding plane, showing the effect of rock anisotropy.

a) at 5 cm/min

b) at 38 cm/min

Figure 8. The relative effect of advance velocity on hole diameter at 55 MN/m^2 jet pressure.

Figure 9. Nozzle series shown after completion of the test program.

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