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

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

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June 1976

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

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Abstract

A nozzle design developed under this contract has drilled Berea sandstone at rates up to 280 in./min. This requires high rotational speeds and a large (30 deg) angle between the forward and the inclined orifices of the nozzle. Tests carried out under simulated borehole conditions show an initial reduction in penetration rate of up to 50 percent as rock and fluid back pressures over 500 psi are applied, but that this effect is reduced as these pressures are further increased. Tests in four rock types show that the uniaxial compressive strength is not a measure of jet drilling performance. Preliminary experimentation has shown that long-chain polymers add 15 percent to the cutting ability of the jets at low concentrations but do not improve jet cutting in concentrations over 200 ppm.

The design of the field drilling unit, which is currently under construction, is presented.

Introduction

This is the second report on progress to be made on contract E(11-1)-2677 between the Energy Research & Development Administration and the University of Missouri-Rolla on the subject of high speed water jet drilling.

In the first report (Ref. 1) research was described which led to the choice of a nozzle design for future program use. Some 24 nozzle designs were evaluated in this study. A dual orifice nozzle, with an orifice diameter ratio of 2:1, and with the smaller orifice directed forward while the larger orifice was angled outward at 30 deg was judged to give superior performance.

This nozzle design has, therefore, been adopted and used in subsequent testing to determine the effect of rock confining pressure, hole back pressure and effective jet pressure on cutting performance. Berea sandstone is a relatively soft sandstone and many of the tests were carried out in this rock, since the effect of changing parameters would more clearly be illustrated.

The effect of adding polymeric additives to the cutting fluid were also evaluated in Berea sandstone.

Because of a delay in arrival of the main pump to be used in this and future testing, the completion of the laboratory testing, prior to taking the unit to the field, is currently in progress (Figure 1). Two sites have been selected for this testing, a dolomite at the UMR experimental mine and a red granite at a test site in southeast Missouri.

Progress beyond that described in the first report is herein described.

Figure 1. Original Work Plan.

Laboratory Test Equipment

In the original test program on nozzle design a simple plexiglas holding frame had been constructed to enclose the sample and contain the ejected fluid and material (Figure 2). Feed water under pressure was brought to a Harwood rotary coupling from which it was fed, through a straight stainless steel pipe section, to the nozzle.

In the earlier test reports brass nozzles were used, since these were easy to machine, and little wear was observed for the limited testing of each nozzle. In the current and proposed future programs steel nozzles are used. These are welded to the straight feed pipe sections, thus eliminating the large diameter nozzle holder, and providing a stronger, longer lasting component.

Drive to the drill stem is through a meshed pair of gears from a variable speed d-c motor. In the course of the current test program feed rates up to 280 in/min were achieved. The ribs between succeeding nozzle revolutions protrude into the hole and can interfere with the nozzle passage. High rotational speed is thus required to insure that there is only a small advance between revolutions and thus an adequate rib removal, and, in the progress of the research up to this speed, the gear ratio was changed three times.

The sample platform is raised and lowered by an overhead wire rope fed over a pulley to a take-up winch driven, through a gear reduction, by a second d-c motor. This also was modified to give the higher advance rates found attainable in this part of the program. The motor was not, however, sufficiently powerful to lift the triaxial chamber at these high velocities.

Figure 2. General View of Drilling Test Stand.

and the program was accordingly changed. Firstly, any remaining high speed drilling rate determinations were postponed until the field rig could be used, and secondly a large concrete and scrap iron counterweight was attached, through a pulley to the top of the specimen platform, giving sufficient balance that advance rates up to 40 in/min could be safely achieved with the triaxial chamber in place.

The pressure vessel, a modified Soiltest model #T-8154 chamber is presently being used to simulate underground conditions to a depth of approximately 6,000 ft. The chamber (Figure 3) is located in the test stand in place of the plexiglas case, with a feed line to the lateral pressure pump and an exhaust line which can be gated to increase fluid pressure in the hole. The pressure vessel cap has been modified to allow access for the cutting nozzle (Figure 4). An original design using "O" ring seals against the drill stem as it rotated and advanced did not prove satisfactory. The high tolerances required to retain a seal did not provide a smooth enough passage for the drill pipe at high rotational speed when the system was pressurized. A teflon seal was made as a replacement and, as shown, has proved successful in testing to date. Elimination of the nozzle holder has improved test program turn-around time since the nozzle is withdrawn from the head before the cap can be lifted from the chamber.

A recessed top plate and rubber seal were found necessary to seal the upper surface of the rock from the surrounding constraining fluid. Tests with a thin plate and rubber washer (as originally proposed) over the rock were not successful.

A bottom plate was placed beneath the rock samples to protect the chamber base plate from damage if sample penetration occurred. The sample is encased in an inner tube to seal it from the surrounding oil used as a

Figure 3. Drilling Test Stand with Modified Triaxial Pressure Vessel.

Figure 4. Modified Triaxial Pressure Vessel.

pressurizing medium. Other methods of large triaxial sample preparation successfully used by other investigators (Ref. 2) have not proved successful in this study.

Experimental Results

DRILLING RATE STUDIES:

Tests carried out in the earlier part of the program and described earlier (Ref. 1) have shown that a dual orifice nozzle (Figure 5) was superior for the drilling of a sandstone under no confining pressures. Further the tests had shown that there was a relationship between feed rate and hole diameter (Figure 6) with an intersection at an advance rate of 2 in/minute. This advance rate had been used in preliminary testing (Ref. 3) and had led to the erroneous conclusions that hole diameter was not feed-rate dependent.

Modifications, described above, in the testing equipment gave the opportunity for advance rates of up to 280 in/min, and under these conditions it was possible to determine, over a much greater range of velocities, the rotational speed effect (Figure 7). However, a problem arose which indicated a purely mechanical reason for high rotational speed, as opposed to the experimental relationship to jet cutting depth. As the speed of nozzle advance increased, so the axial distance moved by the nozzle between succeeding rotations also increased, for a fixed rpm. A rib of rock was isolated which grew wider and longer as the advance rate:rpm ratio increased. Beyond a certain ratio this rib extends far enough into the hole to interfere with the nozzle assembly. (It also makes an accurate assessment of hole diameter very difficult.) (Figure 8). Increase in rotational speed removes the ribs and allows an easier nozzle passage (Figure 9).

Figure 5. Nozzle Design Used for Advance Rate Studies.
(Type 22 Nozzle).

Figure 6. Variation in hole diameter with feed rate in the form $y = Ax^B$.

Figure 7. Hole Diameter for Two Nozzles and Two Rotation Speeds as a Function of Advance Rate.

Figure 8. 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 9. Sample Drilled at 225 in./min with a Nozzle Rotation of 970 RPM.
Note: Sample is 1 ft tall x 4 in. wide.

The holes were sectioned longitudinally to permit easier measurement of the jet cut diameters and also to view the condition of the hole produced by the jets. The fastest speed attainable using the available equipment without a substantial change in the drive configurations was measured at 280 in/min at a rotational speed of 970 rpm. Under these conditions (Figure 10) a small rib was formed, and a higher rotational speed would be required to maintain an open hole. Experiments were not conducted to drill at faster speeds than 280 in/min, since it was considered that this speed was more than adequate for current contractual purposes. However, there are advantages to using this type of unit for drilling small holes in mining--particularly for roof bolt emplacement. The information on the potential of this system was therefore transmitted to Flow Research Inc., who are in negotiation to develop such a drill for the U. S. Bureau of Mines.

SIMULATED DOWNHOLE TESTS:

The modified triaxial chamber was used to develop confining pressures on test samples up to 6,000 psi and with a back pressure, generated in the hole by gating the exit flow from the cavity, up to 2,000 psi. A 3 x 3 factorial experiment was performed to determine the effects with additional points taken to further define the zero confining pressure curve (Figure 11). Because of the high mass of the system, a drilling speed of 40 in/min was used. The application of any pressure to the rock/jetting system sharply reduced the cutting ability of the jets. This effect occurred both with creation of a back pressure and with confinement of the rock. However, once the initial restriction of the rock had been imposed, a further increase in confining pressure appeared to have little effect (Table 1). Similarly while a back pressure of 500 psi over the nozzle lowered the jet cutting

Figure 10. Sample Drilled at 280 in./min with a Nozzle Rotation of 970 RPM (Maximum advance rate currently attainable). Note: Sample is 4 in. wide x 7 in. tall.

Figure 11. Borehole and Confining Pressure Effects on Hole Diameter.

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

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

diameter by almost 100 percent, a further increase in back pressure of 1500 psi further lowered the cutting diameter by only 25 percent. There is, therefore, an apparent change occurring in the jet cutting operation at relatively low levels of applied pressure which, if understood, might lead to greater penetration rates for the system. The first, obvious, possibility is that the effect is caused by the change in the pressure drop across the nozzle. (This would not relate to the confining pressure effect but only to the back pressure). To determine if this were the cause of the drop in cutting effectiveness a series of six holes were drilled at jet pressures from 5,000 to 10,000 psi (Figure 12, Table II). A drop in jet pressure of 5,000 psi did not produce as great a reduction as that of the 500 psi back pressure. The jet parameters are not, therefore, the sole controlling parameters. Creation of a rock confining pressure also has sharply reduced jet penetration, however increase in pressure has little further effect. A confining pressure of 500 psi with no back pressure was applied and yielded a hole diameter of 1.16 in. Thus, it can be supposed that the effect seen in creating a back pressure in the hole is created through a change in the rock response rather than a change in the operating parameters of the jet.

Examination of the bottom of the holes drilled by the jets showed that the typical conic seat with the central hole was not present with the application of borehole pressure (Figure 13). The addition of 500 psi back pressure has reduced the tall cone to a small rounded indentation with a very small hole being detectable to indicate the action of the vertical jet.

It can be concluded that a larger vertical nozzle orifice may be required under these conditions, however the problem requires further investigation to be carried out during the next phase of the research, before a clear solution can be established.

10 ksi

9.0 ksi

8 ksi

7 ksi

6 ksi

5 ksi

Figure 12. Effect of Reduced Jet Cutting Pressure on Drilling Berea Sandstone at 40 in./min Advance Rate, 500 rpm with a Type 22 Nozzle.

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

Figure 13. Detail Showing Change in Hole Shape as a Borehole Pressure of 500 psi is Applied in Drilling Berea Sandstone (The Pressurized Sample is on the Right).

CHEMICAL ADDITIVES:

Previous investigation (Ref. 4) has shown that the addition of low concentrations of long chain polymers often give considerable benefit in improving high pressure jet structure. However, since not all the additives act in the same way, four different polymers were studied to determine their effect on jet cutting ability. The four studied have trade names Polyhall No. 654, Polyox, Nalco No. 524, and the Alfonic No. 1214-60 -- typical properties and availability are given in Table III.

The tests were carried out at a low polymer concentration, but nevertheless showed a consistent improvement in penetration rate over that achieved with plain water (Figures 14, 15). The effectiveness of the additives was seen to increase with back pressure, with no increase in cutting effectiveness where there was no back pressure. Of the four additives the Nalco and Polyox gave a greater improvement than the Polyhall, in turn better than the Alfonic (Table IV). The tests were, however, carried out with the small Kobe unit at the laboratory, and this proved difficult to operate at higher polymer concentrations. The Nalco chemical is a 30 percent polymer emulsion in oil and water, and is easier to put into solution as well as giving a marginally better performance. A test matrix to determine the effect of polymer concentration was therefore carried out with this chemical (Table V).

These tests were run with a different nozzle configuration to that previously used so that only a relative comparison of results within the test data can be made. Preliminary conclusions are that the addition of increasing concentrations of polymer do not improve the performance of the jet, however the small number of data points and the scatter in the data requires that further testing be carried out to confirm this result. At the 2000 ppm concentration pumping the chemical became a little difficult.

Table III. Additives Tested

Additive	Manufacturer	Composition	Molecular Weight	Intrinsic Viscosity deciliters/ gram	Comments
Polyox FRA	Union Carbide Co. P.O. Box 8004 S. Charleston, W.V. 25303	polyethylene oxide	7×10^6	9.5	-
Nalco 524	Nalco Chemcial Co. 6216 W. 66th Place Chicago, IL 60638	polyacrylamide	-	-	emulsion: one phase is polymer dispersed in oil which is dis- persed in water. Dissolves rapidly in contact with large amounts of water
Polyhall 654	Stein-Hall & Co. 605 3rd Ave. New York, NY 10016	polyacrylamide	$4-5 \times 10^6$	24.6	-
Alfonic 1214-60	Continental Oil Co. P.O. Box 727 Westlake, LA 70669	$C_{12}H_{25}(OCH_2CH_2)_6OH$	-	-	non-ionic surfactant

Figure 14. Chemical Additives, Confining Pressure and Borehole Pressure Effects on Hole Diameter in Berea Sandstone, 10,000 psi jet pressure, type 22 nozzle.

Figure 15. Effect of Increasing Borehole Pressure on Borehole Diameter Cut by a Jet Containing 100 ppm Polyox in Berea Sandstone, 10,000 psi Jet Pressure, Type 22 Nozzle. From the Left, 0, 500, 1000, 1500, 2000 psi Pressure.

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

Table V. 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> psi		<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

Field Drilling Rig

The test unit for jet drilling of in-place rock has been designed (Figure 16), the components to be built in-house have been fabricated, and delivery has been taken of the power unit for the drilling mast drive. The design consists of three major components: 1) the high pressure intensifier, 2) the hydraulic power unit, and 3) the converted drill mast. At present the high pressure intensifier is being used for in-house simulated drilling tests and will be transferred to the truck bed when tests are completed. The drill mast is a TR 4000 Simco drill mast that has the drill stem replaced with high pressure tubing. High pressure swivel couplings are used to allow rotation of the drill (Figure 17). The mast is complete and is installed on the trailer. The hydraulic power unit will be installed the week of July 5, 1976. It is anticipated that following proving tests, field trials will begin on August 1, 1976.

Scanning Electron Microscopy

The results of the test program to date have confirmed earlier conclusions (Ref. 5) that the uniaxial compressive strength of the rock is not an adequate measure of its cuttability by water jets. For example, at an advance rate of 15 in./min at 970 rpm at 25,000 psi a jet system cut a hole 1.06 in. in diameter in Missouri red granite, compressive strength 27,200 psi, but only 0.72 in. in diameter in Tennessee marble, compressive strength 17,100 psi.

Similarly the same jet system cut a cavity 2.35 in. in diameter in Berea sandstone, compressive strength 7,500 psi, while a diameter of 1.28 in. was cut in Indiana limestone, compressive strength 6,400 psi (Figure 18). However, both these rocks are anisotropic and the strength and cuttability are a function of the direction of drilling.

Figure 16. Design of Field Drilling Rig.

Figure 17. Plumbing Diagram of Field Drilling Rig.

Figure 18. 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.

In order to better understand the failure mechanisms of the jet a scanning electron microscope has been used to examine crater damage under droplet, continuous jet and cavitating jet impact. Target materials of aluminum, natural quartz, and Missouri granite have been used. The data is currently being analyzed and the results will be submitted with the next progress report.

Planned Program for the Second Year of the Contract

1. Two rocks (Indiana Limestone and Holston Limestone) will be tested in the modified triaxial test chamber to examine the effect of borehole pressure and confining pressure on drill rate at higher jet pressures. The nozzle geometry currently used on sandstone (Figure 5) will be used for this study, and the resulting hole diameter will be used as the measure of effectiveness. Based on current data from the sandstone trials, several other nozzle designs will be tested.
2. 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.
3. The field drilling rig will be completed and preliminary field tests to depths of 20 ft will be carried out to provide a data base and will also offer a proof of concept. Drilling will be conducted in Missouri Limestone, Missouri Dolomite, and Missouri Granite. The tests will be carried out at various drilling angles to determine if there are field controls on drilling performance.
4. Testing of the effects of cavitation on drilling rate. The study of cavitation enhancement of drilling will be carried further and will combine a small study of the best nozzle geometry for inducing cavitation with the drilling of three crystalline rocks: Holston limestone (a marble), Missouri granite, and Barre granite. A series of tests will be carried out on blocks of Holston limestone varying the ratio of probe to nozzle diameter to determine the optimum relationship. The benefit of cavitating

through one and both nozzles of the dual orifice nozzles will be studied; with the optimum geometry established, a comparative study at three feed rates and three jet pressures will be made on the drillability of the above three rocks. The diameter of the hole drilled will be used as the measure of performance.

5. The effect of cavitation as a long-term factor on drill head life. This forms part of the initial proposal and will consist of three 12-, 24-, and 36-hour runs of the equipment to determine any erosion problems on the cutting head. The effects will be measured by mass loss.
6. The benefit of adding a reaming bit to the nozzle. This program is also part of that initially proposed. A series of holes will be drilled in three stages: a) drilling the central access hole with the nozzle system already developed; b) slotting the hole side for reaming with a second jet; and c) breaking the slotted rock with a rotating cutter head. Stresses in the cutter will be monitored, and the relative specific energy required for the various stages of the process will be measured.
7. Design of a drilling system. Working with Dr. W.C. Maurer and faculty in the Petroleum Department at UMR, a design, based on the conceptual idea of a down-the-hole motor driving the cutting head and using the data obtained from the experiments, will be developed for construction in the third year of the program.
8. Field trials of the system. The nozzle geometries will be modeled at different sizes and pressures on a field rig. Results will be measured drilling in dolomite and granite. The problems of high pressure drilling to 200 ft will be determined, particularly the problems of the pipe couplings, maintenance of alignment and diameter with passage through rock of varying strength.

9. Theoretical analysis of data. Sufficient data will have been established to form the basis for establishing a predictive equation for water jet drilling. This study will begin in the second year and will be continued and developed in the third year of the project.

The program proposed for this contract term (Figure 19) is one and one-half months behind schedule. Late pump delivery has caused the slippage, but current forecasts are that the original schedule can be recovered.

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 C00-2677-1.
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 are being sent, under separate cover to ERDA.
4. A paper entitled "Environmental Effects on a Water Jet Drill" has been accepted for presentation at the 31st Annual Petroleum Mechanical Engineering Conference, ASME, in Mexico City, September 1976. This will be submitted to ERDA when printed.

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.

Figure 19. Revised Work Plan

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.

Acknowledgment

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. Jet cutting of rock samples was performed by Mr. A. Krause with the assistance of graduate students and undergraduate students. It is a pleasure to record our gratitude for this assistance.

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