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

Progress Report

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Introduction

This report covers the penultimate period of the second year of the research contract on water jet drilling of rock. The major accomplishment within this time frame has been the modification of the nozzle in order to achieve a drilling rate of 40" per minute in Missouri Red Granite. The major problems encountered have been a failure in the cavitation test rig, necessitating its return to the manufacturer and delays in obtaining the necessary equipment for the field drilling unit.

Laboratory Testing

Testing of the water jet nozzle design to determine drilling rate parameters has continued. The rock testing has mainly concentrated on the drilling in Missouri Red Granite (compressive strength approximately 30,000 psi). While demonstration testing for a granite company (Granite Division of Matthews Corporation) has shown that the Georgia Granites can be cut and drilled much more easily, the local rock was retained as the test material. A matrix of the test results is given in Table 1.

A drill head was obtained from Gruner-Williams which had been modified to accommodate the jet cutting nozzles. Test data were obtained in the laboratory using Indiana Limestone as a test material and data on the test results from the first set of runs is given in Table 2.

A paper describing part of the research program has been submitted to the 32nd Petroleum-Mechanical Engineering Conference of ASME and is herewith appended.

Cavitation Testing

The test unit was received and initial acceptance trials initiated. A fault in the equipment was detected and the unit returned to the manu-

facturer for investigative and remedial action.

Field Test Equipment

The field unit has been refurbished ready to go to the field and the receipt of the 200 ft of drilling steel is awaited. High pressure tubing and other necessary equipment have been obtained and the unit is otherwise ready for operation.

Table 1. Nozzle performance effects on drilling diameter in Missouri Red Granite. Pressure 15.5 ksi.

Nozzle Angle	Advance Rate (in/min)				Flow Rate (gpm)
	10	20	30	40	
	Hole Diameter (in)				
10°	1.1	.76 ⁷⁶	.65	-	9.16
15°	.78	.70 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			With assist				
	rpm			rpm				
	58	91	136	58	91	126	342	536
	Applied Load on Bit (lb)							
5.5	550 ⁵⁵⁰	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

HYDROMECHANICAL DRILLING OF HOLES LARGER
THAN ONE INCH IN DIAMETER

by

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Introduction

In conventional oilwell drilling, mud is used purely as a means of improving bit performance by the removal of the cuttings from the environment of the cutting action. In recent years this has changed and with the advent of the jet bit, a higher pressure mud delivery is used not only as a means of flushing the cuttings from the bit teeth but also as an assist in the cutting process itself. However, this improvement in jet cutting ability is generally restricted to very soft rock and the major penetrating mechanism remains due to the bit teeth on the roller cones. In the recent past, Maurer (Ref.1) has demonstrated that increasing the pressure of the jet still further and reorienting the jet nozzle location relative to the bit surface could result in an improvement in penetration rate by factors from 3 to 10. Further, in such instances, rock removal was primarily by water jet action with only subsidiary breakup being through the mechanical action of the bit itself. This result has led to considerable investigation in other facilities of the potential advantages of water jets. Among the leading investigators in this area are the personnel at the Shell Research Facility in the Netherlands, Holland (Ref. 2). Their research has examined not only the ability of water jets to drill softer rock but also has carried the investigation further in order to look at harder materials which are often found in the drilling of holes down to oil bearing horizons.

The University of Missouri-Rolla has been under contract to the Energy Research and Development Administration for 18 months to investigate the use of water jets in a suite of rocks ranging from the soft sandstone rocks originally drilled by Maurer to rocks of igneous origin, harder in strength than those investigated in Holland. During the first part of the research program which has been described in previous publications (Ref. 3 and 4)

work was described where holes were drilled mainly in sandstone. More recently the work has moved into harder rock materials up to the level of strength of Missouri Red Granite.

Drilling Rate Effects

It was decided to initiate the research program by testing nozzle geometries in Berea sandstone since this rock is extremely easy to cut using high pressure water. Therefore, any susceptibility to change in jet cutting parameters would very clearly be discerned in the jet performance rate. Tests were carried out on the effects of nozzle angle, nozzle geometry, jet pressure, confining pressure, and back pressure within the hole. The results of the tests showed that high pressure water jets were capable of drilling at advance rates up to 300 inches per minute (Fig. 1) in the Berea sandstone, when a dual orifice nozzle was used as the drilling device (Fig. 2).

The program investigating the parameter effects was not, however, carried out at such advance rates, since it was considered that the ultimate application of the technique will be in situations similar to that currently found on oilwell platforms. In such localities, the logistics of feeding equipment into the hole preclude an advance rate much in excess of 300 feet per hour (Ref. 5). In consequence, the experimental program has continued but examining penetration rates ranging from 2 to 60 inches per minute, since this is felt to be the range over which the jets will be applied in practice. At an advance rate of 40 inches per minute, the effect on cutting rate of downhole conditions has been evaluated and described in detail elsewhere (Ref. 4). The conclusions of the study were that after the first 500 to 1000 feet had been penetrated, in which zone there is a considerable effect due to back pressure and confining pressure, the effect of depth diminishes as the depth increases further. The studies have continued since that time

Figure 1. Hole Diameter for Two Nozzles and Two Rotation Speeds as a Function of Advance Rate.

Figure 2. Nozzle Design Used for Advance Rate Studies.
(Type 22 Nozzle).

Figure 3. The Effect of Incremental Distance on Hole Diameter for
a) sandstone drilled with a $22\frac{1}{2}^\circ$ nozzle at 10,000 psi
b) limestone drilled with a 30° nozzle at 20,000 psi

examining the effect of nozzle angle, rotational speed and advance rate on hole diameter and it has been concluded in similar manner to that of Pols (Ref. 2) that rotational speed has very little direct effect on jet drilling. The angle of the jet and the advance rate have, however, considerable effect in combination on how fast the head can be advanced and, in turn, influence the diameter at which the hole is drilled. This, in part, is caused by the presence of ridges on the side of the hole where successive passes of the jet do not overlap. These can interfere with the hole advance if the unit is not rotated fast enough as the advance rate increases. The advance rate or rotational speed therefore by itself is not the most accurate parameter to use. One should rather consider the advance per rotation of the drill bit. In earlier work, for example, Summers has found (Ref. 6) that as succeeding jet cuts approach the preceding cut the depth of cut increases (Table 1) and if this factor is included within the analysis of the data then a slightly different interpretation can be made (Fig. 3). The research on effect of nozzle geometry has been continued in Indiana limestone (Figs. 4 and 5) and the investigation has now turned to the examination of the drilling behavior in crystalline rock matter.

Crystalline Rock

In crystalline material, the behavior of the rock under jet attack is much different to that found for granular material. Where water jets cut in a granular material, individual particles are generally eroded from the mass by fluid wedging around the grains and the particle size of the product is therefore equivalent to the particle size of the mass itself. Conversely, where the water jet is drilling through crystalline rock, the failure mechanism is commonly by means of a crack growth phenomenon. The crack boundaries around the crystals do not always fall within the bounds of the jet impact

Table I. Averaged results from a factorial experiment showing the effect of incremental distance between adjacent jet traverses with a 0.023 inch diameter jet on the depth of slot cut in a) Berea sandstone, b) Indiana limestone.

Incremental Distance Between Successive Jet Passes over the Rock (0.001 inches)	Depth of Cut (inches)	
	(a)	(b)
20	1.51	.58
40	1.22	.43
80	0.89	.31
160	0.65	.20

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.

zone and the jet will in consequence seek to penetrate the rock by exploiting any weakness planes present within the individual crystal although where a crystal boundary does occur then this also will be exploited. However, the length of the crystal boundary or weakness plane under the jet is generally greater than that found in granular material and in consequence as the water penetrates the crack, a longer fluid wedge is generated and greater force can be applied to the rock structure. As a result, the fragments that are produced are generally larger and the crack growth is transcrystalline for crystalline rock whereas for the granular rock it generally is restricted to one grain since the pores in the rock form crack arrest locations. This factor in turn has caused a re-evaluation of the optimum nozzle design required to drill crystalline rock. The use of a small jet directed straight forward is of considerable advantage in drilling granular material, since the water directed forward penetrates into the mass and creates a pressure within the grains which the angled jet will remove. This advance jet does not have the same benefit in crystalline rock, where a single orifice jet of relatively equivalent mass flow to the dual jets used in granular rock drilling, inclined from the main direction of advance cuts much more effectively. At the time of writing, an advance rate the order of 150 feet per hour has been achieved at a jet pressure slightly in excess of 15,000 psi using a jet nozzle of diameter .056 inches in Missouri Red Granite.

In the drilling of harder rocks, two factors have become evident. One is that the water jets do not cut a smooth walled hole and this is particularly true as the jet goes through rock of different material. An extreme example (Fig. 6) can be seen where the jet encounters a change from a soft sandstone to a harder limestone. Since a good hole bore is a necessary prerequisite for the installation of casing, and is also a factor in easy

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.

retraction and advance of drilling bits, such a wide variation in hole diameter would be unacceptable in practice. The second consideration is that the holes which have been drilled to date have been of approximately only 1 inch or less in diameter. While such holes have application in the mining industry, particularly in the installation of roof bolts into the roof and walls of underground mines, their application outside this area is extremely limited. The smallest diameter that is drilled in oil and geothermal reserve exploitation is on the order of $4\frac{1}{2}$ inches and for the research to have practical results it is therefore important that the emphasis of the program be changed from drilling the small diameter holes at a very high rate to developing an equivalent drilling rate to that already achieved but at larger hole diameters. To this end the research emphasis at the University has changed and consideration is now given to the drilling of larger holes. In this situation, the use of water jets by themselves has a diminishing advantage. Water jets traditionally remove granular material on a grain by grain basis and crystalline material at somewhat larger particle sizes. The amount of energy that is therefore required to comminute the material is rather large and high horsepower are required to generate it. Concurrently, the zone of influence of an individual water jet is very limited (Fig. 7) even where the jet will cut quite deep slots. Figure 7 shows slots cut to depths up to 2 inches while leaving very narrow kerfs of material as narrow as three jet diameters between successive cuts. To remove such ribs by water jet action would be inefficient since it requires very little force (Ref. 7) to break these ribs away mechanically. The water jet design therefore for hole diameters in excess of 1 inch has been oriented to changing the mechanism of breakage from that of a purely water jet action to that of water jet action with combined roller cone bit cutting. In this regard, attention has been paid to work

Figure 7

Water jet sculpture in sandstone which was presented to BHRA by the Rock Mechanics and Explosives Research Center, Rolla, Missouri (the University of Missouri-Rolla), during the Second International Symposium on Jet Cutting Technology. Each face of the cube was cut in less than half a minute; the rock was rotated as the jet of water moved across it, producing the patterns on each face.

on cutting quartzite carried out in South Africa (Ref. 8). It has been shown in this study that the addition of a high pressure water jet to a drag bit can improve bit performance by a factor of 2 or more. Concurrently, it was felt that the development of the high speed drilling design already carried out and its benefit could be lost if this design was not incorporated within the new system. Pols (Ref. 2) for example, has found that where jets of equivalent pressure to that herein investigated were incorporated across the face of the bit that the advance rate improvement was insufficient to justify the use of high pressure jets and drilling. These considerations have led to the development of the drilling bit shown in Figure 8. In this bit design, the water jet bit which has given high advance rates is located in the center of the device. This jet system will drill ahead of the main bit at a diameter of approximately 1 inch at any speed which will be within the attainable range of the following mechanical system. Behind this advancing jet a drilling bit of conventional design will be located such that the teeth will ream the hole out to the required diameter. Such a system will guarantee that the hole walls are generally smooth and will remove the high pressure jet action from the walls of the opening where the effect of the jet, particularly in softer material, might otherwise cause the hole to be widened considerably beyond the diameter required. In order, however, to improve the cutting of the mechanical bits additional water jets are located around the nozzle assembly. The exact location of these bits is currently under study but the purpose of the jets is to wash the crushed material away from under the bit as it is created. This will, therefore, remove the plastic zone (Ref. 8) which creates so much problem in oilwell drilling and also solve the hold down problem (Ref. 9). Concurrently, as with the South African work, we anticipate an improvement in drilling rate of sufficient magnitude to justify the development of this design. Experiments are continued at the present time to justify this conclusion.

Fig. 8. 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).