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

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David A. Summers and Terry F. Lehnhoff

MASTER

Rock Mechanics & Explosives Research Center

University of Missouri-Rolla

Rolla, Missouri 65401

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Introduction

The University of Missouri-Rolla is midway through the second year of a research program, funded by the Energy Research and Development Agency, with the object of developing a more effective means of drilling for access to geothermal resources. The means by which this will be achieved is by application of high pressure, small diameter water jets. Within the first year of the contract a nozzle design was established and the effects from rock confining pressure and hole back pressure on drilling rate were established in granular rock.

This report will review not only the work carried out in the last two months on the current contract but will place this in terms of the progress achieved within this contract year. Experimental results will be illustrated since the publishing of papers on the program runs behind the current status. A paper presented at the 31st annual meeting of the Petroleum-Mechanical Engineering Conference of ASME in Mexico City in September 1976 is appended.

Field Testing

A test rig built around a Flow Industries* 150 hp intensifier and a SIMCO drill feed system was assembled on a flat trailer bed, modified to allow drilling from the back end. The unit (illustrated in C00-2677-2 and C00-2677-3) was successfully tested in limestone and dolomite beds within the neighborhood of the University. Drilling rates up to 3 ft/min were achieved before mechanical difficulties, first with the water supply pump and then with the oil pump driving the intensifier, postponed further field research. While both problems were solved, the onset of winter has precluded any further testing of the system in the field. The intensifier

*The use of brand names is for the purpose of identification only and should not be considered as an endorsement of any product by the University of Missouri or the Energy Research Development Agency.

package has, therefore, been temporarily located at the research laboratory with the intensifier itself remotely located inside the building to allow research to continue.

Design development of the equipment has, however, continued and, based on the needs for the succeeding portions of the program, the rig is being modified to drive a 4-1/2 in. diameter bit, together with the necessary feed pipe and hydraulic jet system, down a distance of 200 ft.

Laboratory Testing

Results from the first year of the program had shown a marked effect due to rock confining pressure or fluid back pressure on drilling diameters in sedimentary rock. The program was extended to examine the effects in crystalline rock and equivalent effects were found (Fig. 1, 2), where back pressure was applied to the system.

Because the increase in external pressure reduces the effective cutting radius of the jet, this may affect the relative performance of nozzles with differing included angles between the orifices. In order to determine whether or not this is the case, and to parameterize the relationship, a series of experiments are in progress.

The first part of the program is to observe the effect of nozzle angles, rotational speed and advance rate under zero pressure and then to run the same tests under pressure. The conditions tested were below those developed earlier in the program, where advance rates up to 280 inches/min had been achieved. The reason that this was done is that practical considerations limit effective drilling rates at depth to levels below 300 ft/hour (60 inches/min).

With no confining pressure on the sample the optimum angle of penetration was found to be 37° for sandstone with the optimum angle being slightly

Fig. 1. The effect of increasing back pressure from 500 to 1500 psi (l to r) on drilling in Missouri Granite. (in/minute at 25,000 psi)

Figure 2. The effect of back pressure on hole diameter in drilling Missouri Granite (5 inches/min at 25,000 psi jet pressure).

smaller, 30°, when the jet cut limestone at equivalent pressure (Fig. 3). Where jet pressure is reduced and feed and rotational speeds increased, an optimum was not found for the softer rock (curve B). There appeared to be only a small effect of rotational speed on advance rate, although where the rpm was slow the ribs between adjacent cuts became too-thick to allow progress of the head into the hole (Fig. 4). It should be noted, however, that this effect is a function of feed rate and the faster the unit advances, then the diameter increases. At the rates chosen, the effect of advance rate is a reduction in diameter (Fig. 5) with advance rate.

The marked difference in drilling ability in two rocks of roughly equivalent compressive strength raised a question as to the effect of going through one rock into another. Since this is likely to occur at different orientations to hole alignment a simple series of tests were initiated to determine what the effects might be. The results of the tests (Fig. 6) suggest that, in order to maintain a constant hole diameter, such as would be required in most situations, that some control must be applied to the system. At the present time it is proposed that such a system would be controlled by the thrust applied to the drilling stem.

The variation in diameter which is achieved under varying conditions is of prime concern, most particularly as it related to larger hole diameters and applications where rock properties will vary much more greatly than can be modeled in the laboratory. This concern became evident at the same time as a change in emphasis was made in the research program. Until this time the research had been concerned with demonstrating that a water jet drill could achieve satisfactory advance rates. Applications for the technology are, however, mainly in holes of diameter 4.5 inches and greater. Thus, while research is continuing on the effect of change in nozzle parameters on drilling ability, the main emphasis on the program has turned to adapting the technology to the drilling of large holes.

Figure 3. The effect of included angle on drilling diameter for holes drilled in A) Limestone at low rpm and feed B) Sandstone at high rpm and feed C) Sandstone at low rpm and feed.

Figure 4. The effect of rotational speed on drilling diameter as a function of feed rate in Berea sandstone.

Figure 5. The effect of feed rate on drilling diameter for A) limestone at low rpm, B) sandstone at high rpm, C) sandstone at low rpm.

Fig. 6. Water jet drill holes through a) a "hard-soft" rock interface, b) a "soft-hard" interface, c) a rock with thin, hard inclusions.

The first step in this process has been to obtain and modify a drilling bit to accept a jet cutting head. A 4-1/2 in. drill bit was donated to the University by Gruner Williams, a primary modification has now been made in adding the nozzle assembly (Fig. 7). A set of six jets is required to operate the head, two are inclined forward, as shown, and serve to cut an access hole for the nozzle assembly. Concurrently, the four lateral jets are directed across the face of the bit on the rock/button contact surface. In this way, as the button bites into the rock the jet immediately removes the crushed rock and concurrently exploits any fractures developed by the button.

The bit has so far been tested only in limestone blocks in the laboratory. In the current program it is intended to carry out a series of laboratory tests to determine the most effective location of the lateral jets, in cutting limestone, granite and dolomite, prior to taking the test rig into the field.

The effectiveness of the geometry will be determined by the change in load on the drill bit as it is advanced. At the present time the base load conditions are being determined at different feed rate and rotational speeds.

The University is currently also seeking bids for the supply of the drill pipe for the 200 ft hole program to be carried out this summer. The drill rig is also being modified to allow the dual system to operate.

Research on the application of cavitation has been delayed by component supply problems. This has, however, now been solved and this program will begin a detailed study of the effects of cavitation on enhancing drilling performance.

Fig. 7. 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).

Time Allocated

Dr. Summers and Dr. Lehnhoff have committed and will continue a 25% time allocation to this contract during this Academic Year.

ENVIRONMENTAL EFFECTS ON A HIGH PRESSURE JET DRILL

by

**David A. Summers
Dwight J. Bushnell**

Presented At

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ENVIRONMENTAL EFFECTS ON A HIGH PRESSURE JET DRILL

Introduction

Under contract to the Energy Research & Development Administration, the University of Missouri-Rolla has been investigating parameters which control the manner in which water jets can be used to drill through rock. The experiments were initially carried out in Berea sandstone. This is a standard rock (Ref. 1) and relatively soft so that any variation in drilling due to changes in the test conditions could be easily discerned. Following this the program was expanded to include tests in Indiana limestone, Tennessee marble, and Missouri granite.

The first part of the investigation examined the effect of change in nozzle design on drilling. A major objective of the program is to effect a faster drilling rate particularly in the harder rock materials. However, to use drilling rate as a complete criteria of judgement would require an extremely large test program and this was felt impractical and unnecessary. Because water jets are known to cut shallow slots at greater advance rates, it was determined to relate hole diameter and advance rate and to then use hole diameter as the test parameter.

Equipment Design

Two high pressure pumps have been used to date in this project, a 75 hp Kobe pump used to deliver 10 gpm at 10,000 psi for the earliest part of the program and a 150 hp Flow Research Intensifier* capable of 10 gpm at 25,000 psi for the work with harder rock. The fluid used for the tests was tap water with a small percentage of soluble oil present

*The fact that certain commercial products referred to herein were used in this investigation is not to be considered as an endorsement of these products by either the Energy Research & Development Administration or the University of Missouri-Rolla.

to provide pump lubrication. High pressure water was fed from the pump, through 9/16 in. OD high pressure steel tubing to a Harwood high pressure rotary coupling (Fig. 1). A straight section of tubing from the coupling served as a drill stem. This was rotated by a meshed pair of gears powered by a variable speed d.c. motor. In the earlier tests brass nozzles were used, since these were easily machined to give the required range of designs. These nozzles, however, were sensitive to rock contact and required that a large nozzle holder be used to fasten them to the drilling stem. Once the best nozzle design had been determined, further nozzles have been made from steel and welded to the end of the drill stem. While the brass nozzles stood up well in the limited test program, they were not capable of drilling more than 10 ft in sandstone without discernable wear. Field tests on another project (Ref. 2) have revealed that life expectancy of less than an hour can be anticipated before orifice erosion becomes critical.

Nozzle Design Studies

In the initial concept of the nozzle design (Fig. 2) a forward directed jet would cut an access for the nozzle body while a second jet would ream out the hole and a mechanical bit would ensure a smooth base for the hole.

In order to correlate drilling rate and hole diameter, drilling rates of up to 280 in/min were run in Berea sandstone. From these data experimental curves have been obtained (Figs. 3, 4) which can be used to estimate potential drilling rate for a given set of conditions.

There has been some difficulty in discerning the exact role of rotational speed of the nozzle on hole diameter and thus possible advance rates. The reason for this is the peculiar action of the jet drilling

Figure 1. General View of Drilling Test Stand..

Figure 2. Preliminary Design of the Reaming Nozzle Drilling Head.

Figure 3. Variation in hole diameter with feed rate in the form $y = Ax^B$.

Figure 4. Hole Diameter for Two Nozzles and Two Rotation Speeds as a Function of Advance Rate.

system, in that the initial jet impact is not the sole rock removal process and that the jet cuts beyond the limits of the nozzle holder. Thus, as the nozzle advances it can leave a rib of rock between adjacent jet passes along the same hole diameter (Fig. 5). Should the rotational speed/advance rate ratio of the head be too low, then the intervening ribs will be large enough to extend into the path of the nozzle body and thus impede progress. Conversely, too high a rotational speed can increase wear on system components. At the speeds considered (up to 1,000 rpm), the linear traverse velocity of the jet at a 1 in. radius is of the order of 500 ft/min with the jet cutting the 1 in. depth to that radius. At these speeds there is little effect of traverse velocity change on cutting depth, a conclusion shared by other investigators (Refs. 3, 4). However, the need to retain sufficient rib removal for clear passage of the nozzle (Fig. 6) dictates that as high a nozzle rotation speed as possible be maintained.

Environmental Effects on Jet Drilling

As a drilling head penetrates into the ground to increasing depths, two effects occur which have an affect on the speed at which the drill will penetrate the rock: confining pressure on the rock increases and the weight of fluid above the drill bit creates a back pressure in the hole. These effects can be simulated in laboratory testing using triaxial chambers and suitable auxillary equipment. For the purposes of initial experimentation it was decided to simulate conditions to a depth of 6,000 ft where confining pressures would be of the order of 6,000 psi and a back pressure of approximately 2,000 psi could be anticipated.

A Soiltest model No. T-8154 chamber was obtained for these trials. The chamber was chosen based on the range of confining pressures that could be generated within its design capacity and for its ability to contain

Figure 5. Sample Drilled at 225 in./min with a Nozzle Rotation of 520 RPM
(Note threaded effect). Note: Sample is 1 ft tall x 4 in. wide.

Figure 6. Sample Drilled at 225 in./min with a Nozzle Rotation of 970 RPM.
Note: Sample is 1 ft tall x 4 in. wide.

6 in. diam specimens, 1 ft long. The weight of the chamber restricted the speeds at which tests could be carried out since (Fig. 7) the specimen was raised rather than the drill lowered. A counterweight was required to attain advance rates up to 40 in/min, the upper limit for this test series. The pressure cap for the triaxial chamber was modified (Fig. 8) to allow the high pressure pipe access to the sample. Initially a steel plug with "O" ring seals was used to interface between the plug and the pipe; however, this gave too high a friction component to the pipe as confining pressures were applied to the sample and the plug was replaced with a teflon seal.

Previous investigators (Ref. 5) have used a plastic polymeric seal to coat the samples and have found this adequate. For this program it was not found possible to repeat this success and instead rubber tubing jackets were used to seal the samples from the fluid used to apply confining pressure.

Tests were carried out initially on samples of Berea sandstone, at jet pressures of 10,000 psi, at a rotational speed of 500 rpm, and with rock confining pressures to 6,000 psi (Table 1). A feed rate of 40 in/min was used and the dual orifice nozzle described above was used for the tests. The back pressure levels were achieved by gating the flow of fluid from the test chamber.

The results of this initial test matrix indicated that the application of external pressure to the cutting area sharply reduced the effectiveness of the jet while, once this initial drop had occurred, subsequent increase in pressure had much less effect. Thus, for example, a back pressure of 500 psi reduced the diameter cut by the jet by almost half from the unconfined condition, while the subsequent increase in back pressure of 1,500 psi further reduced the diameter by only 12.5 percent of the initial

Figure 7. Drilling Test Stand with Modified Triaxial Pressure Vessel.

Figure 8. Modified Triaxial Pressure Vessel.

Table I. Simulated Drilling Data (Hole Diameters are in inches),
(Berea Sandstone)

CONFINING PRESSURE			
	0 PSI	4000 PSI	6000 PSI
BACK PRESSURE			
0 PSI	2.0 IN	1.050 IN	1.025 IN
500 PSI	1.025 IN		
1000 PSI	.800 IN	.625 IN	.75 IN
1500 PSI	.875 IN		
2000 PSI	.750 IN	.575 IN	.575 IN

value. Concurrently, while there was a reduction in diameter with application of rock confining pressure, an increase in confining pressure from 4,000 to 6,000 psi had no clear effect on cutting diameter.

It was initially conjectured that the reduction in cutting effectiveness was due in part to the creation of the back pressure in turn lowering the effective jet pressure. In order to determine the validity of this idea five tests were carried out at reducing levels of jet pressure (Table II) without confining or back pressure. These tests indicated that it would require a drop in effective pressure of over 5,000 psi to achieve the drop in cutting rate achieved by the application of 500 psi back pressure to the hole. This in turn indicated that the reduction in cutting was unlikely to be a purely jet phenomenon.

For this reason confining pressure tests were carried out under no back pressure and at 10,000 psi jet pressure, with similar test conditions to those above with rock confining pressure of 0, 4,000, and 6,000 psi. The results of this test (first line of Table I) showed that a 4,000 psi confining pressure on the rock resulted in the same change in drilling conditions as did the 500 psi back pressure in the hole, within the limits of experimental accuracy.

The change in the cuttability of the rock under pressure, since in both cases there is a pressure effect on the rock in the cutting zone, indicates that there are rock properties which control jet cuttability to a degree much beyond change in jet pressure. The investigation to delineate the property or properties in question is as yet still in its infancy but should prove interesting. Clues which might later prove significant are that, compressive strength is not the property, as can be seen by comparing equivalent holes drilled in Berea sandstone, Indiana

Table II. Effect of Change in Jet Pressure on Cutting Diameter.

<u>Jet Pressure</u>	<u>Diameter</u>	
10,000 psi	2.180	Back Pressure - 0 psi
9,000 psi	1.875	Confining Pressure - 0 psi
8,000 psi	1.725	Rotational Speed - 500 rpm
7,000 psi	1.650	Advance Rate - 40 in./min
6,000 psi	1.350	Rock - Berea Sandstone
5,000 psi	1.150	Nozzle - Type 22

limestone, Tennessee marble, and Missouri granite (Fig. 9) under the same conditions. Further, under confining pressure generated by directing two jets together at 5 deg within the sample, tensile stresses are generated around the impact point sufficient to generate cracks, or in some cases fracture the rock (Fig. 10).

Polymeric Additives

Long chain, high molecular weight polymers, exemplified by polyethylene oxide, are now being used as friction reducing agents in improving pipe flow (Ref. 6). These friction reducing agents have been used in oil well muds to improve hole stability (Ref. 7) and have been found to improve liquid jet cohesion beyond the nozzle (Ref. 8). Because a water jet drill will operate submerged and as such is more rapidly destroyed by turbulence than a similar jet in air, an experiment was carried out to determine the effectiveness of such polymers under simulated down-hole conditions (Table III).

Four polymers were tested in this program: polyethylene oxide (Polyox), two polyacrylamides (Nalco 254 and Polyhall 654), and a non-ionic surfactant (Alfonic 1214-60). The tests were run at 700 ppm initially, and the tests were carried out in Berea sandstone. The results (Fig. 11) indicated very little differentiation between the polymers but they appeared to improve penetration by approximately 15 percent.

Increasing concentrations of the Nalco chemical were then tested to determine the effectiveness of a stronger solution, but no apparent benefit could be observed (Table IV). A possible reason for this is that the jet is cutting very close to the nozzle where tests elsewhere (Fig. 13 in Ref. 9) have shown the polymer has a lesser effect, and Dr. Zakin (Ref. 10) has suggested that such gain as has been achieved is possibly due to a drag reduction effect in the feed lines to the nozzle.

Figure 9. Comparative Hole Sizes Drilled in (from the left) Indiana Limestone, Berea Sandstone, Tennessee Marble, and Missouri Red Granite at 25,000 psi Jet Pressure, 500 rpm, and 15 in./min Advance Speed.

Figure 10. Sectioned Side of a Cavity Cut by a Converging Jet Pair Showing Tensile Cracks Generated Around the Cavity.

Figure 11. Chemical Additives, Confining Pressure and Borehole Pressure Effects on Hole Diameter in Berea Sandstone, 10,000 psi jet pressure, type 22 nozzle.

Table III. Effect of Polymer Concentration on Cutting Diameter in Berea Sandstone at 10,000 psi Jet Pressure, Type 22 Nozzle, 40 in./min Feed Rate

<u>Back Pressure</u> <u>psi</u>	<u>ppm Nalco 254</u>			
0	200	500	1000	2000
0	1.49	1.37	1.14	1.28
500	.75	.83	.72	.73
1000	.71	.72	*	*
2000	.73	*	*	*

* data not available

Values in inches

Table IV. Effect of Chemical Additives on the Cutting Diameter in Berea Sandstone at 10,000 psi Jet Pressure, Type 22 Nozzle, 40 in./min Feed Rate.

Chemical (at 100 ppm)	<u>0</u>	<u>500</u>	<u>1000</u>	<u>1500</u>	<u>2000</u>
Nalco BX-254	2.00	1.05	.95	.95	1.00
Polyox	2.00	1.06	1.00	.94	.94
Polyhall 654	1.98	1.05	1.00	.98	.80
Alfonic 1214-60	1.95	1.02	.98	.95	.88

Hole diameters in inches

Conclusions

The results to date from this ongoing research program suggests because of the high drilling rates achieved in the laboratory, that high pressure jet drilling has a useful potential in industry, but that the parameters controlling such application are as yet undetermined. It is evident that the rock properties have a greater effect on the drillability than jet cutting pressures.

The use of polymeric additives does not appear to have as great a potential for improving drilling rate as they have in other applications where standoff distances are greater..

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