Water Jet Drill R
DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.
THE DESIGN OF A WATER JET DRILL FOR DEVELPOMENT OF GEOTHERMAL RESOURCES

Final Report

by

David A. Summers
Terry F. Lehnhoff

Rock Mechanics & Explosives Research Center
University of Missouri-Rolla
Rolla, Missouri 65401

Prepared for:
Department of Energy

under contract:
DOE EY 76 S 02 2677.M003

September 1978

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness or any information, apparatus, product or process disclosed or represents that its use would not infringe privately owned rights.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>v</td>
</tr>
<tr>
<td>Chapter 1 - INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>Chapter 2 - RESEARCH PROGRAM</td>
<td>4</td>
</tr>
<tr>
<td>Introduction</td>
<td>4</td>
</tr>
<tr>
<td>Experimentation</td>
<td>4</td>
</tr>
<tr>
<td>Simulated Down Hole Drilling</td>
<td>10</td>
</tr>
<tr>
<td>Effect of Polymers</td>
<td>15</td>
</tr>
<tr>
<td>Nozzle Manufacture</td>
<td>19</td>
</tr>
<tr>
<td>Larger Hole Drilling</td>
<td>20</td>
</tr>
<tr>
<td>Field Testing Program</td>
<td>24</td>
</tr>
<tr>
<td>Underground Field Trials</td>
<td>28</td>
</tr>
<tr>
<td>Jet Pressure Considerations</td>
<td>31</td>
</tr>
<tr>
<td>Cavitation Testing</td>
<td>42</td>
</tr>
<tr>
<td>Chapter 3 - CONCLUDING REMARKS AND RECOMMENDATIONS</td>
<td>44</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>46</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>48</td>
</tr>
<tr>
<td>BIOGRAPHY - David A. Summers</td>
<td>50</td>
</tr>
<tr>
<td>LIST OF RELEVANT PUBLICATIONS</td>
<td>57</td>
</tr>
<tr>
<td>APPENDIX</td>
<td>58</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Fig. 1. Nozzle Design Used for Advance Rate Studies, (Type 22 Nozzle)................................. 6

Fig. 2. 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........ 9

Fig. 3. Effect of Increasing Borehole Pressure on Borehole Diameter Cut by a Jet Containing 100 rpm Polyox in Berea Sandstone, 10,000 psi Jet Pressure, Type 22 Nozzle. From the left, 0, 500, 1000, 1500, 2000 psi Pressure.............. 14

Fig. 4. Chemical Additives, Confining Pressure and Borehole Pressure Effects on Hole Diameter in Berea Sandstone, 10,000 psi Jet Pressure, Type 22 Nozzle.......................... 18

Fig. 5. Water Jet Drill Holes through a) a "hard-soft" Rock Interface, b) a "soft-hard" interface, c) a rock with thin, hard inclusions........... 21

Fig. 6. 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.......................... 23

Fig. 7. Hole Drilled in Destressed Ground. The Hole Diameter is Approximately 2 in. (5 cm)......... 32

Fig. 8. Hole Drilled in Stressed Ground. The Oval Hole Measures Approximately 1 1/2 in. (3.75 cm) Across the Horizontal Diameter........ 33

Fig. 9. Hole Diameter for Two Nozzles and Two Rotation Speeds as a Function of Advance Rate............ 34

Fig. 10. Relative Erosive Capability of Jets at Various Pressures, as a Function of Standoff Distance..... 36

Fig. 11. Relative Erosive Capability of Jets at Various Pressures, as a Function of Standoff Distance. 37

Fig. 12. Relative Erosive Capability of Jets at Various Pressures, as a Function of Standoff Distance. 37

Fig. 13. Red Granite Sample Sectioned after Impact by an Abrasive-Laden Jet. (Magnification 6x).... 39
Fig. 14. Red Granite Sample Sectioned after Impact by a Cavitating Jet. (Magnification 6x) 39

Fig. 15. Relative Erosion Capacity of Jets as a Function of Pressure at 15 cm Standoff 40
LIST OF TABLES

Table 1. 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. 11

Table 2. Additives Tested .......................... 17

Table 3. Load Required to Drive a 3-7/8 in. bit through Rock with, and without, Jet assistance. Load Values are in lbs ........... 25
ABSTRACT

Water jet drilling of rock is shown to be a feasible method for potential improvement in gaining access to the earth's resources. Drilling rates of up to 280 in./min in sandstone and 40 in./min in granite have been achieved. While the addition of polymers to the jet stream is found advantageous the low (15%) level of improvement and the difficulty in maintaining concentrate negated further development. The application of confining pressure was found to reduce jet performance, but this was found to be a function more of the rock response than of the jet parameters. Field tests of water jets underground indicated the jet system could be modified to cope with this change.

Water jets were found to be more effective, for drilling larger holes, where a combined water jet:roller bit system was developed and laboratory and field trials of this are described.

As well as determining the controlling parameters affecting jet drilling performance, and proving that rock compressive strength is not one of them, the research examined other methods of improving jet cutting performance. At jet pressures below 10,000 psi abrasive laden jets were found most advantageous while, for drilling granite, a cavitating flow proved more effective at pressures above 10,000 psi. A reason for this is postulated. Experiments to develop a standardized cavitation resistance test for rock specimens have also been undertaken.
Chapter 1
INTRODUCTION

This report describes work carried out over a three-year period at the Rock Mechanics and Explosives Research Center of the University of Missouri-Rolla under a contract from the Geothermal Division of the Energy Research and Development Administration (now incorporated in the Department of Energy). The research program was directed at evaluating the potential benefits which might accrue through the use of high pressure water jets as a means of drilling rock to gain access to the geothermal resource.

It is germane to begin by briefly discussing what is meant by high pressure water jets, since these will be referred to without qualification from this point.

High pressure water jets now exist in industrial applications in three pressure domains. In the first of these, water jets at pressures generally below 2,000 psi are used for the large volume removal of material and for the underground mining of coal at flow rates on the order of several hundred gallons per minute. At the other extreme, water jets at flow rates of approximately one gallon per minute but at pressures ranging from approximately 45,000 to 100,000 psi are used in the industrial cutting of material, such as for example, paper products. The third domain, and that which will be addressed in this report, occurs where water jets are operated in the range from 10,000 to 30,000 psi at flow rates from 10 to 25 gallons a minute. Industrially, equipment is already available which operates at these pressures, mainly
for cleaning purposes, and this has meant that the equipment is becoming available as off-the-shelf items, capable of being operated by workmen without a great deal of training. These water jets have been shown capable of drilling through many rocks and are generally operated at nozzle diameters of approximately .03 to .05 inches. This diameter range is predicated on the fact that below diameters of perhaps .020 of an inch, the nozzle becomes susceptible to blockage of the fluid flow, and is insufficient to attain the required pressure levels due to insufficient flow at nozzle diameters above .05 inches. The horsepower requirements for this type of system are on the order of 150 hp.

The ability of water jets to cut rock had previously been proven. It was the purpose of this contract, in part, to evaluate the practical viability of using water jets to drill through such rocks as are typically found within the environs of a geothermal deposit. The program looked not only at the use of water jets alone, but also considered some of the mechanisms for potential improvement in the jet cutting performance which had been proposed by other investigators. The contract research examined the application of water jets, not only in the surface cutting of rock, but also examined what effects and changes in performance were likely to occur where the cutting took place within the confines of a borehole at depth, where the confining stress on the rock and the back pressure on the water jets would reduce the effective cutting performance.
In the initial premise upon which the program was founded it was proposed that water jets alone would provide the mechanism by which the rock would be penetrated. It was one finding of this program that such a system would not be economically advantageous and that a better method of rock penetration would be achieved were water jets to be combined with pre-existing mechanical rock cutting equipment, specifically, the tricone bits of a conventional rock drill.

Much of the research which was carried out during the course of this program has previously been described in the progress reports which have been submitted as a part of this contract. Concurrently, the research findings which have been developed have been released to the general public through the publication of papers presented at learned societies during the course of the last three years. Several of these papers have been incorporated as parts of progress reports previously submitted. Both these papers and the previous progress reports will be referenced as a part of this Final Report; however, it is not our intention to repeat in detail the work previously described. Papers which have not previously been submitted as part of progress reports will be attached as an appendix to this report, and again, the work described therein will only be summarized within the context of this document.
Chapter 2
RESEARCH PROGRAM

Introduction

As an initial objective of the program it was necessary to show that high pressure, small diameter water jets could cut through rock at an adequate advance rate. Conventional drilling technologies already exist which drill at significant performance levels, and for water jets to become a method with widespread application in the future it would be necessary as part of the contract to demonstrate that drilling speeds equivalent to, or in excess of, those already achievable with conventional equipment, were available through the use of high pressure water jets. Concurrently, it was necessary to do the basic research to find out what type of nozzle configuration would be most advantageous for drilling through rock and to obtain performance figures for this configuration. This, then, was the major thrust of the initial program and this development has been described in progress reports (Refs. 1 and 2) and papers (Refs. 3, 4, and 5) previously submitted.

Experimentation

To evaluate the practicality of using water jets as a means of drilling and to provide a relatively easy method of determining the effects of changing jet parameters on the drilling rate, a relatively soft sandstone, Berea sandstone, was chosen as the target material. This rock is readily cut by water jets and has provided one member of the suite of rocks generally considered as the standard rocks for testing in the United States, and as such has been identified by the Bureau of Mines (Ref. 6).
A series of tests were carried out in this rock (Ref. 2) and identified one particular nozzle (Fig. 1) as that most suitable for drilling through this type of sedimentary rock. Advance rates in excess of 280 in./min were achieved at the end of the program of nozzle evaluation using this nozzle. This speed did not comprise a limit to the potential performance of the drilling system; however, it was felt that this level of achievement sufficiently indicated the practical application of water jets for drilling and attempts to increase the drilling speed beyond this level were not made.

Research carried out in granite in a subsequent program indicated that a different nozzle design was more advantageous in the crystalline rock of which granite is a member, the reason for this most likely being that there is a difference in the rock structure and therefore in the way the materials fail under water jet attack. Granular rock is eroded on a particle by particle basis by the water jet impact and removal is localized under the impact point. Maximum erosion is achieved with a minimum of jet nozzles, so that flow rate can be increased through those used. However, in granular rock, a single inclined nozzle would be cutting rock from the central core out to the final radius. This would rapidly destroy the cutting jet and reduce the effective jet cutting distance. It was found advantageous, therefore, to direct part of the flow forward through a second, smaller orifice, to cut preliminary clearance for the head and the jet inclined at the side. This will remove part of the rock to be cut by that jet and thus
Figure 1. Nozzle Design Used for Advance Rate Studies. (Type 22 Nozzle).
markedly increase the jet cutting distance, in turn increasing the hole diameter and the potential advance rate. This design has since been patented (Ref. 7).

Granite fails under a different failure mode. Because of the intergrowth of crystals within the rock structure, particles are removed on a transcrystalline basis and rock fracture can extend quite considerably beyond the impact point of the jets. For this reason it is not as advantageous for the jet flow to be divided into a main cutting jet and the small clearance jet which comprised a sedimentary cutting nozzle. Rather, it was found sufficient to concentrate all the jet energy into a single inclined cutting jet, the growth of cracks from the impact point of this jet being sufficient to cut across the central core which would otherwise be left, removing it and making advance of the nozzle practical at advance rates up to 40 in./min at a jet cutting pressure of between 15 and 16,000 psi (Ref.12).

One point should be made in evaluating this test data based on data from tests more recently carried out under the program funding. The nozzles which were used during the course of the preliminary evaluation of nozzle performance were made of brass and were machined with as great a degree of care as could be achieved by technical staff of the Rock Mechanics and Explosives Research Center. The subsequent research, which is described in a paper attached as an appendix to this report (Ref. 8) has indicated a much greater susceptibility of the cutting jets to nozzle internal surface finish than was considered the case at the time that this experimentation was
carried out. Thus, while the results which are herein re-
ported indicate a level of performance and a basic comparison
of nozzle cutting ability, the ultimate reliability of the re-
sults must, regrettably, be questioned. This should not be
taken to mean that the rates of advance so far achieved are
not repeatable or are limiting, but rather that these indicate
a level potentially much lower than that which can be achieved
were optimum nozzle construction techniques to be achieved.
However, the expense involved in manufacturing nozzles to the
quality level which has now been found necessary (individual
nozzles currently cost $500 each) would preclude a study of the
order of magnitude of that earlier undertaken. This study,
however, must be evaluated with this new caveat borne in mind.

Because of the different cutting mechanism and operating
geometry of a water jet system relative to that of the pre-
existing mechanical drilling systems, a new parameter has been
introduced as a controlling parameter in the drilling of material
by water jets. This parameter is identified as the "incremental
distance" and it is defined as that distance which the nozzle
moves forward for each revolution of the head. This parameter
plays a much greater role in water jet drilling than is the
case with other systems because the cutting action takes place
through only one or two cutting jets which have cut along a line,
so that not all the rock within the borehole is necessarily ex-
cavated by the jet itself. Thus in the advance of the jet a
rib of material may be left between adjacent passes of the jet
across the rock's surface (Fig. 2). This rib of rock can, if
the incremental distance is large enough, be sufficient to
Fig. 2. 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.
protrude into the path of the advancing nozzle and block its progress. On the other hand, where the incremental distance is relatively small, the jet will be cutting very close to the previous pass and this may advantageously affect the cutting depth which is achieved. The effect of this has also been described in a previous paper (Ref. 9) from which the table (Table 1) given below is taken. The effect of this incremental distance is such that in order to achieve high penetration rates high rotational speeds are also required. For example, in the field research program, it was found that an incremental distance of approximately 1/4 in. was the maximum which could be left before progress of the drill forward was impeded by the ribs of material left. This, therefore, suggests a rotational speed of approximately four times the advance rate of the drill in inches be the minimum for a system to drill that particular rock. This distance, however, is a characteristic of the rock which is being drilled. In other rocks another incremental distance may prove optimum and may change this interrelationship.

Simulated Down Hole Drilling

When water jets cut rock at the surface, the jet meets relatively little resistance from the nozzle to the rock, and the velocity of the fluid flow from the nozzle is directly relatable to the driving pressure from the supply pump. Once the jet impacts on the rock it will cut forward, in part, by exploiting any weakness planes, cracks, and microfissures which exist within the rock structure. The jet fluid will penetrate these flaws and will become pressurized by the impact of subsequent
Table 1. Averaged results from a factorial experiment showing the effect of incremental distance between adjacent jet traverses with a 0.033 inch diameter jet on the depth of slot cut in a) Berea sandstone, b) Indiana limestone.

<table>
<thead>
<tr>
<th>Incremental Distance Between Successive Jet Passes over the Rock (0.001 inches)</th>
<th>Depth of Cut (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>(a)</td>
</tr>
<tr>
<td>1.51</td>
<td>.58</td>
</tr>
<tr>
<td>40</td>
<td>1.22</td>
</tr>
<tr>
<td>80</td>
<td>0.89</td>
</tr>
<tr>
<td>160</td>
<td>0.65</td>
</tr>
</tbody>
</table>
water flow, thus creating a fluid wedge to cause the flaw to grow, leading to the failure of a part of the rock structure.

Where the drilling operation, however, takes place in a borehole, sunk to some depth within the earth's crust, then the conditions are considerably changed. For example, to an approximate rule of thumb, the pressure in a borehole, due to the weight of superincumbent liquid within the borehole, will increase at approximately half a psi per foot of depth, while the pressure on the surrounding rock, due to the superincumbent strata between that point and the earth's surface, will increase at approximately one psi per foot of depth.

The effects of these two pressures will be to reduce the effective penetration ability of the water jet, in two ways. Firstly, the fluid pressure generated in the borehole will reduce the pressure drop across the nozzle, thus reducing the velocity at which the jet emerges from the nozzle, and further, this pressure will cause a more rapid ablation of the jet by the surrounding fluid, now water instead of air, once it has left the nozzle. The second effect is on the rock. The rock pressure applied will close many of the microfissures and cracks within the structure, making it more difficult for the fluid to penetrate these and create the fluid wedges necessary for the destruction of the rock mass.

It was considered important that the effect of such changes in the drilling environment be investigated at an early stage in this contract. Although previous researchers in the oil industry had drilled at considerable depths with success, using
water jets, nevertheless the jet diameters proposed for this research are much smaller than those previously used and therefore appear much more susceptible to the effects of increasing depth. In order to simulate the effect of such depths, tests were carried out in a modified triaxial chamber which allowed simulation of the effects of drilling at depths of up to 6,000 feet. These tests have been described in detail elsewhere (Ref. 2) and the results will, therefore, be only briefly summarized in this presentation.

The experiments were initially carried out in Berea sandstone and it was found that beyond an initial relatively strong effect when confining pressure was applied there was little change in jet cutting ability as this pressure was increased (Fig. 3). It was conjectured that a large portion of this change may be due to the change in the differential pressure across the nozzle and for this reason tests were carried out at reducing jet pressures to determine if this were the case. The results showed that this was not the primary factor causing the change in the cuttability of the rock. It was concluded therefore that an important factor was the change in the rock response as described above, in that the flaws in the sandstone were being closed by the increase in rock pressure. This conclusion was, to a degree, verified in later research carried on the jet cutting of granite. It was determined that with the increase in pressure a much smaller change in the rock drilling rate was obtained.

The results showed qualitatively that with an increase in pressure of 500 psi on the sandstone, a reduction in diameter of approximately 50 percent was achieved, both when this pressure was applied to the rock and when it was applied as a back
Fig. 3. 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.
pressure in the bore. Where the pressure drop was reduced across the nozzle, such a change in hole diameter required a pressure drop in the jet supply pressure of some 5000 psi. However, when a 500 psi pressure drop was applied across a granite sample, then the decrease in hole diameter was only approximately 12 percent from one inch to .82 inches (Ref. 10). One can thus deduce the above observation, that the change in hole diameter, with change in pressure on the system, is due to a change in the physical response of the rock rather than the change in the jet cutting characteristics, per se.

It was noted in testing the granite samples that some difficulty arose in running the tests, because, whereas in the granular rock the material is eroded on a particle by particle basis, in the crystalline granite the particles removed are formed across transcrystalline boundaries and therefore can be much larger. In this case fragments up to half an inch in size were created. These were too large to get through the screens which were set up in the test chamber to provide the necessary confining pressure on the chamber. This result does, however, also substantiate the conclusion reached above.

Effect of Polymers

As a part of the evaluation of the effects of borehole conditions on water jet drilling, an investigation was also made, in a preliminary manner, of the benefits which may accrue by adding long chain polymers to the jet fluid. These polymers are conventionally used in certain oil field applications for maintaining the well bore when drilling through weak shales susceptible to water damage. The polymers also have the advantage
of increasing the cohesive length of water jets in industrial applications such as fire fighting and have been shown in other research (Ref. 11) to improve jet cutting ability. A series of polymers were tested (Table 2). Although some increase in diameter was obtained (Fig. 4), the relatively small increase in advantage was not felt to be sufficient to warrant any further investigation during the course of this particular program.

The reason for this was that the polymeric additives have an aging characteristic and also must be mixed up in an accurate concentration for the same result to be achieved on repeated tests. The way that the water jet laboratory is set up involves recycling some of the fluid which has passed through the pump to the 200 gallon supply reservoir. There would be a problem in maintaining an adequate supply of polymeric fluid under the same age for each test and the test runs would be limited by the fluid available. Additionally, when the polymeric additives pass through the pump, the shearing action of the pumping motion tends to destroy the polymeric bonds. This is particularly true in multiple pass situations where fluid is recycled more than once and therefore repetitive test data could not be guaranteed. This, in turn, would mean that an uncontrollable variable would be imposed on top of the other test results and may, therefore, shield other significant effects. For this reason, it was decided that under this program polymeric additives would not be used in the drilling fluid, although it is accepted that some advantage could be achieved through their use.

A further reason for this decision was that the polymeric additive generally improves jet cutting ability more markedly
Table 2. Additives Tested

<table>
<thead>
<tr>
<th>Additive</th>
<th>Manufacturer</th>
<th>Composition</th>
<th>Molecular Weight</th>
<th>Intrinsic Viscosity deciliters/gram</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyox FRA</td>
<td>Union Carbide Co. P.O. Box 8004 S. Charleston, W.V. 25303</td>
<td>polyethylene oxide</td>
<td>$7 \times 10^6$</td>
<td>9.5</td>
<td>-</td>
</tr>
<tr>
<td>Nalco 524</td>
<td>Nalco Chemical Co. 6216 W. 66th Place Chicago, IL 60638</td>
<td>polyacrylamide</td>
<td>-</td>
<td>-</td>
<td>emulsion: one phase is polymer dispersed in oil which is dispersed in water. Dissolves rapidly in contact with large amounts of water</td>
</tr>
<tr>
<td>Polyhall 654</td>
<td>Stein-Hall &amp; Co. 605 3rd Ave. New York, NY 10016</td>
<td>polyacrylamide</td>
<td>$4-5 \times 10^6$</td>
<td>24.6</td>
<td>-</td>
</tr>
<tr>
<td>Alfonic 1214-60</td>
<td>Continental Oil Co. P.O. Box 727 Westlake, LA 70669</td>
<td>$C_{12}H_{25}(OCH_2CH_2)_6OH$</td>
<td>-</td>
<td>-</td>
<td>non-ionic surfactant</td>
</tr>
</tbody>
</table>
Advance rate = 40 in/min

Figure 4. Chemical Additives, Confining Pressure and Borehole Pressure Effects on Hole Diameter in Berea Sandstone, 10,000 psi jet pressure, type 22 nozzle.
with distance from the jet nozzle, and very significant improvements occur at distances greater than approximately 2 inches (Ref. 11). However, in this particular application, where the water jets generally cut less than two inches from the drilling nozzle, then the advantage of the polymeric additive is diminished.

Nozzle Manufacture

The research carried out during this contract led to the submission of an ultimate award of a patent on the nozzle design which had been found most successful in drilling sandstone. However, when pressures above those required for drilling such relatively soft rock were developed, it was found that the use of brass as a nozzle material was no longer satisfactory, due to the very short lifetime of the brass at pressures above 10,000 psi. For this reason, some development work was carried out manufacturing nozzles from other metals. Previous research at UMR had looked at the potential benefits to be achieved by using a titanium alloy for a nozzle material. The likelihood of several different nozzle designs being required in the course of an investigative program precluded the use of such materials insofar as their machinability was much more difficult than is the case for the brass. It was discovered, however, that if a relatively thin coating (approximately .002 of an inch) of nickel were plated on the brass nozzles, then this would be sufficient to protect the underlying softer material and give an extended nozzle life. When this procedure was first adopted, a high degree of precision and care was taken by the electroplating company and good results were obtained from the program. However, as the plating of these nozzles has become commonplace...
and a routine operation, the quality of workmanship required for this type of equipment has not been maintained.

**Larger Hole Drilling**

In the course of the research carried out in the cutting of sandstone it had been demonstrated that only the rock immediately underneath the jet pass would be removed by water jet cutting action and therefore, in order to remove a full face of rock in front of the drilling bit, the jet must sweep this entire area. However, it had also been demonstrated that the water jets will cut quite deep kerfs in the rock surface as they traverse across it, and that the intervening ridge left between these adjacent kerfs is sufficiently weak that only very small forces are required to remove this material. This ridge of rock will fail in tension or shear under cantilever loading in such circumstances, rather than under the conventional failure under a tricone bit where a significant portion of the rock is failed under triaxial compression in the crushing of the rock under the tooth. This result suggested that it would be advantageous to develop a combined water jet-mechanical bit for drilling holes larger than one inch in dimension.

A study of the effect of rock properties on water jet drilling rate reinforced the conclusion on the benefits of combining jet and mechanical cutting, while indicating the irrelevance of rock compressive strength as a parameter in determining a rock response to water jet attack (Ref. 2). Where two rocks of approximately equivalent compressive strength, Berea sandstone and Indiana limestone, are cemented together and the water jet drills through them (Fig. 5) there is a marked
Fig. 5. Water jet drill holes through a) a "hard-soft" rock interface, b) a "soft-hard" interface, c) a rock with thin, hard inclusions.
change in the hole diameter cut by a water jet. Some variation in this diameter can be eliminated by making the water jet drill operate on a thrust sensitive mode rather than at a constant drilling rate. This control, however, as well as being difficult to manage in deep hole drilling operations, is unlikely to be sufficiently sensitive to totally remove the initial variation in hole diameter which will occur where such a rock interface is penetrated. Since wide variations in hole diameter can lead to obstruction of the bit upon its withdrawal from the hole, it is not advantageous that such variations occur. These diameter variations can have other unforeseeable effects, and it is therefore better that the hole diameter be assured by a mechanical device.

Subsequent research efforts have been directed toward a combination of a water jet drilling system in cooperation with a tricone drilling bit. In this regard the University effort has been very generously assisted by the Grüner-Williams Division of Smith International who have supplied the tricone and quadracone bits used in this program at no cost to the University. The premise upon which this new drill was developed (Fig. 6) has been described in detail in earlier publications (Refs. 12, 13 and 14).

Within the new concept of the drilling of the design, two factors were combined. Firstly, the high drilling rates achievable with a conventional water jet nozzle indicated that this could be anticipated to drill much faster than the conventional drill under normal operating conditions. Therefore, a
Fig. 6. 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).
water jet assembly could excavate ahead of the main body of the drill, creating a cavity in advance of the bit. A water jet nozzle could be located in this hole and direct jets outward underneath the point of impact of the roller cones. This would have a dual effect - it would improve the cleaning ability of the fluid flow under the bits, and would also precut the rock ahead of the bits and weaken it so that bit action would be enhanced. A laboratory test program was designed (Table 3) and the test results (Ref. 15) indicate improvements in performance levels of approximately 25 percent could be achieved where the water jets were added to the bit. The program thereafter was moved out into the field for testing on a larger scale.

Field Testing Program

The University developed, during the course of this contract, equipment to carry out field drilling trials. This was initially built around a 40 ft trailer with haulage unit, upon which were mounted a 250 kw generator, two large water tank reservoirs, and a drilling frame supplied by SIMCO (Southern Iowa Manufacturing Company). The rig was used during the first year to satisfactorily drill holes of one inch diameter at rates of up to 3 ft/min in limestone and dolomite up to 30,000 psi compressive strength. During the second year of the contract the rig was modified to take a 3-1/2 inch diameter drilling bit, which could be operated with or without high pressure water jets.

In order to run the equipment satisfactorily, it was found necessary to add a compressed air supply to the drilling system. While 25 gal/min is adequate to clean the hole when drilling horizontal holes, it did not prove adequate in this particular
Table 3. Load required to drive a 3-7/8" bit through rock with, and without, jet assistance.

Load values are in lbs.

<table>
<thead>
<tr>
<th>Feed Rate (in./rev.)</th>
<th>RPM</th>
<th>Dry</th>
<th>RPM</th>
<th>With Jets</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>36</td>
<td>58</td>
<td>91</td>
</tr>
<tr>
<td><strong>Limestone</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.5</td>
<td>---</td>
<td>550</td>
<td>600</td>
<td>650</td>
</tr>
<tr>
<td>11</td>
<td>1175</td>
<td>1025</td>
<td>1100</td>
<td>850</td>
</tr>
<tr>
<td>17</td>
<td>1400</td>
<td>1250</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td><strong>Dolomite</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.5</td>
<td>2500</td>
<td>2000</td>
<td>2500</td>
<td>---</td>
</tr>
<tr>
<td>11</td>
<td>3100</td>
<td>2650</td>
<td>3100</td>
<td>---</td>
</tr>
<tr>
<td>17</td>
<td>3200</td>
<td>2900</td>
<td>3400</td>
<td>---</td>
</tr>
<tr>
<td><strong>Marble</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.5</td>
<td>1000</td>
<td>1550</td>
<td>1670</td>
<td>1970</td>
</tr>
<tr>
<td>11</td>
<td>2500</td>
<td>2400</td>
<td>2600</td>
<td>---</td>
</tr>
<tr>
<td>17</td>
<td>2700</td>
<td>3200</td>
<td>3200</td>
<td>---</td>
</tr>
</tbody>
</table>
operation to satisfactorily clear the hole and for this reason a 375 CFM air compressor was obtained to supply air to the bit and blow the water and debris out. This it proved capable of doing and trials were carried out in local rock adjacent to the University property.

During the course of the development of this equipment for these field trials, several problems became evident (almost all of which have now been corrected) which have in large measure, been generated by the use of drilling equipment for a new purpose. For example, the need to supply a high pressure water jet flow down through the center of conventional tubing at the same time as air is fed to the bit has restricted the flow of both fluids in the vicinity of the nozzle. A special adaptor was also required for the swivel through which air is supplied to the drill pipe. Unfortunately, since this part was specially designed for this purpose, its recent failure has slowed completion of the program.

One factor which may not have sufficiently been considered in other applications of high pressure cutting, and which was not in the earlier work carried out on this contract, is the considerable friction loss incurred in driving fluid through the very high pressure couplings and high pressure tubing used in plumbing from the primary supply pump to the water jet nozzles. Thus, for example, in one early test rig the pump was operating at 22,000 psi and drilling in dolomite. However, the flow from the pump to the nozzle passed through three high pressure rotary couplings and approximately 40 ft of high pressure 3/16 I.D. piping. This combination in hindsight leads
to a pressure drop prediction of something in the order of 12,000 psi, so that while 22,000 psi was being generated at the pump, only approximately 10,000 psi was available at the nozzle and while this was sufficient to penetrate the dolomite it was not sufficient to generate a satisfactory drilling rate.

In passing it may be mentioned that at the end of this contract, where the connection between the pump and the drilling rod was made with 1/2 in. I.D. high pressure hose, thus negating the need for two of the rotary couplings and 30 ft of tubing, it proved possible to drill the dolomite much more effectively with a registered pump pressure of 15,000 psi. The flow was still passing through one of the rotary couplings (across which testing would seem to indicate a pressure loss of between 1500 to 2000 psi at this operational pressure).

The field drilling program also ran into some problems in the preliminary application of the drilling bit in the area around Rolla, in softer formations such as the Roubideaux sandstone which is predominant in parts of the surrounding environs, it was found that the water jet drill would adequately cut a hole ahead of the main body of the bit. As the jet came down onto a hard inclusion such as a dolomite stringer or on occasion, a piece of chert, then the water jet was no longer capable of drilling at a sufficiently high advance rate to maintain a hole ahead of the main body of the bit which was still penetrating through the sandstone. In such a case the full load on the bit was transferred from the quadracones to the drilling nozzle and in the initial design this was sufficient
to wear the bit away very rapidly. A protective collar was developed for the nozzle body to overcome this problem and has worked satisfactorily. The collar was provided by adapting a one-inch diamond coring bit to fit around the edge of the nozzle to cut clearance for the nozzle body where this encountered a particularly difficult strata of rock to penetrate.

One other problem which has been discovered in the Rolla area is that the dolomite formations are karstic in nature, having cavities within their structure. The water jet system is no better able to penetrate through this type of structure than a conventional drill, and problems have been experienced in adequately cleaning the hole where such a formation was penetrated. In one instance at a depth of some 70 ft one of the drill bodies was lost in this type of operation.

The field test program, as has been mentioned above, has been delayed by several major equipment component failures and slow deliveries of parts. This, unfortunately, continued right through the program and the field program could not be satisfactorily concluded due to the premature failure of the part carrying the swivel supplying compressed air to the drilled steel.

Underground Field Trials

Water jet drilling was not a novel idea originated at the start of this contract. Field programs had been previously carried out by Shell, Exxon and Gulf research divisions, of which the most successful was Gulf, who had been able to achieve a drilling depth of 14,800 ft and that of Shell who have recently proved able to put high pressure water jets on a drilling bit
and drill holes less expensively than without the high pressure bit addition.

In one of the reports of the progress of this research, Exxon investigators indicated that at a depth of 6000 ft the water jets no longer became capable of improving the drilling rate on a conventional bit. This finding was of some concern and it was discovered at the same time as the principal investigator on the contract was discussing the contract with the research director of St. Joe Lead Company. Accordingly, an agreement was made between St. Joe and the University of Missouri-Rolla in which the mining company would provide access to and personnel to assist with research in one of the lead mines in Missouri. This research, which has been documented in two recent papers (Refs. 16 and 17) took place at the Indian Creek Mine of St. Joe in the winter of 1977-78.

One reason for undertaking the program at that time was that conventional field drilling operations were restricted due to surface weather conditions. It was hoped that, were the operations to be transferred to a mine, it would be possible to continue drilling while the weather on the surface was hostile. Unfortunately, it was not anticipated that the surface conditions would become so bad as they were in the winter 1977-78 that travel from the University to the mine became extremely difficult and on several days it was impractical to get to the mine site because of this inclement weather.

The objective in the mine was two-fold. Firstly, to determine the effect of stress on rock upon water jet performance. It was noted that in a mining situation there would be quite
a large variation in stress as one drilled into a support pillar in the mine and it should prove possible to get stress levels of over 4,000 psi in the rock. This would occur where the hole was located in a pillar, some 1,000 ft underground, in an area pockmarked with previous drilling tests. A secondary feature of the program was to demonstrate to the St. Joe Lead personnel and to others, that water jets could successfully operate in a mining environment, with performance levels up to that of existing mining equipment, and with the environmental advantage of being quieter than existing drilling systems.

A modified Gardner-Denver drilling jumbo was used as the support for the drill used in this program. One defined objective was to determine if water jets alone could drill 2 in. diameter holes for blast hole purposes horizontally into a pillar. It was found possible to control the advance rate of the head quite successfully to achieve this diameter, by incorporating a thrust-sensitive drill mechanism into the hydraulic line, controlling the hydraulic motor which advanced the drill. However, a relatively sophisticated design was required for this piece of equipment and the high degree of abrasion which the part received, due to the flow of sandstone-laden water across it, at the cutting surface, led to the removal of this device shortly after its success had been demonstrated, because of its very short life. Nevertheless, the practicality of this type of system has been demonstrated, and it is believed that Flow Industries, who have used the water jet drilling design described earlier, on a contract for a roof bolting machine developed under a Bureau of Mines contract, have used a similar thrust-sensitive system in their
equipment, developed, however, along their own line of approach.

The program at St. Joe did indicate that there was a change in the shape of the holes drilled under stress. The shape varied from a circular shape, under no stress, to an oval shape where stress was present on the rock, and also that the drilling rate was affected by the stress on the rock (Figs. 7 and 8). This was seen indirectly in that where the rock was destressed the hole was larger than the case where the rock was stressed and since it has been shown earlier (Fig. 9) that hole diameter and drilling rate are interdependent, then it can be seen that there is quite a marked effect on drilling rate of ground stress. Nevertheless, the water jet was capable of drilling the rock in a satisfactory manner and this, taken together with discussions which have been held with among others, Maurer Engineering, would serve to indicate that there will be no problem in drilling to the required depths using high pressure water jets, from the aspect of the cutting of the rock. A short film, "Water Jet Drilling in Lab and Field" was prepared during this experimentation and copies have previously been submitted.

Jet Pressure Considerations

Although it has been shown in the research that has been carried out under this contract that water jets can satisfactorily drill all rock material which have been tested in this program, nevertheless, the pressures required to adequately drill some rocks are greater than those which can, at the present time, be satisfactorily generated on the rig floor.
Fig. 7. Hole drilled in destressed ground. The hole diameter is approximately 2 in. (5 cm).
Fig. 8. Hole drilled in stressed ground. The oval hole measures approximately 1\(\frac{1}{2}\) in. (3.75 cm) across the horizontal diameter.
Figure 9. Hole Diameter for Two Nozzles and Two Rotation Speeds as a Function of Advance Rate.
Equipment also to operate at these pressures is not always available outside the research laboratory. The previous research carried out by Exxon, Shell, and Gulf does indicate, however, that it is possible to drill in the field at pressures up to 15,000 psi and recent developments in the high pressure cleaning industry have made equipment capable of operating at 10,000 psi relatively commonplace. If, therefore, means can be developed whereby the effective cutting rates which have been achieved at high pressures can be obtained with a lower jet pressure then the advent of water jets into the drilling industry will be more rapid.

Two major efforts were undertaken during the course of the research program and form the basis for two graduate theses, one at the Ph.D. level and one at the Master's level (Refs. 16 and 17). The major finding of the Ph.D. thesis has been reported elsewhere (Refs. 18 and 19).

The thesis examined two methods whereby jet penetration could be improved. The first of these was through the addition of an abrasive to the fluid flow in the same manner as Gulf had used in their research which had drilled to depths of 14,000 ft. The thesis compared this approach with that proposed by Hydronautics, whereby water jet performance could be improved by cavitating the jet flow. A modification of the Hydronautics method was developed at the University of Missouri-Rolla, wherein the cavitating bubble collapse induces flaws into the rock structure, but that the pressure of the fluid flow in the conventional jet is adequate to exploit these flaws. The results of this research can be summarized in three figures (Figs. 10, 11 and 12). They show that at pressures below 10,000 psi,
Fig. 10. Relative erosive capability of jets at various pressures, as a function of standoff distance.
Fig. 11. Relative erosive capability of jets at various pressures, as a function of standoff distance.

Fig. 12. Relative erosive capability of jets at various pressures, as a function of standoff distance.
approximately, it is more effective to add an abrasive to the water jet than it is to either cavitate the water jet or leave it alone. At these pressures, the work done by the cavitating bubble collapse is sufficient to achieve penetration of the rock body, but the main fluid flow is at an insufficient pressure to exploit to any major extent the fractures which are developed. Thus, for example, Conn and his work at Hydronautics has shown (Ref. 20) that advance rates still remain in inches per hour levels at these pressures, rates which are comparable to those achieved in this study. However, the abrasive at this pressure is sufficient to improve the removal rate of the jet flow considerably.

As the velocity moves through 10,000 psi, the jet pressure generated in the flaws by fluid impact becomes sufficient to exploit the fractures induced by cavitation damage and much improved drilling rates can be achieved. This holds true as the pressure increases further, and ultimately a plain water jet becomes more effective than an abrasive-laden one. The reason for this lies in the relative depth to which the fractures are propagated by the two methods. Where the damage is by water action, the water can penetrate into the fractures generated in the rock surface; this fluid is pressurized by subsequent fluid flow and the crack increases in depth until a crystalline interface is reached and the material is removed. Conversely, the depth to which the surface is damaged where abrasive particles are used is much narrower (Figs. 13 and 14) because the wear of the abrasive removes the damaged surface much more rapidly and leaves a relatively smooth and much
Fig. 13. Red granite sample sectioned after impact by an abrasive-laden jet. (Magnification 6X)

Fig. 14. Red granite sample sectioned after impact by a cavitating jet. (Magnification 6X)
Fig. 15. Relative erosion capacity of jets as a function of pressure at 15 cm standoff.
narrower fracture zone in the rock. Thus, it is more effective at above 10,000 psi to use high pressure water jets with a cavitating system than it is to use an abrasive.

In this research, it was demonstrated by interpolation (Fig. 15) that the rate achievable at 20,000 psi, where the fluid is not cavitated, can be achieved at a pressure of approximately 12,000 psi when the fluid is cavitated. In earlier research on this contract and in other research on other contracts it has been found that pressures between 15,000 and 20,000 psi are most suitable for drilling granite in the ranges required. This would, therefore, suggest that a pressure level of 10,000 to 12,000 psi would become equally advantageous were the fluid flow cavitated.

A further advantage would accrue if the fluid pressure could be lowered in that the quantity of water put out by a pump at a given horsepower is inversely proportional to the pressure at which the pump can operate. If a pump can effectively operate at 10,000 psi, then the fluid flow will be twice as great as that if the jet has to operate at 20,000 psi. A consequent advantage to this is that the area impacting the rock is quadrupled and therefore the chance of finding suitable flaws to exploit is also quadrupled. Thus, the advance rate of the system will be that much greater. Preliminary evidence, not only in granite, but also in other rock materials, has shown considerable advantage to using lower jet pressures and higher fluid flows where satisfactory pressure has been reached for adequate penetration of the rock. This advantage can be further exploited, therefore, if cavitation is achieved.
The findings so far on this research are, it must be
stressed, as yet only preliminary. Much further testing will
be required before definitive conclusions can be reached.

Cavitation Testing

It has been a major task of this program to develop a
method of improving the drilling rate of water jets in rock,
but at the same time, to do this it is necessary to understand
better the ways in which the water jet penetrates the rock.
On a large scale this requires many samples and is very expen-
sive. It was conjectured that some degree of understanding
the mechanics of water jet penetration could be achieved if
one could examine in more detail the rock response to cavita-
tion impact. This would have the subsequent advantage of also
developing an understanding of the cavitation impact, allowing
design of a better mechanism for improving jet drilling ability
through addition of cavitation. In order to study cavitation
it was necessary that a standard method of test for rock re-
sponse to cavitation attack be developed.

A preliminary review of the current state of the art of
this testing indicated that the ASTM Committee G-2 on Erosion
and Wear was the group most concerned with this program and
that there did exist an ASTM method of test for cavitation
erosion of materials. Unfortunately, when this method was
examined in the laboratory it did not prove satisfactory for
use with rocks, because the method of test required that the
samples be prepared and screwed into the end of a vibrating
horn. Rock cannot be machined to that degree of accuracy on
any large scale and since it is weak in tension, so vibrating
it at the required rate would cause total sample failure. It
was therefore established it would be necessary to go to a stationary sample test for the program to be undertaken. This program was undertaken by Mr. P. Scott, who has prepared an M.S. thesis on his work (Ref. 17).

The thesis describes work undertaken to examine the benefit of the stationary specimen test and describes some of the problems which have been encountered in running this particular method. The problems encountered include large size fragments which are generated where the specimen tested is a crystalline rock. Consequent to this, Mr. Scott reviewed the Lichtarowicz cell method of cavitation testing developed by Dr. Lichtarowicz at the University of Nottingham (Ref. 21). As a result of this investigation a test method is currently being prepared for submission as a standard for the ASTM Committee G-2.

As a result partially of our work, other investigators in the United States are examining this method and it is expected that in time a standard method of test based on the Lichtarowicz method will be established. The program from this point will be directed toward building on the standard method currently in process and then carrying out a series of tests on individual rock types to determine how these respond to cavitation attack. For practical reasons, mainly due to the homogeneity of the samples under test, the development work to date has mainly been built around metal samples, rather than rock.
CONCLUDING REMARKS AND RECOMMENDATIONS

When this research program was first undertaken the practicality of water jet applications for drilling was not sufficiently proven. Within the time frame of this contract it has been adequately demonstrated that there are several advantages to the use of high pressure water jets in drilling.

While not a particular part of this program, there have also been several developments leading from the research carried out and described herein which are already moving toward commercial application in the mining industry. Two of these are perhaps at the present time worthy of mention, although there are others too premature to be described. The first of these is the use of high pressure water jets as a roof bolt drilling mechanism. Consequent to a demonstration to the Bureau of Mines on the practicality of water jets as a roof bolt drilling system, the Bureau of Mines let two contracts for the development of water jet drilling systems for roof bolt emplacement. The principal investigator on this contract was cited as a consultant to both the companies awarded contracts but in the interests of fair dealing with the government, chose only to serve with the industrial company developing this system. That company has developed a roof bolting machine capable of drilling roof bolt holes at speeds of up to 24 ft/min (Ref. 23).

In a second area a contract has recently been awarded to the University of Missouri by Sandia Labs to develop a drill capable of drilling out horizontally from the bottom of a vertical borehole (Ref. 24). The concept proof of the system design has
already been made, and the mechanical development of a system to reliably carry out this method of drilling is currently in progress. This equipment will be of considerable advantage to the development of in situ gasification resources of the United States and can also be used for methane drainage purposes.

In drilling larger diameter holes, it has been shown by this research that water jets need to be used in combination with a mechanical form of cutting and to this purpose the research has examined the addition of water jets to a conventional tricone bit. Performance improvements have been noted, but the research should be continued to determine the optimum positioning of these water jets and to determine the relative economics of adding such a system to a conventional drill. In this regard the ongoing development of high pressure equipment, mainly seals, rotary couplings and high pressure hose, will hasten the introduction of this technology to industry.

The program has demonstrated that improvements in drilling are achievable where fluid flow is either cavitated at above 10,000 psi or if abrasives are added to the jet, below 10,000 psi. Where cavitation is introduced, it is possible to reduce the pressures required to drill crystalline rock to those pressures only slightly above those obtainable with commercial available cleaning equipment and well within the ranges which have been used in the past for water jet drilling trials by the research organizations of some of the major oil companies.

While the economic practicality of water jets has also been demonstrated elsewhere during the course of this contract (Ref. 22) this has only been for the softer rock formations which are attacked during conventional oil drilling. It is
believed by the authors that one of the significant findings of this research program is that water jets can effectively be used for drilling the harder rocks encountered in drilling for geothermal resources, and that rates can be achieved which are significantly greater than those currently available with conventional equipment. Further, it is likely that with the advances in water jet technology, equipment will be available which, using the techniques developed during the course of this research, will make it possible for water jet application in drilling through granitic rock to become an economic reality. It is, however, recommended that a considerable amount of further development be undertaken before this field application be undertaken. The major effort required lies in the fluid mechanics of the flow through multiple orifice nozzles located in the drill head and the emplacement of the drilling nozzles on the drill head, and in the change in the forces required to encompass the required drilling program. This program should be carried out in close cooperation with industry, since for the program to succeed it is necessary that the system developed be able to fit within the logistics of existing drilling equipment, a fact that must be considered whatever novel techniques are evaluated in their application toward drilling in the field.

Acknowledgments

This research was carried out with the cooperation of the faculty and staff of the Rock Mechanics and Explosives Research Center of the University of Missouri-Rolla. We would like specifically to thank Dr. Clark R. Barker, Dr. Dwight Bushnell, now at Oregon State University, and Mr. Jim Blaine,
Mr. Ron Robison, Mr. John Tyler, Mrs. Snelson, and Mrs. Rotramel for their assistance during the course of this research work.

We are also deeply indebted to the staff of the Department of Energy, Geothermal Division, Mr. Morris Skalka, Mr. Cliff Carwile, and the monitoring panel at Sandia, Dr. Sam Varnado, Mr. Max Newsom, and Mr. Jon Barnett, for their considerable advice and counseling during the course of this program. Advice was also obtained from Maurer Engineering Company in Houston, Texas, and this we also gratefully acknowledge.

Ms. June Wiinikka and Ms. Cheryl Povalish of the Chicago office of the Department of Energy were the Program Administrators on this contract, and we are grateful for the invaluable assistance which they have from time to time been called upon to give to us. While this program was prepared under the auspices of the Department of Energy at the University of Missouri-Rolla, the views and comments expressed herein are of the authors alone.
REFERENCES


BIOGRAPHY

Name: David Archibold Summers

Title: Professor of Mining Engineering and Director of Rock Mechanics & Explosives Research

Academic Degrees:

B.S. (Class I), Mining Engineering, The University of Leeds, Leeds, England, 1965


Professional Affiliations:

American Institute of Mining, Metallurgical and Petroleum Engineers
Sigma Xi
Institute of Mining Engineers (Great Britian)
North of England Institute of Mining Engineers
International Society for Rock Mechanics
Institution of Mining and Metallurgy
Chartered Engineer (1970)
British Tunnelling Society
American Society for Testing and Materials
Committee G.2, "Erosion and Wear"
Committee D.18.12, "Rock Mechanics"
American Society for Engineering Education
American Society of Mechanical Engineers
Rock Mechanics Subcommittee
Drilling and Production Committee
American Underground Association

Honors:

MASUA Lecturer 1978-79
MSM-UMR Alumni Association
Alumni Merit Award for Exemplary Research

Professional Experience:


Experience in surface workshop and administration facilities at a coal mine and six months underground on haulage of supplies to the mine face, work on a longwall coal face, and ground support for the face and entries.

1963 (summer), National Coal Board, Kent, England

Experience on a power-loading longwall face in a coal mine.
1964 (summer), Praktikant (Student Apprentice) with the Bolidens, G.B., Adakgruvan, Sweden.

Experience in mine surveying and rock extraction in a cut and fill sublevel stopping system.

1965 (summer), Forestry Commission, Southern Scotland; attached to the Surveyor.

Surveying and mapping future road development in a National Forest.

1968-1974, Assistant Professor of Mining Engineering and Senior Research Investigator in Rock Mechanics & Explosives Research Center, University of Missouri-Rolla, Rolla, Missouri.

1974-1976, Associate Professor of Mining Engineering and Senior Research Investigator in Rock Mechanics & Explosives Research Center, University of Missouri-Rolla, Rolla, Missouri.

Research in the measurement of material surface energy and the excavation of rock by a high pressure water jet. Lecturer on rock mechanics and strata control.


Instructor to Peabody Coal Company on Underground Coal Mining, Spring, 1973.

Relevant Publications:


LIST OF RELEVANT PUBLICATIONS


APPENDIX

1. "Water Jet Drilling in Sandstone and Granite"

2. "Hydromechanical Drilling of Holes Larger than One Inch in Diameter"


4. "Can Nozzle Design be Effectively Improved for Drilling Purposes"


6. "The Effect of Stress on Water Jet Performance"


8. "Cavitation and the Cutting of Rock"

9. "The Use of High Pressure Water Jets in the Mining Industry"

10. "Progress in the Water Jet Assisted Drilling of Rock"

11. "Environmental Effects on a High Pressure Jet Drill"
WATER JET DRILLING IN SANDSTONE AND GRANITE

By

David A. Summers
Associate Professor of Mining Engineering
Interim Director
Rock Mechanics & Explosives Research Center
University of Missouri-Rolla
Rolla, Missouri

Terry F. Leinhoff
Associate Professor of Mechanical Engineering
Research Associate in
Rock Mechanics & Explosives Research Center
University of Missouri-Rolla
Rolla, Missouri

ABSTRACT

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

INTRODUCTION

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

RESULTS FROM CUTTING Berea sandstone

In the preliminary research on sedimentary rock the effect of rotational speed, advance rate, jet pressure, and nozzle angle were all examined (1). The results of the program indicate that advance rates of up to 300 inches per minute can be attained (Figure 1) in sandstone at a hole diameter of approximately 1 inch. While this has application in the roof bolt drilling operation for mining, it has little practical application for deep hole drilling since there is a limit to the speed at which holes can be created. This limit is imposed by the speed at which pipe can be fed into the hole and the limit currently runs at approximately 200 to 300 feet per hour. For this reason test procedures have since been adapted to change the feed rate to a maximum of approximately 60 inches per minute (300 feet per hour). This rate is used in the experiments which follow. The sandstone and the granular rock tested is relatively permeable and it has been found advantageous to drill this type of rock with a dual orifice water jet (Figure 2) in which one of the orifices is directed straight forward while the other is inclined out at an angle sufficient to cut to the required hole diameter. While this works extremely well for the sedimentary rock, in part perhaps because the infusion of the rock ahead of the nozzle by the leading jet weakens it sufficiently that the reaming jet is able to cut more effectively, such is not the case in crystalline material. The granular material is removed on a grain by grain basis and the jet cutting action is extremely localized under the impact point. The presence of the grain boundaries serves to arrest any cracks which initiate in and around the cutting location, and for this reason the jet will cut very narrow slots not much wider than the jet diameter itself and this must be taken into account when relating advance rate and rotational speed. The reason for this is that the jet which reams the hole will only cut the jet diameter each revolution; and where the advance rate is greater than the jet diameter per revolution, the hole will no longer become smooth but rather ribs will be created on the sides of the hole which will eventually work in towards the center interfering with the passage of the drilling bit. Where these ribs are small they can easily be broken by the main jet assembly but this causes abrasion of the drilling tool when no mechanical cutter is incorporated in the system and provides a limit to the jet performance. Where the feed rate is less than the jet diameter then there is a noticeable increase in hole diameter (Figure 3).
Crystalline rock in general does not have the number of voids and the high permeability of Berea sandstone used in the earlier part of the tests. Thus the trials which were carried out in Oouri Red Granite (which has a compressive strength of approximately 30,000 psi) using the same design as that which had given very promising results in the sandstone did not give the same fit in the granite. On the contrary it was found that use of a single larger diameter orifice rather than using two orifices from the nozzle with ensuing jet angled to drill the peripheral hole this would, at the same time as giving a better rate, remove the central core to a sufficient ee that the nozzle would not interfere with it. Improvement in performance by going from a dual single orifice nozzle in the crystalline rock is in the granite. It was found, for example, that without jet assistance the forces required to advance the bit are 136 rpm and a feed rate of 5.5 thousandths per revolution were too great for the lathe assembly. However, this speed and feed could be achieved with the jet assist. Consideration must be given, in the design of the nozzle system, to the potential of the jets cutting the rock while at the same time being capable of cutting the bit. It should also be borne in mind that under these test conditions the bit is not cutting the rock but merely crushing the material under the teeth, and is therefore not operating under optimum conditions.

FUTURE WORK

A bit has been constructed incorporating these modifications and is currently undergoing preliminary testing. The object of the research is not merely to determine baseload conditions for the system and to provide some initial parameters for evaluation. In drilling these small 6 inch cubes of limestone the equipment layout is as follows (Figure 5). The rock sample is chucked into the lathe and as the lathe rotates so the drill bit is advanced under controlled conditions to drill the required hole (Figure 6). The loads are monitored by a strain gaged load cell at the front of the lathe mounted ahead of the load cell. The data which has been achieved from the test to date are shown (Table 2). Preliminary conclusions from this series of tests are that using the water jet reduces the force required to cut the rock while the jet assistance the forces required to advance the bit at 136 rpm and a feed rate of 5.5 thousandths per revolution were too great for the lathe assembly. However, this speed and feed could be achieved with the jet assist. It should also be borne in mind that under these test conditions the bit is not cutting the rock but merely crushing the material under the teeth, and is therefore not operating under optimum conditions.

ACKNOWLEDGEMENTS

This work was funded by the U.S. Energy Research and Development Administration under contract ERDA EY 76 S 02 2677 MOD 1 with Mr. C. Carwile, Technical Project Officer, Ms. J. Wiinikka, Contracting Officer. We are grateful for this support. The
Research was carried out with the assistance of
sr's. A. Krause, J. Blaine, J. Tilman, and R.
ison of the Rock Mechanics & Explosives Research
Staff and we are pleased to acknowledge this
istance.

REFERENCES

Summers, David A. and Dwight J. Bushnell, "En-
vironmental Effects on a High Pressure Jet Drill," presented at the 31st Annual Meeting of the
Petroleum Mechanical Engineering Conference of
ASME, Mexico City, September 1976.

of Rock Anisotropy on the Excavation Rate in
Barre Granite," Second International Symposium
on Jet Cutting Technology, Cambridge U.K.,
paper HS, April 1974.

Hood, M.J., discussion at the 3rd International
Symposium on Jet Cutting Technology, Chicago,
1976.

Maurer, William C., "Drilling R&D Underway in
the United States," presented at the 1977 Drilling
Technology Conference of the International
Association of Drilling Contractors, New Orleans,

TABLE CAPTIONS

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

Nozzle design used for advance rate studies.

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

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

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

Specimen configuration showing the pilot hole.

Table 1

<table>
<thead>
<tr>
<th>Flow Rate (gpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
</tr>
<tr>
<td>.78</td>
</tr>
<tr>
<td>1.25</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hole Diameter (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Advance Rate (in/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5</td>
</tr>
<tr>
<td>11</td>
</tr>
<tr>
<td>17</td>
</tr>
<tr>
<td>20</td>
</tr>
</tbody>
</table>

Table 2

The effects on drill bit load where jet assist is
applied to a 3-3/4" diameter coring bit.
HYDROMECHANICAL DRILLING OF HOLES LARGER THAN ONE INCH IN DIAMETER

by

David A. Summers
Terry F. Lehnhoff
James G. Blaine
Anthony L. Krause
J. Erik Tilman
Ahmed A. El-Saie

Offered for
The 32nd Annual Meeting of
The Petroleum-Mechanical Engineering
Conference of ASME

Houston

September 1977
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 (Refs. 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 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 examining the effect of
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\(^{\circ}\) nozzle at 10,000 psi
b) limestone drilled with a 30\(^{\circ}\) nozzle at 20,000 psi
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.

<table>
<thead>
<tr>
<th>Incremental Distance Between Successive Jet Passes over the Rock (0.001 inches)</th>
<th>Depth of Cut (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1.51 0.58</td>
</tr>
<tr>
<td>40</td>
<td>1.22 0.43</td>
</tr>
<tr>
<td>80</td>
<td>0.89 0.31</td>
</tr>
<tr>
<td>160</td>
<td>0.65 0.20</td>
</tr>
</tbody>
</table>
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 transcristalline 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 horsepowers 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
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).
ADAPTATION OF JET ACCUMULATION TECHNIQUES

FOR ENHANCED ROCK CUTTING

by

Dr. Marian Mazurkiewicz
Instytut Technologii Budowy Maszyn
Politechnika Wrocławska - Poland

Dr. Clark R. Barker
Rock Mechanics and Explosives Research Center
University of Missouri-Rolla

Dr. David A. Summers
Rock Mechanics and Explosives Research Center
University of Missouri-Rolla
ABSTRACT: The velocity of water jet flow can be increased when the jet impacts a target material or another water jet. A theory describing such augmentation in terms of velocity, mass and energy change is considered. The phenomena is sensitive to jet structure and the jet velocity profile. Jet velocity profiles do not remain constant over great distances from the nozzle, and ultimately disrupt into droplets. Within the droplet the profile is more regular and the velocity constant. The theory is extended to cover this case and experimental evidence of jet augmentation and its effects is presented.

KEY WORDS: impact pressure distribution, fluid jet augmentation, droplet impact, erosion, rock.
INTRODUCTION

The use of high pressure water jets as a cutting tool has, within the last five years, become a commercial reality. The range of application has covered a spectrum from cardboard and wood through coal and rubber to metal.

Research investigators have carried out test programs at pressure levels up to 40,000 bar, well above the 25 to 4 Kbar level of commercially available equipment. Such research has shown that there can, under certain circumstances, be benefits to working at these higher pressures. Equipment for this type of work is, however, generally only of the "one of a kind" research tool variety, and results of test findings at the higher pressure levels have indicated relatively short lives for the generating pressure systems and particularly the nozzles, in which the transition to cutting speed occurs.

Because of the problems associated with creating pressures within a piece of equipment, consideration has turned to the possibility of generating high velocities beyond the nozzle by the use of interacting jets or jet impact on a solid surface.

This approach has already been shown successful in the development of shaped charges, particularly for military applications during the last world war [1-3]. Theoretical and experimental analysis of this phenomenon has shown that directional cumulative jet accelerations to velocities of
the order of 1,000 to 2,500 m/s can be achieved. The velocity achieved is a function of the charge size and the shape and material composition of the liner which, upon collapse, will create the cutting jet.

This paper examines the related field where an augmented velocity jet or "fast jet" is produced by the impact between two identical water jets or of a single water jet with a rigid flat surface. The paper extends the existing theory developed for shaped explosive charges to describe the formation and nature of the secondary water jets formed when two identical jets meet. The secondary jets move in opposing directions along the line bisecting the angle between the original jets. The motion of the secondary jets must satisfy the principles of conservation of mass, energy, and momentum. Calculations are thereupon described which govern the mass and velocity of these secondary jets.

Particular considerations are given to the case where one of the secondary jets is of sufficient velocity to have the capability of cutting a target material.

In the passage of a water jet from the nozzle into a surrounding fluid the effect of the jet of the surrounding fluid is to cause a change in the pressure profile (velocity profile) of the jet (Fig. 1). The initial condition with a constant velocity across the profile changes to a Gaussian distribution with increasing distance from the nozzle as the water on the outside of the core is abraded. Conventional theory on jet impact is based on those portions of the curve where the primary jet still retains a constant velocity across
FIG. 1 - Impact pressure profiles at various distances along a water jet issuing from a 1.5 mm nozzle diameter at 545 bar.
the profile, and will then expand this to the case where the jet is broken into droplets.

ANALYTICAL MODEL

Consider an original primary fluid jet in the region close to the nozzle where it retains an even pressure profile across its section. Let such a jet have a square cross-section of area \( b \times b \) and with a leading edge which is a flat surface. If it is assumed that all portions of the original jet are approaching a rigid flat surface with the same velocity vector inclined at angle \( \alpha \) relative to the flat surface and with the leading edge of the primary jet inclined at angle \( \gamma \) to plane \( A_1A_2 \). The first portion of the leading edge of the primary jet contacts the plane \( 00 \) at point \( A_1 \) (Fig. 2). This simulation is equivalent to the intersection of two similar jets approaching a common plane of symmetry \( 00 \) at angle \( \gamma \) (Fig. 3).

If the flow were a continuous laminar flow, then the primary jet would divide to produce two streams flowing in opposite directions along the surface \( 00 \). Each stream would have a velocity magnitude \( V_0 \), where \( V_0 \) is the magnitude of the inflow velocity. Such a condition is non-typical and a more generalized case will be considered.

Velocity of the Secondary Jets

Sims [4] used a control volume approach to determine the velocity relationship between the primary and secondary jets
FIG. 2 - Geometric representation of the stages of impact of a flat faced water jet on an oblique plane.
FIG. 3 - Collision of two flat faced square jets.
for the special case $\gamma = 90^\circ$. We concluded that, as the jet contact point $A'$ moves along plane 00 at a speed $V_A$, jets created at the plane would have velocity magnitudes $V_{fj}$ to the right, herein referred to as the "fast jet", and $V_{sj}$ to the left, herein referred to as the "slow jet") given by the equations

$$V_{fj} = |\vec{V}_R + \vec{V}_A| = V_R + V_A$$

$$V_{sj} = |\vec{V}_A - \vec{V}_R| = V_A - V_R$$

where $V_R$ is the relative velocity of the primary jet to the jet contact point. From the velocity polygon in Fig. 2 we can derive the following

$$V_R = \frac{V_o \sin \alpha}{\sin(a+\gamma)}$$

$$V_A = \frac{V_o \sin \gamma}{\sin(a+\gamma)}$$

If Eq 2 is substituted into Eq 1, then

$$V_{fj} = V_o \left[\frac{\sin \alpha + \sin \gamma}{\sin(a+\gamma)}\right]$$

$$V_{sj} = V_o \left[\frac{\sin \gamma - \sin \alpha}{\sin(a+\gamma)}\right]$$
Hence, the speed of the secondary jets depends only on $V_o$, $\alpha$, and $\gamma$.

Mass of the Secondary Jets

The mass of the secondary water jets can be estimated by applying the equations for conservation of momentum and mass at point $A_1$ (Fig. 2)

$$
\int \rho V_R^2 \cos[180^\circ - (\alpha + \gamma)] \, dA_{in} = - \int \rho V_R^2 \, dA_{fj} + \int \rho V_R^2 \, dA_{sj} \quad (5)
$$

and

$$
\int \rho V_R \, dA_{in} = \int \rho V_R \, dA_{fj} + \int \rho V_R \, dA_{sj} \quad (6)
$$

where $dA_{in}$ is the elemental vertical cross section of the inflow jet,

$dA_{fj}$ is the elemental vertical cross section of the fast jet,

$dA_{sj}$ is the elemental vertical cross section of the slow jet.

$$
dA_{in} = b \, dw,
$$

$$
dw = V_o \sin(180^\circ - \gamma) \, dt
$$

substituted into Eqs 5 and 6 gives
\[(A_{fj})_{\text{max}} = \int_0^{(A_{fj})_{\text{max}}} dA_{fj} = \frac{b^2[1 + \cos(\alpha + \gamma)] \sin(\alpha + \gamma)}{2 \sin \alpha} \quad (8)\]

\[(A_{sj})_{\text{max}} = \int_0^{(A_{sj})_{\text{max}}} dA_{sj} = \frac{b^2[1 - \cos(\alpha + \gamma)] \sin(\alpha + \gamma)}{2 \sin \alpha} \]

The area of the vertical cross section of the secondary water jet impacting on the surface increases linearly from 0 to the value \((A_{fj})_{\text{max}}\). This occurs during the time \(T\) that point \(B_1\) moves to \(B_1'\). If we let distance \(B_1B_1'\) be \(x\) and consider triangles \(A_1CB_1\) and \(A_1B_1B_1'\), then

\[T = \frac{x}{V_0} = \frac{b \sin(\alpha + \gamma)}{V_0 \sin \alpha \sin \gamma} \quad (9)\]

The length of the secondary jet is therefore

\[\ell = V_R T \quad (10)\]

from Eqs 2 and 9 this gives

\[\ell = \frac{b}{\sin \gamma} \quad (11)\]

Secondary jets will have a wedge shape with an area of the base of \((A_{sj})_{\text{max}}\) and \((A_{fj})_{\text{max}}\), width \(b\), and length \(\ell\). Letting
the mass density of the water be \( \rho \), the mass of the secondary jets will be

\[
(M_{f_j})_{\text{max}} = \frac{\rho b^3}{4} \left[ 1 + \cos(\alpha + \gamma) \right] \frac{\sin(\alpha + \gamma)}{\sin \alpha \sin \gamma}
\]

\[ (M_{s_j})_{\text{max}} = \frac{\rho b^3}{4} \left[ 1 - \cos(\alpha + \gamma) \right] \frac{\sin(\alpha + \gamma)}{\sin \alpha \sin \gamma} \]

The total mass that participates in the formation of the secondary water jets is the sum of \((M_{f_j})_{\text{max}} + (M_{s_j})_{\text{max}}\):

\[
M_{\text{in}} = \frac{\rho b^3}{2} \frac{\sin(\alpha + \gamma)}{\sin \alpha \sin \gamma}
\]  

Energy of the Secondary Jets

Using Eqs 3, 4, and 12 the kinetic energy of the secondary water jets can be derived:

\[
E_{K_{f_j}} = \frac{\rho b^3 V_0^2}{8} \left[ 1 + \cos(\alpha + \gamma) \right] \frac{(\sin \alpha + \sin \gamma)^2}{\sin \alpha \sin \gamma \sin(\alpha + \gamma)}
\]

\[
E_{K_{s_j}} = \frac{\rho b^3 V_0^2}{8} \left[ 1 - \cos(\alpha + \gamma) \right] \frac{(\sin \alpha + \sin \gamma)^2}{\sin \alpha \sin \gamma \sin(\alpha + \gamma)}
\]

The kinetic energy of the secondary jets is a function of \( V_0, b, \) and angles \( \alpha \) and \( \gamma \).
Concentration of Energy

Even more significant than the energy ratio is the concentration of energy. This information, important in estimating the cutting potential of the secondary jets, is obtained by dividing the kinetic energy by the cross-sectional area of the secondary jets. Hence

\[
K_{fj} = \frac{E_{K_{fj}}}{(A_{fj})_{\text{max}}} = \frac{\rho b v^2}{4} \frac{(\sin \alpha + \sin \gamma)^2}{\sin \gamma \sin^2 (\alpha+\gamma)}
\]

(15)

\[
K_{sj} = \frac{E_{K_{sj}}}{(A_{sj})_{\text{max}}} = \frac{\rho b v^2}{4} \frac{(\sin \alpha - \sin \gamma)^2}{\sin \gamma \sin^2 (\alpha+\gamma)}
\]

The concentration of energy for the primary jet can be written as

\[
K_{in} = \frac{E_{K_{in}}}{A_{in}} = \frac{\rho b v^2}{4} \frac{\sin^2 (\alpha+\gamma)}{\sin \alpha \sin^2 \gamma}
\]

(16)

where \(A_{in} = b^2\), the area of the cross section of the primary jet. The concentration of energy ratio is then defined as

\[
\frac{K_{fj}}{K_{in}} = \frac{(\sin \alpha + \sin \gamma)^2 \sin \alpha}{\sin^3 (\alpha+\gamma)}
\]

(17)

\[
\frac{K_{sj}}{K_{in}} = \frac{(\sin \alpha - \sin \gamma)^2 \sin \alpha}{\sin^3 (\alpha+\gamma)}
\]
Analysis of the Theoretical Results

It is obvious from studying the previous equations that the values of $\alpha$ and $\gamma$ are very important in determining the characteristics of the secondary jets. Fig. 4 was computed for the case $V_0 = 1$ and $b = 1$. Note that the actual value of $\alpha$ and $\gamma$ is not as critical as the sum $(\alpha + \gamma)$. The velocity ratio is high as $(\alpha + \gamma)$ approaches 180 degrees.

The importance of the accumulation phenomena is illustrated by consideration of the pressure ($P$) that would be required to produce the high velocity ($V = 14\sqrt{P}$) possessed by the secondary water jet if conventional nozzle extrusion methods were used, relative to that of the primary jet stagnation pressure ($P_o$) where augmentation occurs. If, for example, $V$ is 5051 m/s, then $P_o$ would be 1,000 atm if $\alpha = 80^\circ$ and $\gamma = 90^\circ$. To produce the same velocity with conventional methods would require $P$ to be 65,322 atm.

Fig. 5 is a plot of the kinetic energy ratio $E_{K_{fj}}/E_{K_{in}}$ for various values of $\alpha$ and $\gamma$. From this figure it can be seen that the kinetic energy ratio is at a maximum value of 1 when $\alpha$ and $\gamma$ are equal. Three types of flow can be identified based on the relationship between $\alpha$ and $\gamma$ (Fig. 5). When $\gamma = \alpha$, all the energy is possessed by the fast secondary jet and the slow jet has none. In the region where $\gamma < \alpha$, the slow secondary jet moves to the left. In the region where $\gamma > \alpha$, the secondary slow jet moves to the right along with the fast secondary jet. Fig. 6 is a plot of the concentration of energy ratio. This figure is very similar to
FIG. 4 - Velocity augmentation ratio as a function of the impact angles $\alpha$ and $\gamma$. 
FIG. 5 - Kinetic Energy augmentation ratio as a function of the impact angles $\alpha$ and $\gamma$. 
FIG. 6 - Energy intensification ratio as a function of the impact angles $\alpha$ and $\gamma$. 
Fig. 4 and the same comments apply. Based on the information that the kinetic energy ratio is maximum for $\alpha = \gamma$ (Fig. 5) the optimum condition for energy concentration can be plotted as a dashed line on Fig. 6.

EXPERIMENTAL APPLICATIONS

Under normal circumstances it is extremely difficult to obtain a flat leading edge to a water jet or to maintain a uniform velocity across the jet profile. The surface or profile is generally curved (Fig. 1) or more severely distorted by jet movement relative to the surrounding medium.

However, at the point where the jet breaks into droplets, the contour of the leading surface will stabilize and the velocity will be sensibly constant within the droplet. This set of conditions allows the above analysis to be extended to cover this case. Analysis of this phenomena has been carried out in Cambridge [5] and only a comparative relation will therefore be made.

Fig. 7 shows an element sliced from a spherical droplet, of radius $R$ and moving at speed $V_o$ toward the flat surface 00 at an angle $\alpha$. Every phase of the collision can be considered using the previously derived equations with suitable transformations to adapt them to the present geometry. For example, when the face of the element from $M'$ to $M''$ contacts the flat surface, the geometry is the same as that of Fig. 2. The droplet first contacts the plane 00 at $M_1$ and during
FIG. 7 - Geometric representation of the impact of a bubble with an oblique surface.
impact the contact point moves along radius \( R \) to the point \( M_n \). The value of \( \beta \) will vary from \( \alpha \) to \( 180^\circ \) in the interval

\[
0 < t < \frac{R(1 + \sin \alpha)}{V_0 \sin \alpha}
\]

and

\[
\gamma = 180 - \beta
\]

which can be substituted into Eqs 3, 14, 16, and 17 to give a new set of equations valid for the central portion of the droplet,

\[
\frac{V_{fj}}{V_0} = \frac{\sin \alpha + \sin \beta}{\sin(\beta - \alpha)}
\]

\[
\frac{E_{K_{fj}}}{E_{K_{in}}} = \frac{[1 - \cos(\beta - \alpha)] (\sin \alpha + \sin \beta)^2}{2 \sin^2(\beta - \alpha)}
\]

\[
\frac{K_{fj}}{K_{in}} = \frac{(\sin \alpha + \sin \beta)^2 \sin \alpha}{\sin^3(\beta - \alpha)}
\]

Representative values obtained using these equations are shown in Fig. 8, 9, and 10.
FIG. 8 - Velocity augmentation ratio for a droplet impact as a function of the angles $\alpha$ and $\beta$.

\[ \frac{v_{fl}}{v_o} = \frac{\sin \alpha + \sin \beta}{\sin (\beta - \alpha)} \]
FIG. 9 - Kinetic energy augmentation ratio as a function of the impact angles $\alpha$ and $\beta$ for a droplet.

\[
\frac{E_{K_{\text{fi}}}}{E_{K_{\text{in}}}} = \frac{(1-\cos(\beta-\alpha))(\sin\alpha + \sin\beta)^2}{2 \sin^2(\beta - \alpha)}
\]
FIG. 10 - Energy intensification ratios as a function of the impact angles $\alpha$ and $\beta$ for a droplet impact.

\[ \frac{K_{fi}}{K_{in}} = \frac{(\sin \alpha + \sin \beta)^2 \cdot \sin \chi}{\sin^2 (\beta - \chi)} \]
Discussion of These Results

The fast jet velocity ratio (Fig. 8) when plotted as a function of the angle indicates that the curves for various values of $\alpha$ are similar in shape but displaced as a function of $\beta$. In every case the velocity ratio becomes very large as the angle $\alpha$ approaches the value of $\beta$. For practical considerations, the range of $\beta$ that leads to the formation of satisfactory fast jets is considered to be $\alpha < \beta < \alpha + 15^\circ$.

From the curves on Fig. 9 which show the kinetic energy ratio as a function of the angles $\beta$ and $\alpha$, the same conclusions can be drawn as for the earlier case of a flat impact shown in Fig. 5. The highest energy ratios occur when $\alpha$ and $\gamma$ are equal ($\gamma = 180 - \beta$).

The concentration of energy ratio shown plotted in Fig. 10 is similar to that for a flat faced jet (Fig. 6). It is again found that as $\alpha$ approaches $\beta$ so the energy ratio tends to infinity. Where values of $\alpha$ are small the range of $\beta$ over which the jet energy is highly concentrated is also small, but as $\alpha$ increases so the width of the angle $\beta$ over which a highly intensified jet is produced is also increased. It is interesting to note that the kinetic energy augmentation is at an optimum where $\alpha = \gamma$ and that the energy intensification is at an optimum where $\alpha = \beta$. Since $\gamma = 180 - \beta$ this suggests that the optimum energy augmentation with the most concentrated jet might occur when $\alpha = \beta = \gamma = 90^\circ$. Under such circumstances the fast jet would be at greatest damage potential when the vertically impacting drop
is at its maximum contact diameter. In this regard investigators at Cambridge [5] have found that damage from impacting droplets is confined to the periphery of the droplet impact zone. The equivalence of the relationship between droplet flow and continuous jet flow is suggested by a corresponding result obtained at Rolla with a high pressure continuous jet directed at an aluminum target located 2.5 cm from the jet nozzle (Fig. 11), where damage is also confined to the region at and beyond the jet impact periphery.

Experiments have, however, concentrated on examining the zone of jet interaction further down the jet stream where the flow has disrupted into droplets. Fig. 12 shows a photograph of such a jet collision with an impact angle of (a) 10° at 4 bar. obtained by the strobe flash technique [9]. All the droplet components of each jet do not impact other droplets since there is no control over their spatial distribution and velocity. However, when two droplets do collide, the shock wave generated by the fast jet is clearly visible. The results are similar to those of a collapsing cavitation bubble which produces a Monroe jet with accompanying shock waves [6]. It is similar to the photographs obtained by Edney [7] of the explosive extrusion of the water jet in a vacuum.

In practice the structure of a high pressure water jet, particularly at velocities of the order of 300 m/s, is extremely sensitive to interference from adjacent bodies [8].
FIG 12 - Views of water jets at a pressure of 4 bar converging at an angle of 10° at the point where the jet turns into droplets (a) top view showing the angle of impact, (b) side view showing shock waves generated by the small augmented jet velocity.
For this reason, while water jet impact on solid bodies can be used to generate augmented velocities, the diffuse structure around two continuous jets will interfere with the jet structure prior to impact and negate much of the proposed augmentation. Conversely, once the jet has disintegrated into droplets this is no longer the case, although the target location should be in the immediate vicinity of the impact point since the fast jets produced are extremely small and thus rapidly disrupted. Further research on the effectiveness of interfering jets, designed to interact beyond the jet collapse distance is therefore required.

ROCK CUTTING EXPERIMENTS

As a practical test of the potential effectiveness of converging jets, an experiment was carried out on Berea sandstone samples, 15 cm diameter and 30 cm long, with test nozzles placed 1.25 cm above the sample. The jet pressure was 680 bar for this study in which approximately 20 different nozzle geometries were examined. Nozzles were constructed to produce two parallel jets of diameter 1 mm, separated by distances of 1.27 mm, 1.78 mm, and 3.0 mm. Nozzles were also constructed to produce converging jets at included angles of 1°, 2°, 5°, 10°, 15°, and 20°. All the nozzles were machined from brass and the inside surfaces of the nozzles were lapped.

The best results were obtained with the parallel nozzles with the 1.27 mm and 1.78 mm spacing and the convergent
nozzles with 1° and 2° included angle. The results from the 5°, 10°, 15°, and 20° angle were poor, no cumulative effect being observed. The sandstone samples were split after an exposure time of 10 to 15 s when either the 1° or 2° nozzles were tested (Fig. 13).

Fig. 14 shows one of the convergent nozzles located just above the sandstone. Using the parallel nozzles with 1.27 mm and 1.78 mm spacing gave similar results to those of the 1° and 2° convergent nozzles. One reason postulated for this is the Coanda effect by which two jets flowing close together tend to merge into one jet.

Subsequent to the conclusion of this experiment the authors were engaged in research on a hydraulic mining unit in a surface mine in northern Missouri [8]. The seam of coal was being mined by water jets at a pressure of 680 bar when it was discovered that the coal was interlayered with pyrite lenses, compressive strength of the order of 2,000 bar. Under normal conditions the jets would not cut this material and a set of converging jet nozzles was inserted into the cutting head. The jets produced cut the pyrite satisfactorily allowing the mining machine to advance at a rate of 1.7 m/min.

CONCLUSIONS

The use of external augmentation techniques to improve water jet cutting ability has been demonstrated to be an effective way of improving the cutting of rock and is a means of generating higher pressures than those extant within
FIG. 13 - Cavity cut into Berea sandstone by a converging jet showing the narrow cut made by secondary jet action.
FIG. 14 - Proposed geometry for augmented cutting using the enhanced velocity effects from colliding droplets.
the pro-existing flow. Because of the problems which arise in bringing two flat ended jets together exactly symmetrically, it is proposed herein that a more effective technique would be to converge the jets at a point where they have just broken into droplets. Photographic evidence of such an event shows that large velocity augmentation is possible.

REFERENCES


Can Nozzle Design be Effectively Improved for Drilling Purposes

D. A. SUMMERS
Professor,
Mining Engineering;
and Director,
Rock Mechanics & Explosives Research

C. R. BARKER
Associate Professor,
Mechanical Engineering;
and Senior Research Investigator,
Rock Mechanics & Explosives Research
Assoc. Mem. ASME

B. P. SELBERG
Associate Professor,
Aerospace Engineering
University of Missouri-Rolla
Rolla, Mo.

This paper describes continued research on the use of high pressure water jets as a means of improving drilling rate. In order to more effectively test the effect of stress on jet drilling rate, tests have been carried out in an underground mine. These tests have shown that stress markedly reduces jet cutting ability in rock in situ contrast with laboratory test conditions. In order to achieve improvement in performance, new nozzle designs have been developed which markedly increase jet performance in cutting rock in air. The potential of this development on conventional bit performance in downhole conditions is discussed together with an initial analysis of the problems which can be solved in fluid flow through a bit. A discussion on the relative merits of optimizing fluid impact force as opposed to optimizing fluid velocity or bit hydraulic horsepower concludes the paper.


Copies will be available until August 1, 1979.
Can Nozzle Design be Effectively Improved for Drilling Purposes

D. A. SUMMERS  C. R. BARKER  B. P. SELBERG

ABSTRACT

This paper describes continued research on the use of high pressure water jets as a means of improving drilling rate. In order to more effectively test the effect of stress on jet drilling rate, tests have been carried out in an underground mine. These tests have shown that stress markedly reduces jet cutting ability in rock in situ contrast with laboratory test conditions.

In order to achieve improvement in performance, new nozzle designs have been developed which markedly increase jet performance in cutting rock in air. The potential of this development on conventional bit performance in downhole conditions is discussed together with an initial analysis of the problems which can be solved in fluid flow through a bit.

A discussion on the relative merits of optimizing fluid impact force as opposed to optimizing fluid velocity or bit hydraulic horsepower concludes the paper.

INTRODUCTION

Over the course of the past three years the University of Missouri-Rolla has been engaged in research examining potential benefits of high pressure water jet usage in drilling rock. During this time two separate and distinct approaches have been taken. In the first of these, water jets have been applied by themselves as a means of drilling rock and it has been found that the jets are capable of drilling small diameter holes at a high penetration speed (in consequence of which two water jet systems for drilling roof bolt holes have been funded by the U.S. Bureau of Mines). In a more recent development of this study the University of Missouri-Rolla has, in cooperation with the Mining Research Division of St. Joe Mineral Company, carried out a series of tests to determine if high pressure water jets could advantageously be used for drilling larger diameter holes for use in the emplacement of explosives in a blasting round. This combined research was of advantage since it not only allowed a demonstration of the adaptability of water jet technology to this size hole, but it also allowed a determination to be made of the effect of ground stress on the drilling performance of a water jet system.

Effect of Stress on Water Jet Drilling

The program which was carried out at the Indian Creek Mine of St. Joe Minerals involved the replacement of a conventional compressed air pneumatics drill with a high pressure water jet drilling system. The drill itself consisted of a replaceable nozzle attached to the end of a 9/16 in. (14.29 mm) diameter high pressure stainless steel tube which was rotated by a hydraulic motor attached through a chain and sprocket system to the tubing. The nozzle cross section installed in the stainless steel tube is shown in Figure 1. The drilling sash was further modified in that a hydraulic motor was located underneath the sash rather than the conventional compressed air motor in order to test and observe the hydraulic system of the unit. The system was tested in a mine in a series of experiments which have been described in more detail elsewhere (1).

While there were many conclusions drawn from the study, two are relevant to the topic described in this paper. One of the experiments carried out in the mine was to partially destress a block of the sandstone in the area being mined. The holes drilled in this, essentially unstressed, ground were compared with those made in the adjacent rock where no stress relief had taken place. The results of this experiment (Figs. 2a and 2b) show a very marked effect of the presence of ground stress on the drilling rate. Thus, since these results tend to confirm previous data obtained in the laboratory on the effect of ground stress on water jet drilling, it can be anticipated that there will be, as the water jets further penetrate the rock, an increasing effect of ground stress on drilling rate. However, in this regard it was determined in the laboratory experiments that the effect of ground stress is most marked in its initial application and that once a confining pressure of 500 psi (3.5 MPa) or so has been applied to the rock there is very little further reduction in drilling performance as stress continues to increase. A summary of these tests is presented in Table 1. For this reason, therefore, it is felt that water jet drilling can still be considered a viable method of drilling holes.

However, it must be mentioned that the problems likely to be encountered under varying ground stress are likely to include a noncircular hole should water jets be used alone as a drilling mechanism. This factor in conjunction with other considerations has led to the conclusion, particularly at hole diameters larger than 2 in. (5 cm) and where water jets would be required to drill regular circular holes, that a more advantageous use of water jets would be in cooperation with a mechanical drilling device.

A research effort has, therefore, been undertaken whereby water jets have been combined with mechanical tri-cone bits in order to obtain a better performance. This research program is not unique to the University of Missouri-Rolla. Experiments have also been carried out by Gulf, Exxon, and Shell (2,3,4) in seeking to
In research at the University of Missouri-Rolla, a much smaller scale has been undertaken under funding from the Geothermal Division of DOE. Laboratory studies wherein water jets were incorporated into the quasiconical bit structure, donated by Gruner Williams has shown (Table 3) that there is a marked improvement, even at low thrust levels, when water jets were added to the bit. It should be mentioned that even at these loads, chipping of the rock does occur, under apparently similar conditions as would hold were higher bit weights applied.

The research has looked at several different factors in the application of jets to tri-cone bits. The initial purpose of a drilling fluid is threefold. Primarily it is conventionally used to clear cuttings from the hole and also to cool the bit, but it must also count any downhole pressure which may enter into a hole when a high pressure zone is breached thus acting to prevent a blowout. There has been considerable development in the use of high pressure jets as a means of enhancing hole cleaning during the operation of the bit. Allerton (5) has made a study to determine the necessary hydraulic horsepower required to overcome jet floundering as a function of bit weight and mucus (6) has developed charts showing the effect on improving drilling rate as the flow rate of the jets and the hydraulic horsepower is increased. However, a hydraulic horsepower is improved, the normal effect of jet cleaning becomes minimized as the hole becomes perfectly cleaned. This effect becomes more important the deeper one drills since the pressureiding the chips down increases with depth. It is, therefore, important that a coherent, properly directed jet be utilized for the cleaning purpose. This becomes even more important as the jet pressure increased further to the point where not only are the jets cleaning the rock surface but are actually entraining into the rock, thus preweakening it and improving further the performance of the tri-cone bit.

In field research at Rolla, improvements in advance rates of up to a factor of eight have been achieved where such a system is incorporated into a tri-cone bit and field reports from Exxon, Gulf, and Shell all have shown that improvements in the field can be substantial in terms of bit life and advance rate. Nevertheless, conventionalally there have been any problems with the adaptation of high pressure jets to tri-cone bits and it has only been within the last two years that a hole has been drilled using high pressure economically advantageously.

It was done by Shal in 1977 (7) and a saving of approximately $140,000 has been reported on the hole. However, in order to achieve this improvement in performance it was necessary to extend the nozzles on the bit so that the jets could most effectively work in the cutting zone at the rock surface. In a similar move at slightly lower pressure, engineers at Smith Tool (8) have shown that extending the nozzles on a conventional rock bit will also improve performance and reduce drilling costs because the more effective cleaning which occurs under a tri-cone bit. However, in both these circumstances the use of extended nozzle bits has been shown to be of considerable advantage, the complexity modifying the bits to accept these extended nozzles has indicated some potential difficulty in getting the size of the bits down below 9-5/8 in. (24.45 cm).

Smith Tool has recently developed a two-cone bit for use in soft formations where extended nozzles can be brought closer to the surface and these nozzles have shown cost savings of between $4 and $5 a foot at a bit diameter of 7 to 7-1/8 in. (17.78 to 18.1 cm). There is, therefore, considerable advantage from both the drilling rate and cost standpoint where better bit hydraulics are achieved but at the present time this is limited to hole diameters of 7-1/8 in. (18 cm) and above and also requires that special bits be manufactured.

The recent research at the University of Missouri-Rolla has shown that a much better performance can be achieved using conventional drilling bits if a change in the nozzle design of the bit can be obtained. The improvement in performance which has been achieved with these nozzles in air, is the difference between jets cutting at a distance of 200 nozzle diameters from the nozzle to a distance of over 1,000 nozzle diameters. These performance improvements were achieved by requiring contour matching between the nozzle and target surface. These contour-matched nozzles are shown in Figure 3. The contrast nozzle lacking this contour matching is shown in Figure 4. In addition a settling chamber was installed upstream of the nozzles to reduce flow turbulence levels and pump pressure pulsations, both of which cause premature jet breakup. However, the biggest improvement in jet coherence was achieved by markedly improving interior nozzle surface finishes. By utilizing an electroforming manufacturing technique interior surface finishes of 8-10 micro inches (.25 m) were obtainable. The improvement due to surface finish above can be seen when a 8 deg diverging dual orifice nozzle machined of brass and polished is compared with an identical geometry nozzle manufactured by the electroforming process. This comparison is illustrated in Figure 5 and Figure 6.

Figures 5 and 6 clearly show the improvement obtained in cutting performance by the electroformed nozzle at large stand-off distances. Close to the nozzle, polished brass appears to be superior but this condition would not be true if the nozzle were moving relative to the target material. In this case fresh material is exposed to the jet and both the volume removed and depth of penetration are greater from a coherent jet produced from a smooth nozzle.

The need for flow improvement from nozzles can be better understood if it is accepted that conventional nozzle stand-offs can be up to 4 in. (10 cm) on a tri-cone assembly (9). Because these submerged jets are more rapidly attenuated than those in air (Figure 7) it can be seen that conventional flows may not cut at all beyond a distance of 3 in. (7.5 cm) where there is no back pressure on the fluid, and even shorter distances as fluid back pressure increases. Thus the...
benefit to be achieved by improving the fluid flow is not merely to improve jet cutting but may be sufficient that the jets will cut the rock whereas, previously, the force of the fluid had been too greatly attenuated.

It can also be pointed out that the slight increase in cutting ability of the submerged water jet over the free air condition is probably due to designs would improve jet effectiveness. By incorporating these improved nozzle designs and flow turning techniques into conventional tri-cone bits one could achieve the same benefits for these bits as are normally achieved with extended nozzle bits only, and therefore, save a considerable amount of money.

In closing, there has been considerable discussion over the years on the relative merits of optimizing the fluid impact force as opposed to optimizing fluid velocity of bit hydraulic horsepower, in improving the way in which a jet assisted bit operates. In seeking to answer this question, consideration must be given as to the purpose which the jets are to carry out. Conventionally, this is a form of erosion or removal where the material is already either broken or badly fractured by the tri-cone rotation. Under these circumstances, once the jets have, at the point of impact, reached a certain critical velocity so that the fluid within the cracks of the rock is pressurized by the impact of the jet to the point where the crack will grow or the fluid will create an uplift force on the fragments, then there is no great advantage to increasing the velocity of the jet much further since the primary purpose of the fluid has been achieved. It is more important in this regard, if any additional power is available, to put this into increasing fluid flow. Increasing the diameter of the jet within the zone is more likely to bring weakness planes, cracks, or grain boundaries within the zone that the jet is cutting, and in this manner, to create a much larger area of failure than would be the case if a smaller jet were used. The argument for using as large a jet diameter as possible at a pressure above that critical to the first removal of the fragments of rock is also enforced by the fact that the jets must penetrate through the surrounding fluid for several inches conventionally before the impact zone is reached, as the jet passes through the highly aggressive environment between the nozzle and the rock. Since mass flow rates increases as diameter squared while surface area increases only as diameter than a larger diameter jet will not be made ineffective as early as a smaller jet due to the viscous stripping process on the outer surface.

ACKNOWLEDGEMENTS

This work was partly funded under U.S. Energy Research and Development Administration contract EY 76 S 02 2677.AGO2 with Mr. Cliff Carwile as the Technical Project Officer, Ms. June Winiakka and Ms. Cheryl Povalish acted as Contracting Officers. We are pleased to acknowledge this assistance. The research was carried out with the assistance of Mr. J. Blaine, who made the nozzles, Mr. L.J. Tyler, and Mr. K. Davis of the Rock Mechanics and Explosives Research Center staff. We were also ably assisted by Mr. B. Larkin, Mr. L. Ashby, and Mr. J. Carter of the St. Joe Research Department, and Mr. Alan Weakly, Director this assistance and the help furnished by St. Joe under Mr. Casteel, Vice President - Mining of St. Joe Minerals is gratefully acknowledged.

REFERENCES

nozzle holder
9/16" O.D. x 3/16" I.D. stainless tube
typically 25° - 35°

Fig. 1. Original Nozzle Design Configuration

2(a). Hole drilled in destressed ground. The hole diameter is approximately 2 in (5 cm).

2(b). Hole drilled in stressed ground. The oval hole measures approximately 1½ in (3.75 cm) across the horizontal diameter.

Fig. 3. Improved Nozzle Orientation Geometry Showing the Smooth Transition of Flow

Fig. 4. Original Nozzle Geometry Showing the Poor Transition and Flow
Fig. 5. Improvement in Jet Flow with Improved Geometry

Fig. 6. The Effect of Nozzle Geometry on Cutting Depth in Berea Sandstone
Fig. 7. Depth of Cut as a Function of Standoff Distance - at 50,000 psi in Red Granite (nozzle diameter 0.2 mm). (after Cheung)

Table 1. Simulated Drilling Data (Hole Diameters are in Inches)
(Berea Sandstone)

<table>
<thead>
<tr>
<th>Confining Pressure</th>
<th>0 psi (2)</th>
<th>4000 psi</th>
<th>6000 psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>back pressure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 psi</td>
<td>2.0 in.</td>
<td>1.050 in.</td>
<td>1.025 in.</td>
</tr>
<tr>
<td>500 psi</td>
<td>1.025 in.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000 psi</td>
<td>800 in.</td>
<td>.625 in.</td>
<td>.75 in.</td>
</tr>
<tr>
<td>1500 psi</td>
<td>.875 in.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000 psi</td>
<td>.750 in.</td>
<td>.575 in.</td>
<td>.575 in.</td>
</tr>
</tbody>
</table>

Table 2. The Effects on Drill Bit Load Where Jet Assisted is Applied to a 3-3/4" diameter Coring Bit.

<table>
<thead>
<tr>
<th>Advance Without Assist With Assist</th>
</tr>
</thead>
<tbody>
<tr>
<td>rpm</td>
</tr>
<tr>
<td>Rate (0.001 in./rpm)</td>
</tr>
<tr>
<td>58</td>
</tr>
<tr>
<td>91</td>
</tr>
<tr>
<td>136</td>
</tr>
<tr>
<td>Applied Load on Bit (lb) (3)</td>
</tr>
<tr>
<td>5.5</td>
</tr>
<tr>
<td>550</td>
</tr>
<tr>
<td>600</td>
</tr>
<tr>
<td>650</td>
</tr>
<tr>
<td>400</td>
</tr>
<tr>
<td>500</td>
</tr>
<tr>
<td>450</td>
</tr>
<tr>
<td>750</td>
</tr>
<tr>
<td>600</td>
</tr>
<tr>
<td>750</td>
</tr>
<tr>
<td>750</td>
</tr>
<tr>
<td>1000</td>
</tr>
<tr>
<td>1150</td>
</tr>
<tr>
<td>1100</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>1650</td>
</tr>
</tbody>
</table>

(1) 1 psi is equivalent to 6.89 kPa.
(2) 1 inch is equivalent to 2.54 cm.
(3) 1 lb is equivalent to 0.4535 kg.
Introduction

Research into the application of high pressure water jets as a means of improving the drilling rate in rock has been carried out in several locations for the last ten years. Experiments have been tried in oil well drilling, for example, down to depths of over 5,000 m. (Ref. 1) with steel shot used in addition to the high pressure water jets and at depths over 2,000 m. using high pressure jet cutting alone at pressures up to 1,000 bar (Ref. 2).

In 1974 the Rock Mechanics & Explosives Research Center of the University of Missouri-Rolla was funded under contract to the U.S. Energy and Development Administration to develop water jet drilling designs which would allow for the more rapid development of geothermal deposits within the United States. The emphasis to be placed on the research was in application to the drilling of the harder rocks, such as granite, which are more typically found in geothermal sites rather than the softer sedimentary rocks which are more frequently found when drilling for oil and gas deposits. In previous papers (Refs. 3, 4) the development of nozzle designs which have been used to achieve penetration rates in the laboratory of the order of 7.5 m. per minute in sandstone and 1 m. per minute in granite have been described. Laboratory testing, however, can only partially allow simulation of the real world and it is necessary that trials be carried out in the field before a proper evaluation can be made of the true effectiveness of water jets for drilling holes. A secondary problem relating to the use of high pressure jets is that laboratory data indicates (Ref. 4) that the change in stress field applied to a rock changes the resistance of that rock to jet cutting. With this in mind tests have been initiated in cooperation with the St. Joe Mineral Company to determine the effect of stress on drilling rate, using high pressure water jets.

Laboratory Tests

The previous field work which has applied high pressure water jets to oilwell drilling (Ref. 1, 2) has mainly used existing oil field nozzle sizes which range from 3 mm. and above. The designs which have
been developed at UMR use nozzle sizes of the order of 1 mm. For this reason a concern when the testing program was originally undertaken for ERDA was that the jets would be able to cut through materials as the pressures increased on the rock and back pressures built up within the hole as its depth increased. Simplistically a rule of thumb applied in the field is "1 psi per foot of depth for rock pressure and 0.5 psi per foot for fluid pressure". For this reason a series of tests were carried out in the laboratory to examine the effect of confining pressure and back pressure on drilling rate. These tests which have previously been reported (Ref. 4) indicate that there is an effect on drilling rate as the pressure originally comes on to the rock whether applied through a confining pressure or a back pressure within the hole. The result of this was most clearly established in sandstone but was also found present in granite. Nevertheless, despite this change in cutting rate it was possible to drill most materials at rates of over 1 m. per minute. This rate has been established as the upper achievable limit for drilling and is based on the logistic limitations in feeding drill pipe into the hole. Tests in the laboratory have, therefore, restricted to this advance rate.

It is perhaps interesting to note that the change in drilling ability of the jet with confining pressure and back pressure was not in major part related to the pressure drop across the nozzle. This could be easily verified by comparing the difference in the hole geometry as back pressure was increased in the hole (Fig. 1) with that which occurred when the pressure drop across the nozzle was reduced by lowering the driving jet pressure with no back pressure in the hole itself. In the latter case the hole geometry remained of the same shape (Fig. 2) as that of the 10 ksi, no confinement case, but smaller rather than the square ended shape where confinement is applied. Because of this condition, it was felt that there was some change in the rock response due to the effect of confining pressure or back pressure, the exact nature of which has yet to be determined.

Field Test Program

Laboratory testing of the effects of stress on drilling rate was restricted since the tests were carried out in a 15 cm. diameter sample, 30 cm. long, confined within a modified triaxial test chamber (Fig. 3). This did not give a completely realistic stress situation and for this reason it was decided to seek a more suitable test site. Concurrently, since the water jet drill showed promise as a means of improving the drilling rate over that of existing rock drills while reducing the noise levels associated therewith, the St. Joe Mineral Company became interested in this research program. A corporative agreement was signed in the summer of 1977 and a high pressure drilling rig was taken underground at the Indian Creek Mine of St. Joe Mineral and tests were begun in October of that year. The preliminary intention of the tests were twofold; firstly, to demonstrate the potential of the water jet drill as a means of drilling holes to the required geometry for blast rounds, and secondly, to determine the effect of the rock stress on the ability of the water jet to satisfactorily drill through it. At the present time this test program is still in progress and only preliminary data can be reported due to the deadline set for presentation at this meeting. Indications are, however, that there is a considerable effect due to in situ stress on the rock on the cutting ability of the water jets.
Underground Tests

The site which was chosen for the tests is a layer of lead-bearing sandstone located approximately 300 m. below the surface in a barrier pillar area relatively close to the mine shaft. The drilling unit used was a modified Gardner-Denver* drilling jumbo, to one sash of which a high pressure water jet tubing was attached complete with nozzle assembly and rotary coupling. Hydraulic motors were used to rotate the assembly and also to provide an advance for the drill stem as drilling progressed (Fig. 4).

Power to the hydraulic unit was supplied from a hydraulic pump assembly located adjacent to the drilling sash and fluid flow to the high pressure drill and coupling was supplied through a Kobe 150 hp Size 4J pump which fed the water through a high pressure flexible line to the Harwood coupling. Water, filtered twice, at 5 micron, was drawn from the mine sump and mixed with 0.8% soluble oil.

Two types of tests were carried out, one of which was a traversing test across the surface of the rock to determine the ability of the jets to penetrate through the rock and the second was a drilling test in which the nozzles were advanced into the rock face. It was also intended that a section of the rock measuring some 1.5 m. high by 3.5 m. wide be slotted to a depth of at least 1.7 m. so that the rock within this area be destressed and that comparative drilling performance could be measured in the destressed zone and that of the surrounding stressed rock. At the present time establishment of this profile is still proceeding; however, the geometry of the area is such that some observations can already be made. To the left hand side of the projected area (Fig. 5) the rock is solid and under stress to a level above 100 bar, due to the fact that the pillar must carry the burden of the rock which had once filled the opening in which the rig now stands. To the right hand side of the area, however, there are several slabs of rock which have separated from the main pillar itself but are sufficiently large that they remain in place on the side of the pillar. These blocks of rock have therefore been destressed and it was through these rocks that the first slotting tests were made at the test site. A comparison of the effect of stress on the rock could therefore be made as the high pressure jets traversed from the right hand side of the cut up across and then down the left hand side as the jet cut from the unconfined blocks of rock into the stressed zone. The results of such a traverse (Figs. 6, 7) indicate the effect that stress has on the cuttability of rock. The change in the depth of the slot was, at maximum, a reduction in slot depth of some 80% from 20 cm. to 4 cm. deep. The cutting head was traversed across the rock at a rate between 1.3 and 2.6 m. per minute. The exact speed could not be controlled accurately due to the mechanisms involved in moving the drilling jumbo boom. The original intention was to cut this slot by traversing the drill boom while the nozzle assembly rotated. Two problems

*Equipment manufacturers are named for identification purposes only, this should not be considered as an endorsement of their product by the Federal Government, the University of Missouri, or the St. Joe Mineral Corporation.
which arose, the presence of marcasite layers not easily cut by the jet at 900 bar and the instability of the cutting arm as it advanced more than 30 cm. from the sash, have stopped this procedure. Currently the slot is being defined by drilling holes along the profile - with the intention of using the jets to slot between these holes at a later date.

Drilling Tests

A number of tests have been carried out, changing the nozzle geometries in order to determine the optimum design for drilling while maintaining a hole diameter equivalent to that required by the mining company. In the evaluation no completely satisfactory design has as yet proven itself. However, the following points can be made based on the tests to date. These are offered for the guidance of those other who are following similar test programs.

1. Where a water jet nozzle assembly, such as that used in early testing (Fig. 8) is used as the sole drilling device, two opposing problems arise. At slow advance rates the jets will cut to a hole diameter larger than the nozzle and holder. Because the jet design is not axisymmetric this will, as the hole depth exceeds 30 cm., force the nozzle body to precess within the hole (Fig. 9), cutting an uneven geometry and possibly jamming the assembly in a rock projection. Conversely if the nozzle is advanced too fast, relative to the rotational speed (bearing in mind that the hole diameter varies inversely as a function of this speed) then large ribs will be cut in the side of the hole. To illustrate this by an example which occurred: at 500 rpm and 1.7 m./min. advance rate, rib width between successive rotations is 0.34 cm. less the jet diameter (1.5 mm.) to leave a rib 0.19 cm. wide - narrow enough to break easily as the assembly advances; however at the same rpm if the unit advances at 6.5 m./min., the rib width left will be 1.15 cm. - too great to be easily broken. In consequence this rib will contact the nozzle body and, in the abrasive sandstone, will rapidly erode the body, in some cases blanking off a nozzle orifice (Fig. 10).

The solution sought was initially to make the system thrust limited so that, as soon as the nozzle contacted the rock the advance would stop until the obstruction was cleared by the jet. This was achieved by a limit switch placed behind the rotary coupling (Fig. 11) connected to the advance motor, which is held open by a spring located on the drill steel. This will only work if the jet is directed along the edge of the nozzle.

2. The nozzle directed outward should be at an angle in excess of 15 deg to the line of the hole. This is because the jet at this angle cuts inward to the hole center rather than maintaining hole diameter and cutting outwards.

3. A passage for the water to exit must be included in the nozzle body - water jet pressure will otherwise build up in the area ahead of the nozzle and stall the unit. In a similar vein large rock fragments can be trapped ahead of the nozzle and, with no free egress, will erode the face of the nozzle and body.
4. The effect of stress on drilling can clearly be illustrated by the variation in hole geometry. Since the holes are drilled parallel to the bedding plane, conventionally the tendency would be to cut a hole oval in the horizontal plane (Fig. 11). Such a hole was cut in a jointed area of the face, however the typical hole drilled was oval in the vertical plane due to the stress distribution around the hole (Fig. 12).

5. Preliminary data indicate that the design prepared earlier (Ref. 4) is superior to other designs tried (for example, multiple orifice holes to solve the problem of too fast an advance rate relative to the rpm) and that coning the entry to the orifice is well justified by results.

Summary and Conclusions

At the present time the following tentative conclusions can be drawn from this program:

Firstly, the presence of a stress field on a rock will reduce the ability of the high pressure jets to cut that rock or conversely may require a higher jet pressure before such a rock can be cut.

Secondly, that the drilling rate and advance rate must be closely correlated in such a system less the advance rate outstrip the rotational speed.

Thirdly, the stress field under the jet must be considered in the orientation of the jets in order to adequately exploit the rock response to jet action.

Acknowledgements

This work was funded under U.S. Energy Research and Development Administration contract EY 76 S 02 2677.A002 with Mr. Cliff Carwile as the Technical Project Officer, Ms. June Winnikka acted as Contracting Officer. We are pleased to acknowledge this assistance. The research was carried out with the assistance of Mr. J. Blaine, who made the nozzles, Mr. L. J. Tyler, and Mr. K. Davis of the Rock Mechanics and Explosives Research Center staff. We were also ably assisted by Mr. B. Larkin, Mr. L. Ashby, and Mr. J. Carter of the St. Joe Research Department, this assistance and the help furnished by St. Joe under Mr. Casteel, General Superintendent, is gratefully acknowledged.
Fig. 1. Change in hole geometry as a function of borehole pressure - jet pressure 690 bar, advance rate 1 m./min. The borehole pressure increases in 34.5 bar increments from 0 to 140 bar from left to right.

Fig. 2. Detail of the change in hole geometry with the application of borehole pressure. The specimen on the right was loaded to 34.5 bar borehole pressure, 690 bar jet pressure, 1 m./min drilling rate.
Fig. 3. Laboratory rig showing the modified triaxial cell.

Fig. 4. Modified drill sash showing the two hydraulic motors used for movement.
Fig. 5. Overview of the main test area.

Fig. 6. Slot cut in destressed rock - the light band (reading from 0 - 8 inches) was cut in a single pass, the rock on the camera side of the slot was then removed.
Fig. 7. Slot cut in stressed rock under equivalent jet conditions (690 bar jet pressure, 1.5 m./min traverse rate) to that of Fig. 6.

Fig. 8. Jet configuration in the early program.
Fig. 9. Hole drilled too slow (above ruler) showing the effect of the steel precessing.

Fig. 10. Nozzle bodies after drilling at too great an advance:rpm ratio.

Fig. 11. Drill stem detail — showing the limit switch for advance control mounted above the rotary coupling. The potentiometer on the back of the sash monitors the advance.
Fig. 12. Drill hole along a joint (hole above the ruler) showing the horizontal spread of the hole.

Fig. 13. Three holes, drilled at (A) 1 m., (B) 1.25 m. and (C) 1.5 m./min. advance rate at 580 bar jet pressure, showing the effect of rock stress in the oval hole shape. (The 1 m./min. hole orientation is initially accentuated by a slot previously cut along the hole axis).
THE EFFECT OF STRESS ON WATER JET PERFORMANCE

David A. Summers*
L.A. Weakly**

Abstract

Research on the use of high pressure water jet systems to date has mainly concentrated on laboratory simulation tests and field trials on the surface. The effects of field stress have only been simulated, therefore, by sample confinement in triaxial chambers. This paper contrasts such results with data obtained from a test site located 1000 ft below the surface in a stressed barrier pillar. Data is further supplied contrasting the water jet performance in this rock under stress with that achieved in the same area when the rock is destressed. A water jet slotting technique which was used for the destressing is described.

Introduction

Conventionally, the vast majority of holes that are drilled underground, particularly in hard rock mines, are drilled by means of pneumatic hammers. These drilling devices have conventionally achieved adequate performance in terms of productivity but are increasingly being cited due to the noise levels they generate, which lie far above the legal requirement of a 90 db level for 8 hour operation.

The noise generated by pneumatic drills can be divided into three types (Ref. 1) that of the exhaust, that of the internal movement of the parts within the drill and that of the bit striking the rock. Of these,

*Dr. David A. Summers is a Professor of Mining Engineering and Director of the Rock Mechanics & Explosives Research Center, University of Missouri-Rolla, Rolla, Missouri 65401.
**Mr. L.A. Weakly, Director of Mining Research, St. Joe Minerals Corp., Viburnum, Missouri 65566.
the first two can be muffled or reduced to an acceptable level. How-
ever, the noise generated by the bit impact of the rock is a function of
the energy transmittal to the rock and if the noise is reduced by reducing
the energy then so the performance of the drilling bit will also be
reduced. This therefore, is an unsatisfactory solution and another
method must be sought.

There has been considerable interest in recent years in drilling
holes less than 1 in. in diameter. This is particularly a problem in
roof bolt drilling for resin bolt emplacement since the cost of resin
makes large diameter holes expensive and it has been shown (Ref. 2) that
if a small diameter rough hole is drilled that this will be equivalent
in strength to a larger diameter smooth walled hole emplacement. Conventional
drilling techniques however make it relatively uneconomic to drill holes
with diameter less than 1 in. since the shaft in such cases becomes
relative small and a high thrust along the shaft will therefore cause it
to buckle, in turn deviating the hole from the straight line required.

In order to solve both these problems, the application of high
pressure water jets to drilling has come under investigation (Ref. 3,4).
To the present time, the vast majority of this research has been carried
out in the laboratory, with extremely promising results. However, it
is necessary at some stage at the development of any process that its
performance, not only in the laboratory but also in the field be evaluated.

Laboratory Test Program

In 1975, the University of Missouri-Rolla came under contract to
the Energy Research and Development Administration to investigate the
application of high pressure water jets for ultimate application in the
development of geothermal resources. It was anticipated that the major
effort in the research would be directed toward the drilling of hard
rocks such as granite at hole diameters of the order of 6 in. However, in order to develop such a drill, the program was initiated working at hole diameters of 1 in. and less and initially starting out drilling in sandstone and other sedimentary rocks. The reason for this approach was that the softer rock is much more responsive to water jet attack and therefore the effect of change in the control parameters is much more evident than would be the case were the granite used as the target material, where changes in the results would be on a much smaller scale and much less easier to discern. In the early test program, which has previously been described, (Ref. 5) it proved possible to achieve drilling rates of the order of 300 in./min and to achieve a hole of programmable roughness (Fig. 1) using 1 ft long samples of sandstone. The roughness of the wall can be controlled by varying the ratio of the advance rate of the machine to the rotational speed of the shaft. Since the water jet cuts beyond the nozzle diameter, the relative speed of the rotation will control the depth of the cut, while the ratio of the advance rate to rotational speed will control the incremental distance between each successive pass of the water jet across the rock surface.

Because the water jets which are being used in this program are much smaller in diameter than those which have been used in the large scale fuel programs carried out by Gulf, Shell, and Exxon, (Ref. 6,7,8), i.e., being of approximately 1 mm diameter as opposed to the 3 or more mm diameters of the oil industry bits. One of the initial concerns of the program was to verify that these small diameter jets would still cut at depth, where not only was the rock pressurized but there would also be a large back pressure within the hole due to the weight of the overlying fluid column. A series of experiments was therefore carried out in which the effect of rock confinement on the hole diameter was estab-
lished. These experiments were carried out at an advance rate of 40 in./min which level was standardized for all the subsequent tests. This figure was based on a discussion with Dr. Maurer who stated that the maximum advance rate that can be achieved in field drilling is of the order of 200 ft/hr. Logistical problems of handling the drill pipe make increased advance beyond this level relatively impractical. In the initial test program, rock was prepared in samples of 1 ft long, 6 in. in diameter and confined in a triaxial chamber. Confining pressure up to 6,000 psi and back pressures up to 3,000 psi were imposed on the rock specimens. The confining pressure was applied through a rubber jacket which was fitted over the specimen and the triaxial cell was conventionally pressurized. The back pressure was established by gating the flow of the spent fluid from the cavity out of the cell through a valve and pressure gage which could be so adjusted to give the required back pressure. The system was stabilized prior to the advance of the drill into the rock and measurements were only taken in the lower half of the hole assuming that the initial section was effected by the end conditions. The results of these tests show that there was an onset (Table 1) effect at a load of approximately 500 psi which effect was discernable whether the load was applied as a confining pressure on the rock or as a back pressure within the bore hole. The initial assumption was that this pressure was due to lowering the pressure drop across the nozzle and that this effect was causing the reduction in jet cutting ability. A second experiment was therefore carried out in which the pressure drop across the bit was varied by changing the jet pressure but at no back pressure and at no confining pressure although the samples of Berea sandstone were submerged. The results indicated that the jet pressure reduction did not create as large effect as did the confining pressure within the bore.
hole and it must therefore be assumed that the effect which was dis-
cerned is a function of some change in the rock properties.

Experiments were carried out in an extended test series in marble, limestone, and granite. And it was noted in, for example, the granite (Table 2) the effect of increased back pressure was much reduced over that for the sandstone. It is postulated that the advance rate is controlled by a structural property of the material which is strongly effected by confining pressure and the likely candidate would be the permeability of the rock structure.

Field Test Program

The results of the laboratory experiments have shown that there is an effect on water jet drilling performance due to imposed stresses on the rock or in the borehole. The small scale of the test program and the possibility of an effect due to the small size of the samples indicated that these results should be treated with some degree of caution. The University therefore, signed a cooperative agreement with the St. Joe Minerals Corp. in the summer of 1977 in order to pursue this program further, by using a water jet to drill a series of holes in a barrier pillar 1,000 ft down in the St. Joe Lead Mine at Indian Creek.

The rock in which this test program is being carried out is predominantly a sandstone, coarse grained in nature in which lead is found. Preliminary investigation with hand samples brought to the laboratory indicated that drilling rates equivalent to that of the Berea sandstone, could be achieved in this rock. The water jet system was accordingly taken underground (in the form of a high pressure pump driven by a 150 hp motor and capable of achieving either 25 gal/min at 10,000 psi flow or 15 gal/min at 18,000 psi flow). The pump unit was attached to a sled and the drilling system was fitted to the drill sash on one arm of a
Gardner-Denver drill jumbo. In the initial configuration based on the laboratory tests, it was anticipated that holes could be drilled successfully at 10,000 psi. The high pressure water was supplied through high pressure hose to drilling steel comprising of a 9/16 OD high pressure steel pipe to the end of which a nozzle was affixed. The connection between the hose and the tubing was through a free floating high pressure rotating coupling (Fig. 2).

Drive to the motor was established through a pair of hydraulic motors, one to provide rotational speed and the other to provide advance. The use of hydraulic motors, a modification of the equipment from the original compressed air drive, was found necessary in order to achieve the acquired control on the advance rate and rotational speed which could not easily be achieved with the compressed air. Once the system had been fabricated a secondary control was also attached to the system behind the coupling and comprised a micro-switch which went contacted by the coupling would temporarily halt the advance rate on the steel. The intention of this device was so that, if the drill bit came in contact with the rock, it would move the steel and the coupling back against a spring triggering the micro-switch and halting the advancement until such time as the water jet cut out the obstacle. The spring would then push the steel forward and the advance rate would be resumed. While this system did work effectively, one of the problems with the original set-up was that a considerable volume of water was being placed in the hole and, as the hole diameters got smaller, particularly with the large drill bits, this water could not easily pass the bit and therefore tended to pressurize the cavity ahead of the nozzle. This in turn provided sufficient resistance to the advance of the bit that the micro-switch was triggered and the device ultimately had to be removed for
this reason.

The tests began at an operating pressure of 10,000 psi through the nozzle. Various different nozzle geometries were tested and it was found that a number of conclusions could be drawn from these early tests. In the laboratory there had been a range of nozzle angles tested in order to determine the most effective angle for water jet drilling. The results of these tests (Table 3) had indicated that the larger the angle of the reaming jet to the advance of the drill the more effective the bit. However, this did not prove to be a valid criterion in the operation of the system underground. A major reason for this is that as the jet angle is increased so the hole diameter correspondingly increased but, concurrently, the thrust component of the jets perpendicular to the axis of the hole also increased. Since the bit does not normally contact the rock, there is no bracing support to hold the head in position and the drill steel as it advanced into the hole (therefore became unstable) and tended to precess within the hole. The results of this, since the hole was larger in diameter, was that the bit became caught in one of the rough spots on the hole profile with the jet directed perpendicular to the obstruction and the rig would seize up. On the other hand it was noted that where the jet was directed with a very small angle forward, that the reaming jet would rather cut to the central core of the hole than to the perimeter and the edge of the bit would bind up. In the laboratory a 15° included angle was sufficient to have the jet cut to the periphery rather than to the central core, however in the field this value had to be increased to between 20° and 25° before a satisfactory clearance was achieved.

In the laboratory testing, the samples had comprised only sandstone and lead. In the field it was found the sand deposit also contained
marcasite, which is considerably harder than either the sandstone or the lead and this material while it could be cut by the water was not cut nearly as effectively as was the sandstone at 10,000. In consequence, the jets would differentially drill the hole. The result of this was that, as the hole depth increased, so the drill would deviate around these hard inclusions and since they could occur on any side of the bore hole the final result was that the flexible steel would bend in a number of consecutive directions and become jammed in the hole. The only satisfactory solution to this problem which has been found is to increase the jet pressure.

In the search for a nozzle which would effectively cut a large diameter hole it was concluded that a rapid and inexpensive method of nozzle manufacture could advantageously tried and therefore preliminary experimentation involved the use of steel nozzles of the ball nose variety (Fig. 3) which were tested to determine the best nozzle geometry. It was accepted that the performance of these nozzles would be reduced over that of better quality nozzles. A discharge coefficient of approximately .7 was measured for these nozzles relative to the .95 of better quality nozzles. However, since the water jets were cutting only a distance of 1/2 in. or less, from the orifice, it was concluded that lack of performance would not critically affect the drilling rate providing that the change in discharge coefficient could be adequately compensated for. One feature of this type of nozzle is that the nozzle orifice is located on the loading surface of the drill. This is in contrast with the conventional method of drill nozzle location in which the nozzle is recessed within a holder and the orifice is not in close contact with the rock. A problem with this particular design was quickly discerned in that the close proximity of the orifice surface to the rock
meant that the face of the nozzle was scoured by the rebound of the water from the target surface carrying with it particles of sand. A very effective sandblasting system developed and very rapidly removed the surface of the drilling bit (Fig. 4). It was established however using the normal nozzle holders that if this distance could be offset from the face by 0.25 in. that erosion was satisfactorily minimized. It was also found that placing a carbide insert across the face of the bit to help achieve this stand-off distance was effective although there was some abrasion of the carbide. This was not felt to be a problem.

Drilling rates in the field have been much reduced over those found in the laboratory. It has also been noted that in areas of the pillar where the rock is stressed, not only is the hole diameter very rapidly reduced from the 2 in. or more which the jet drills at the entrance of the hole down to approximately 1 in. in the stressed zone, but also that the hole no longer remains circular. The normal bedding of the rock is essentially horizontal and where the jets cut through weak layers of the rock under such conditions, then the hole becomes oval aligned along this plane of weakness. However, in areas where stress is evident the hole becomes oval in a vertical direction. This can be anticipated since one would anticipate that the rock at the top and the bottom of the opening being drilled is under some tensile component of load while that on the horizontal diameter is under increased confining pressure and this appears to be evident in the hole result which is achieved (Fig. 5).

Where the pressure of the jet is increased to 16,000 psi, then advance rates of over 90 in./min have been achieved underground and the hole is satisfactorily straight. However at 10,000 psi the water jet does not give an adequately straight hole and drilling rates of no more
than 72 in./min could be achieved in contrast with the 300 in./min achieved in the laboratory. This reduction in drilling rate with rock confining pressure must be anticipated in the movement of water jets from the laboratory to the field. Further, the water jet pressure should be so adjusted that it is capable of cutting through not only material which is anticipated to be present in the hole but also any harder inclusions which might also occur. A pressure of 16,000 psi has proved adequate to drill not only through the sandstone and lead but also through the marcasite in this instance.

One other factor which must be borne in mind is the flow rate through the bit should be optimized relative to the hole size being drilled. Conventionally, it has been a point of belief that the optimum conditions for water jet cutting were where once, the critical pressure of the rock had been achieved, that any major increase in horsepower to the jet should be through an increase in jet diameter rather than through an increase in pressure. However, in the water jet drilling in depth allowance must be made for getting the water out from ahead of the bit and if a sufficiently large hole is not being drilled then the addition of more water to the bit head will be counter productive since it will tend to pressurize the cavity head of the bit and reduce bit performance.

One further measure of the effect of the confining stress on jet cutting ability should also be mentioned. It was originally intended that the rock insitu be destressed by cutting a slot around the test area so that drilling in a destressed block could be contrasted with that of the surrounding stressed material. It was intended that the water jet slot through this rock using a linear traverse of the drilling bit. It was noted that where the water jets cut through the sandstone where the rock was destressed that a cut depth of approximately 8 in.
was achieved on a single pass (Fig. 6). However, where the water jet was cutting through a stressed area of the rock a depth of only some 1 1/2 in. was achieved on a single pass (Fig. 7). Because of the instability of the drill steel system as it was advanced beyond the end of the drill sash it was decided not to use this system for the distressing and instead a series of consecutive holes has been drilled to a depth of 6 ft in order to establish the distressed area. During the drilling of these holes it has been demonstrated that providing some care is taken with the operation of the drill that the water jet drill can drill through the pre-existing hole and continue the alignment of the new bore hole passing through the hole previously drilled.

During the course of these trials noise levels were monitored in order to determine the effect of the water jet drill. It has been noticed that one yard from the hole in noise level of 85 db was monitored during the operation of the drill. While this level is increased during the time that the bit stings into approximately to 95 db, it is nevertheless one advantage to this system that a quiet rock drill has been developed.

Conclusions

The continuing program herein described has shown that water jets can be used effectively for drilling rock underground. However, it is also demonstrated that the results obtained in the laboratory cannot be directly translated into performance underground since the effect of rock confining stress is to reduce the performance of the water jet drill. This performance loss to a degree can be compensated by increasing the pressure of a system over that used in the laboratory trials to an equivalent level to compensate for the increased confining stress. However, the pressure should also be increased to take into
effect the additional likelihood of a higher strength rock existing within the natural formation beyond that of the rock which is being tested in the laboratory. The flow rate and nozzle geometries should be designed to cope with the need to get water away from the bit once the jet has made its cut and the bit nozzle orifices should be recessed within the bit to protect them from the abrasive nature of the initial flow from the cutting surface.

Acknowledgements

This work was partly funded under U.S. Energy Research and Development Administration contract EY 76 S 02 2677.A002 with Mr. Cliff Carwile as the Technical Project Officer, Ms. June Wiinikka acted as Contracting Officer. We are pleased to acknowledge this assistance. The research was carried out with the Assistance of Mr. J. Blaine, who made the nozzles, Mr. L.J. Tyler, and Mr. K. Davis of the Rock Mechanics and Explosives Research Center staff. We were also ably assisted by Mr. B. Larkin, Mr. L. Ashby, and Mr. J. Carter of the St. Joe Research Department, this assistance and the help furnished by St. Joe under Mr. Casteel, Vice President-Mining of St. Joe Minerals is greatly acknowledged.

*The company identified herein is for the purpose of identification only and no product endorsement should be read into this reference.*

141
References


Table 1.
Simulated Drilling Data (Hole Diameters are in inches).

CONFINING PRESSURE (psi)

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>4000</th>
<th>6000</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRESSURE (psi)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>2.0</td>
<td>1.050</td>
<td>1.025</td>
</tr>
<tr>
<td>1000</td>
<td>0.800</td>
<td>0.625</td>
<td>0.75</td>
</tr>
<tr>
<td>2000</td>
<td>0.750</td>
<td>0.575</td>
<td>0.575</td>
</tr>
</tbody>
</table>

Rotational speed-500 rpm.
Advance Rate-40 in./min.
Rock-Berea sandstone.
<table>
<thead>
<tr>
<th>Jet Pressure</th>
<th>Diameter</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>10,000 psi</td>
<td>2.180</td>
<td>Back Pressure-0 psi</td>
</tr>
<tr>
<td>9,000 psi</td>
<td>1.875</td>
<td>Confining Pressure-0 psi</td>
</tr>
<tr>
<td>8,000 psi</td>
<td>1.725</td>
<td>Rotational Speed-500 rpm</td>
</tr>
<tr>
<td>7,000 psi</td>
<td>1.650</td>
<td>Advance Rate-40 in./min</td>
</tr>
<tr>
<td>6,000 psi</td>
<td>1.350</td>
<td>Rock-Berea Sandstone</td>
</tr>
<tr>
<td>5,000 psi</td>
<td>1.150</td>
<td>Nozzle-Type 22</td>
</tr>
</tbody>
</table>
Fig. 1. A Section of Water Jet Drilled Hole Showing the Roughness Achievable.
Fig. 2. The Arrangement of the Water Jet Drill on the Jumbo.
Fig. 3. The Free-Floating High Pressure Coupling and Micro-Switch.
Fig. 4. Water Jet Drilling with the High Volume Flow.
Fig. 5. Ball Nose Nozzles Showing the Erosion (in Profile) due to Fluid Rebound.
Fig. 6. Holes Drilled by Water Jets Showing the Effect of the Stress in Vertically Elongating the Holes.
Fig. 7. Overview of the Test Site Showing Hole and Slot Cutting Results.
A CONTRAST BETWEEN SAND, WATER, AND CAVITATION EROSION OF ROCK

by

A.A. El-Saie*

D.A. Summers**

and

K. Owen***

Abstract

Field research in oil well drilling has shown the advantage of adding high pressure jet nozzles to rock drilling bits. Some additional advantage has been found by adding an abrasive to the fluid, and this has also been tested in the field, but several problems were encountered which stopped the project.

The research described examines the potential benefits of adding sand, as an abrasive, to water jets in order to improve the penetration rate in granite. An improvement in performance is achieved; however, when the fluid velocity exceeds 300 m/sec, it is shown that cavitating the jet flow is a more effective means of improving jet cutting ability.

The reasons for this are discussed with the aid of thin section microphotographs of the rock targets after testing.

Introduction

The major function of many wear engineers is to determine methods and materials whereby the erosion or wear of materials from a surface can be reduced. There is, however, a relatively large industry devoted

*Senior Research Engineer, Ingersoll-Rand Research, Inc., Princeton, N.J. 08540
**Professor of Mining Engineering, Director, Rock Mechanics & Explosives Research, University of Missouri-Rolla, Rolla, Mo. 65401
***Former Graduate Student, University of Missouri-Rolla, Rolla, Mo.
to a completely contrary endeavor. This is the excavation industry, and the sect thereof which most closely relates to the wear engineer is perhaps the group examining the drilling aspect of rock excavation.

Historically, drilling has been achieved by the indention of a hardened tool into the rock surface at either a high or low rate of loading, and in this manner the rock immediately under the tool point is generally crushed and then a subsidiary chip is created beyond the indentation point, giving a relatively larger volume of rock removal than that achieved by straight crushing. This process, whether generated by an impact loading, as with a hammer and chisel, or with the lower rates achieved where a roller cone indentation is used, or in a third option, where a bit is dragged across the surface, indented at some depth into it, have all been improved but only in an evolutionary manner within the past few decades. In order that a more advanced rate of penetration be achieved, there has been within the last ten years a considerable amount of research into the application of novel techniques for improving the drilling rate.

Conventional bit usage causes failure to rock through compressive loading, and the forces required to achieve penetration can be quite high. For example, in drilling a 3-1/2 in. diameter hole in coal, a relatively soft rock, forces of over 2000 lbs are required to push the tool forward (Ref. 1). The structure and strength characteristics of rocks, however, are such that these materials are much weaker in tension and shear than they are in uniaxial compression or, as is more likely in an underground drilling situation, in triaxial compression. (An order of magnitude or greater difference exists between typical rock compressive and tensile strengths.) Under these circumstances the University of Missouri-Rolla has embarked on a series of experiments
to determine if high pressure water jets could advantageously be used in the drilling process. The objective was not a simple one, since it was determined that water jets alone require high levels of energy to remove the rock by direct attack and it was therefore determined that water jets in conjunction with a mechanical device would be much more effective in rock removal.

The benefit which can be achieved by using water jets is that the jet device can transfer a very high level of load to the rock under the jet point of attack, thus cutting a relatively narrow and deep slot in the rock surface. This, if done repeatedly, will leave ribs of rock standing proud of the main surface and these can be relatively efficiently broken off, failing the rock at the bottom of the cantilever either in tension or shear, and thereby reducing considerably the amount of force required to advance the drill into the hole. For certain rocks, where the rock is permeated with tensile weakness planes or bedding planes, such as, for example, coal, very little if any force is required to break off these outstanding ribs of coal, and it has been found possible to drill a hole in coal to a dimension of approximately 7 in. with a forward thrust on the drill device of less than 200 lb (Ref. 2).

There appears to be a number of potential advantages to the use of water jets in the drilling industry. The tests which have been carried out at various laboratories have all, however, indicated that each rock has a threshold pressure required of an impacting jet before this jet can effectively penetrate the target rock. For certain of the igneous rocks this pressure is quite high, exceeding in a number of cases 15,000 psi. The problem that arises in this situation is that there is not, at present, very reliable equipment available for long term use in the mining environment capable of operating at this pressure. While it is
possible to buy commercial equipment which will operate at pressures of 60,000 to 100,000 psi, the ancillary rotary couplings, high pressure tubing, at adequate diameters, and seals, are not readily available, in sufficiently reliable form. To this end, work at the University has been directed toward finding methods whereby the pressure of the water can be lowered and still effectively penetrate the rock material. This has meant examining some of the "problem" areas which arise in normal wear in industrial operations, and seeing if this "problem" can be used as a "solution" in the drilling application. Two main systems have been examined. The first is the use of particulates in the drilling fluid, and the second is the use of cavitation bubbles induced into the drilling fluid.

Abrasive Jets

The use of abrasive-laden jets as a means of jet cutting is not in itself a novel idea. It was first used as a means of cutting the casing and improving the down hole conditions for extracting oil from a rock deposit, in the 1950's. The most extensive evaluation of its usage has been in the development by Gulf Research Corporation (Ref. 3) as a means of improving the drilling rate of oil wells at depth. Holes were drilled to approximately 14,000 ft and it was found that by adding an abrasive to the jet flow system that the drilling rate could be increased to levels of up to 80 ft per hour and that considerable advantage could thus accrue to its development. However, at the time that these experiments were carried out there was a considerable expense involved in the pumping aspects of the high pressure fluid, and this research has in recent years fallen into abeyance. The research at the University of Missouri-Rolla has examined, in the laboratory, the benefits which accrue when an abrasive material, in this case, sand (Table 1), is introduced
The majority of this research, however, has been at jet pressures below 5,000 psi where the force of the cavitation bubble collapse in itself is used as the means of cutting through the target material. This force is very small in duration although high in magnitude, and penetration rates have therefore been relatively low, generally in terms of inches per hour. Since the intension is to increase the advance rate of the drilling over that of conventional equipment, which is capable of advancing at a rate of 10 to 15 ft per hour in granite, then a different approach would appear to be required.

To this end it was the UMR approach that, if water jets could be cavitated at a high pressure in the range from 10,000 to 15,000 psi, then in this event, the water jet itself would have sufficient power to exploit the microcracks generated in the target material by cavitation bubble collapse.

To verify this idea the experiments carried out with the abrasives were repeated, but using instead a cavitation induction with the jet in contrast to the addition of the abrasive.

The results showed that at pressures below 10,000 psi that the abrasive-laden jet was more effective than the cavitating jet (Fig. 1) but as the pressure passed between from 10 to 20,000 psi (Figs. 2 and 3) that the cavitating jet became the more effective. This has a number of advantages, in that the water jet which requires an abrasive is much more difficult to pump due to practical problems associated with introducing abrasives into high pressure lines where the fluid pressure is above 10,000 psi, and also the highly abrasive nature of the particulate-laden jet is likely to cause very rapid wear within the drilling system itself so that the lifetime of the parts may not be great. In contrast, where cavitation is induced, no additional
material is introduced into the jet flow until the cavitation inducing device is attached at the nozzle. This, therefore, has considerable advantage to the operation and lifetime of the equipment.

Target Damage

The samples of granite which had been attacked by the water jet were examined under the microscope and part of the reason for the improvement in the performance of the cavitating jet over the abrasive jet at larger pressures can be seen by contrasting the two types of surface created (Figs. 4 and 5). In the case of the abrasive-laden jet (Fig. 4) the surface profile left in the rock is relatively smooth and the damage to the rock surface is confined to a narrow zone, less than 0.01" thick. The surface profile remains relatively constant across the various mineral crystal boundaries and there is no evident exploitation of the crystal boundaries. Subsurface damage appears confined to cracks, generated in the crystals parallel to the impact surface, and there are no large cracks growing perpendicular to the impact surface. It should be noted that in order to protect the specimen during the preparation of the thin section the sample cavity was first filled with an epoxy, and the sample was not ground to the narrow dimension used in conventional geological practice in order to protect the damaged surface.

In contrast to the abrasively impacted target, the sample subjected to cavitation attack shows a much different result (Fig. 5). The cavity created along the crystal boundary to the left of the center of the photograph extends seven times the depth of the damaged zone for the abrasive sample. The zone of damaged rock is not present in the same form. It is postulated that the penetration of any cavitating jet into this zone would allow the fluid to penetrate into these cracks ensuring immediate material removal. Large crystals have been
removed from the target surface and those that remain have been pitted differentially allowing fluid access and the resulting fluid wedge, due to the impact of the ensuing jet, would thus be able to readily exploit this advantage.

There is little evidence of the multitude of surface pits which are found where metal is impacted by a cavitating flow. One possible reason for this is the relative size and nature of the crystal constituents of the granite, which are less ductile and cracks, once induced are more likely to propagate. The rew that are present would likely be transient in the rapid penetration of the sample.

Virtually all the crystal boundaries have been exploited and penetrated beyond the average surface profile and some undercutting of crystals is evident. The penetration depth is not consistent across crystals of different minerals.

The purpose in changing the content of the cutting fluid was to determine if it would be possible, by such means, to lower the effective pressure required for a cutting jet, while retaining the high penetration rate. The most effective pressure for drilling granite with a jet has, in other work, been found to be 20,00 psi. If the relative performance of the abrasive and cavitating jets is judged against this standard (Fig. 6), it can be seen that only the cavitating jet flow has improved the potential penetration rate over that of the 20,00 psi jet.

At interpolation from the preliminary results obtained suggests that the jet pressure might be reduced to 11,600 psi and still maintain the same cutting ability, where the flow is cavitated. This reduction in pressure brings the operating conditions within the range practically available. It also means that for a given pump horsepower a larger flow volume will be available, thus further increasing the damage potential.
Conclusions

It has been shown, in a small-scale laboratory study, that the necessary pressure required to advantageously drill granite can be reduced from 20,000 psi to 11,500 psi if the fluid flow is cavitated.

The advantage of cavitation in improving jet cutting ability is found to be greatest at pressures above 10,000 psi. Below this jet pressure range a greater improvement is obtained if an abrasive is introduced into the jet fluid.

Acknowledgements

This research was carried out at the Rock Mechanics and Explosives Research Center under funding from the Department of Energy Contract No. DOE EY 76 S 02 2677.M003. Mr. Cliff Carwile was the Technical Project Officer, Ms. C. Povalish and Ms. J. Wiinikka, Contracting Officers. We are pleased to acknowledge this support. The research was carried out with the assistance of Mr. J. Blaine of the Rock Mechanics and Explosives Research Center staff and Mr. M. Roberson of the Geology and Geophysics Department.
References


Fig. 1 Relative erosive capability of jets at various pressures, as a function of standoff distance.
Fig. 2 Relative erosive capability of jets at various pressures, as a function of standoff distance.

Fig. 3 Relative erosive capability of jets at various pressures, as a function of standoff distance.
Fig. 4 Red granite sample sectioned after impact by an abrasive-laden jet. (Magnification 6X)

Fig. 5 Red granite sample sectioned after impact by a cavitating jet. (Magnification 6X)
Fig. 6 Relative erosion capacity of jets as a function of pressure at 15 cm standoff.
Table 1

Size Distribution of Graded Quartz Sand Used

<table>
<thead>
<tr>
<th>Size (m)</th>
<th>Retained Weight (gram)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+0-147</td>
<td>62</td>
</tr>
<tr>
<td>+147-208</td>
<td>325</td>
</tr>
<tr>
<td>+208-295</td>
<td>375</td>
</tr>
<tr>
<td>+295</td>
<td>203</td>
</tr>
</tbody>
</table>

TOTAL 965
CAVITATION AND THE CUTTING OF ROCK

by

Philip R. Scott* & David A. Summers**
University of Missouri-Rolla

Introduction

There is an increasing application of high pressure water jets, at pressures up to 20,000 psi, in the industrial cleaning business and after many years of research water jets are finally being introduced into the mining and drilling industry as potential means of improving productivity.

In order to effectively cut a rock it is necessary that a threshold pressure, a function of the mechanical and structural properties of the rock, be exceeded by the impinging jet. For many of the harder rocks this threshold lies at or above 15,000 psi, the approximate limit for reliable operation of many of the accessories, hoses, swivels, etc., required in the development of a water jet extraction system. Because the jet effectiveness is controlled, to a degree, by the structure of the rock it is possible, where the structure of the rock is modified, to reduce the threshold pressure required for the jet and, therefore, the operating pressure of the system.

The intention of the cavitation program at the University of Missouri-Rolla is to use cavitation in the jet flow to create microcracks in the rock structure, thus weakening it so that the rock can be more easily excavated by the surrounding jet.

---

*Mr. Philip R. Scott is a Graduate Research Assistant in the Rock Mechanics & Explosives Research Center at the University of Missouri-Rolla.

**Dr. David A. Summers is a Professor of Mining Engineering and Director of the Rock Mechanics & Explosives Research Center at the University of Missouri-Rolla.
In order, however, to achieve this result it was considered necessary, as a complimentary program, that a means of assessing the cavitation resistance of rock be established. This paper describes the status of those attempts.

Standard Cavitation Testing

The initial method of test was the ASTM standard method of using a vibratory horn suspended in a container of water (Ref. 1). The specimen, of approximately 5/8 in. diameter is glued to the end of this horn (conventional metal specimens can be machine threaded to screw into the horn, but this is impractical with rock), which is vibrated at 20 Kh.

This test proved impractical for rock specimens since, over a conventional range of adhesives used in conventional tensile tests of rock, the specimen failed early in the test, normally at the horn tip/adhesive/rock interface.

Close Clearance Stationary Specimen Test

The test program was redesigned to evaluate use of the "stationary specimen" method which is currently under standardization evaluation by the Erosion and Wear Committee of ASTM. This method (Ref. 2) requires that the specimen be located close to, and directly under, the vibrating horn which vibrates under the same conditions as that of the standard method.

The specimen is, of necessity, submerged during this test procedure and one of the early problems in evaluating the test for rock was that the various rocks tested had a varying porosity/permeability and this affected the water content. It was decided that each weighing should be carried out in a constant humidity environment after the rock weight had
stabilized. Most rocks achieve this within 24 hr but dolomite and shale required from 36 - 48 hr to so stabilize, too long a period for the many tests which were to be required in the initial evaluation for parameterization of the standard.

For this reason the initial evaluation of the effectiveness of this method has been made using metal targets typically using the metals which have been recommended (Ref. 2).

A preliminary correlation between samples tested with the current standard and the stationary specimen test showed that a lower specimen weight has occurred (Fig. 1), at the recommended standoff distance of 0.018 in. The approximate accuracy of this value was verified in a test series in which standoff distance and horn amplitude were varied. There has been some concern, which has been expressed in meetings of the Erosion and Wear Committee, that heating and particle erosion might occur, especially at the longer exposure times, and this has led to a suggestion that an external flow be directed over the specimen surface. Three methods were examined for achieving this, firstly a cross flow from an orifice located beside the specimen and secondly a central flow directed up through a hole drilled in the specimen center while in the third variation this flow was reversed. There was a considerable variation in the results as a function not only of the flow location but also the volume of the flow (Fig. 2). The effect of flow reversal was examined using a softer aluminum, which thus allowed a more rapid (1 hr as opposed to 2 hr) evaluation (Fig. 3).

In evaluating the two methods it was considered that the variables associated with a lateral flow would be too difficult to accurately control and for this reason the flow through the central orifice was chosen as the standard because of the greater damage potential, flow out 169
was also chosen. However, the degree of variation in the results as a function of the fluid flow and the effect of the gap width on the ensuing lateral velocity across the specimen predicated an experiment examining the effect of flow volume and standoff on the erosion rate.

Flow rates were varied in the range from 0 to 0.8 l/min and standoff in the range from 0.015 to 0.050 in. The results are summarized in Figure 4. During these tests a sequence of rock specimens was also tested to examine the response of the various rocks to cavitation impact, it is noteworthy that the erosion resistance is not a clear function either of the rock compressive or tensile uniaxial strength (Table I).

Conclusions

As a result of the test program to date we have concluded that there are a number of parameters which need to be identified and standardized before an adequate procedure can be defined. While we are still working toward this goal we have constructed and intend to evaluate the Lichtarowicz cavitation cell (Ref. 3) for its potential as a means of testing cavitation resistance. This cell utilizes cavitation in a high velocity fluid flow and it is hoped that this will allow for a more rapid and yet still accurate test method, the results of which will be correlated with the ongoing test described above. One change which will already be made in the standard method we use will be to increase the standoff distance to 0.028 in. at a flow rate of 0.3 l/min.

One other factor which has emerged from the ongoing program with cavitating nozzles in the full scale laboratory and field tests is that, as proposed when the method was conceived, the main fluid flow does considerably enhance cavitation erosion in rock, although not, at 10,000 psi, in aluminum. The identification and separation of these two effects
poses an intriguing problem for our future investigation.

Acknowledgement

This research was funded as part of a contract on the use of high pressure water jets to enhance drilling of geothermal wells, funded by the Geothermal Division of the Department of Energy. We gratefully acknowledge this support and the advice and assistance we have obtained from Mr. C. Carwile, and Ms. J. Winnikka of the Department of Energy and Mr. J. Barnette of Sandia, our contract supervisors.

Equipment for this research was constructed by Mr. B. Hale, Supervisor of the Technical Laboratory at the Research Center and the paper was prepared by Mrs. B. Miloradovich. We appreciate with gratitude this assistance.
Fig. 1. Relative erosion of a nickel horn tip and underlying specimen using the "stationary specimen" test.

Fig. 2. Relative erosion of aluminum specimens under varying coolant flow conditions and cavitation attack.

Fig. 3. Effect of flow direction on cavitation erosion of aluminum.

Fig. 4. The effect of flow rate and standoff distance on the cavitation erosion of aluminum.
THE USE OF HIGH PRESSURE WATER JETS IN THE MINING INDUSTRY

Introduction

It is perhaps fitting that at the end of the 125th anniversary year since Matteson first developed hydraulicking as a means of mining gold in California, that the latest developments in the technology be reviewed.

At the present time the National Coal Board is concluding an investigation evaluating the use of water jets as a means of improving productivity in the United Kingdom coal industry. During this review they have extensively investigated the application mainly of lower pressure, high volume water jets as a means of coal extraction around the world. That report, previously reviewed in this journal (Ref. 1), together with other reviews of this subject which have been written by the present author (Refs. 2 and 3), will sufficiently describe the usage of such systems for coal extraction.

The major application for this low pressure, high volume mining has been in seams which are relatively thick and which dip at some considerable slope so that the volume of water which is used to mine the coal can also be used to transport the coal from the working face back out of the mine. In this manner coal seams have been mined successfully in Russia, China, Japan, Canada, and Germany.

The application of low pressure, high volume mining, however, is in large measure restricted by the geological conditions in which it can successfully be applied. Not only must the coal be relatively thick and inclined but the roof and floor rocks must be capable of standing during the mining operations since no roof support is introduced during the mining process. Concomitantly, the use of the large volume flow of water requires not only that the mine can be very well detailed in order
to allow hydraulic transportation of coal from the working face but also a considerable modification must be made in the coal preparation plant, due to the change in the size distribution of the coal that is produced. In most of the operations the coal is crushed in some part of the extraction process producing considerable amounts of fines which require additional precautions to be taken in the cleaning cycle if the system is to be at its most productive.

Thus, while there are many advantages in terms of productivity and safety where low pressure, high volume hydraulic mining can be used, there are limits to its useful application. It is in this regard that one must consider the potential benefits which may arise if a different use of hydraulic jet cutting is applied, namely, working with a higher pressure and lower volume system.

In this current paper four separate systems which have been developed at the University of Missouri-Rolla will be described and their application in the coal industry outlined. The use of water jets in coal has proven to be successful because of the unique structural characteristics of the coal mass whereby it is interladen with bedding planes, cleat planes, and other fracture plants. Because the water jets which are used at higher pressure, being of smaller volume, are of relatively small diameter (1 mm being typical), the slots which they cut in coal are relatively narrow. Typically one finds that a slot cut will be approximately four times the width of the attacking jet. This means that the jets must be moved relatively rapidly if they are to remove large quantities of material. A second characteristic of such jets which is more discernible in sandstone and other granular rocks than in coal, is that where the jets cut adjacent paths one to the other, that the intervening rock of rib is not necessarily removed (Fig. 1).
such cases the water jet is not by itself the most effective method of rock removal since the ribs between successive jet passes are sufficiently fragile that they can be removed by fingertip pressure. In such circumstances it is obviously, therefore, much better to combine water jet cutting with mechanical assistance. However, where holes of relatively small diameter are required and where the water jets can be sufficiently oriented, then such additional assistance is not the case. Conversely, on holes of diameter larger in rock than approximately 5 cm. and where water jets are used for large scale rock removal such as is the case with the tunnel boring machine program currently under development in Germany, (Ref. 4), then water jets are best combined with a mechanical breakage system.

Small Diameter Hole Drilling

Holes of diameter less than approximately 5 cm are becoming more common in the mining industry, particularly where roof bolting is introduced as the prevalent method of roof support. More particularly in the case of roof bolting, recent developments have led to the more widespread development of the resin-anchored dowel as a major method of roof support. Such dowels have historically shown themselves to be of considerable benefit whether for the emplacement of steel dowels, or major roof support, or with the use of a wooden center piece for support in coal which must later be mined. One of the major problems associated with the use of resin anchors is the relatively high cost of the system insofar as the hole must be completely filled with material. For this reason it is more advantageous to drill the hole to as small a diameter as possible. Conventionally such holes are drilled mechanically and under such circumstances the hole walls are relatively smooth. It has
been shown by Karabin and Debrevec (Ref. 5) that such a hole is not most advantageous to the use of resin since very little mechanical anchorage will then result between the resin and the surrounding rock wall. Conversely, if the wall of the borehole is roughened then a much better anchorage can be achieved and in an example cited it is shown that a 2.5 cm diameter resin bolt emplaced in a roughened hole is almost twice as strong in pull strength to a bolt of 3-4 cm diameter where the hole walls are smooth. As hole diameters less than 2.5 cm are required, however, a further problem arises with the use of mechanical drilling systems since the high thrust of the bolter along the drill steel will, as hole lengths up to 2 m are drilled, cause deflection of the steel under the high forces required for rock penetration at an acceptable advance rate. Under such circumstances it is difficult to maintain hole alignment and problems ensue also with maintaining an adequate advance rate.

In research carried out at the University of Missouri-Rolla under a grant from the Geothermal Division of the Department of Energy it has been shown that by using a nozzle design developed at Rolla that water jets can drill through rock at advance rates of up to 7.5 m per minute at hole diameters less than 2.5 cm (Fig. 2). The holes which are thus achieved are relatively rough in nature, the exact profile of the hole being determined as a function of the rotational speed of the drill itself in relation to the advance rate. By varying this parameter so the roughness of the hole can be to an extent controlled giving either relatively smooth surfaces at high rotational speed and relatively rough surfaces at slower rotational speeds (Fig. 3). As a consequence of this research program two contracts have been let by the Bureau of Mines to Flow Industries of Seattle, Washington and Colorado School of Mines in
Golden, Colorado to develop roof bolting systems which incorporate high pressure water jets for drilling high speed roof bolts (Refs. 6 & 7). Both of these trial systems have been completed through prototype equipment construction and preliminary testing and the Flow device was recently demonstrated through the use of film at the 4th International Symposium on Jet Cutting Technology at the University of Canterbury (Ref. 6). In the film the roof bolting rig is shown drilling through sandstone at rates of approximately 8 m per minute. It is the intention of this program that these devices will be field tested in underground mines within the near future.

Concurrent with these developments the University of Missouri-Rolla has continued its research on the use of high pressure water jets for drilling in rock. During the course of the winter of 1977-1978 an agreement was entered into between the University and the St. Joe Minerals Corporation which operates lead mines in the southeast section of Missouri. The intention of this research program was twofold: firstly, to demonstrate to the industry that water jets were capable of drilling through rock at an acceptable rate and producing holes of the required size for blasting the rock during the conventional drill and blast cycle; and secondly, on the University's behalf to determine the effect of in situ ground stress on the behavior of the water jets as they drill through the rock material. In order to more easily integrate the equipment into the cycle and give some indication as to its potential uses, a water jet drill system was developed and attached to one of the booms of a Gardner-Denver drilling jumbo (Fig. 4). A series of experiments were carried varying the pressure and nozzle geometry of the system as holes were drilled up to 3 m into the sandstone pillar which was being used as a test site. This pillar was located 310 m below the
surface and adjacent to a large worked out area of the mine so that stresses within the body of the pillar were quite considerable and these taken into consideration with the particular geometries used in testing the rock, led to predicted stresses of the order of 28 MPa being present in certain areas of the rock as it was drilled. The only modifications other than the change in the drilling system was to change the conventional pneumatic rotational and advance mechanisms for hydraulic drives. While this gave slightly less power to the system, it also gave a much higher degree of control to the advance rate and rotational speed which was required.

Preliminary laboratory results prior to the field testing had indicated a substantial change in drilling performance with the onset of stress in the rock. However, it was also indicated that once the threshold pressure of the rock had been exceeded, it was more advantageous to use a higher flow rate and lower jet pressure than the converse in obtaining optimum results for drilling. For this reason the initial experimentation in the mine was set up at a pressure of approximately 70 MPa and a flow rate of 100 l per minute.

These trials did not give as high a penetration rate through the rock as had been anticipated based on the laboratory investigations. Upon consideration it was shown that one of the reasons for this was the high volume flow through the nozzles since the jets were cutting a hole only slightly larger in diameter than the nozzle body. Flow of water from the cutting zone was restricted and this led to a buildup of pressure forward of the nozzle. This buildup in pressure reduced the pressure drop across the nozzle and reduced the effective cutting performance of the jets considerably. For this reason in later trials the flow rate was changed from 100 l per minute to 60 l per minute and a
higher advance rate (2.25m/min) was achieved at equivalent hole diameter. It was also found that some changes in the nozzle geometry were necessary in order to maintain high advance rate and, a recurring problem in field applications of water jets tried at UMR, the presence of marcasite in the lead bearing sandstone also proved to present problems. The reason for the problems arising with the marcasite were not particularly that the jet could not cut through this material but rather that it did not cut this material as well as it cut the surrounding sandstone so that the jet would leave residual pieces of marcasite on the sides of the borehole, and as the jet advanced the drill would then ride up over these projections. As a consequence the drill would be slightly deflected and as this continued down the length of the borehole, a series of different deflections would occur so that a) the hole was not maintaining true alignment, and b) the consequent deflections of the steel required a higher torque in order to rotate the steel while at the same time increasing wear on the high pressure tubing. Later experiments were carried at higher jet pressures and it was found that where the pressure was raised to approximately 85 MPa the marcasite was sufficiently penetrated by the jet that these problems no longer developed. At the conclusion of the field trials advance rates of up to 2.2 m per minute had been achieved in the rock and hole diameters up to 5 cm had been drilled. These were sufficient to demonstrate the basic viability of the water jet as a means of drilling the blast holes in the mine.

Two other points which might be pointed out as a result of this preliminary program were that the jets have one advantage over conventional drilling insofar as if the hole is not sufficiently large when the hole is drilled with the bit advancing, then the pressure may be maintained on the bit and rotation continued as the bit is withdrawn
from the hole and under such circumstances an additional centimeter or
so of hole diameter may be achieved. Secondly, if sufficient care is
taken with the materials of which the nozzle is constructed, then this
will not wear out nearly as rapidly in drilling through abrasive materials
such as sandstone as will conventional carbide bits insofar as the cutting
edge of the system is water which has already left the nozzle and,
therefore, there is no direct contact between the nozzle and the metal
components of the drill and the rock being penetrated.

While not a part of this particular experiment, it might also,
however, be of interest to mention that in the preliminary experiments
which were carried out at the University of Missouri testing the sandstone
for its drillability, it was found that where a water jet pressure
between 40 and 55 MPa was used to drill the material the grains of sand
and lead were being eroded out of the solid essentially intact and since
there was a size differential between sand grains and length grains, it
was possible to do a fair degree of concentration at the lead ore from
the sand by a sieve sizing as the debris came out of the borehole.
However, in the field experiments it did not prove possible because of
the higher pressures which were used in the drilling process to overcome
the problem with the marcasite.

One word of caution for other investigators in the field might also
be added to this point. High pressure water, at these flow rates and
pressures can lose a considerable amount of energy (in our case over
30%) if very narrow diameter tubing is used, because of frictional
losses on the pipe walls. It has been our experience that, where
possible, 1 cm inside diameter tubings is required to minimize this
problem. Use of this tubing has the additional advantage of making the
steel more rigid and less easy to deflect within the hole.
High Pressure Coal Mining

In the discussion on drilling using high pressure water jets, above, it was mentioned that where holes of diameter more than 5 cm were required, it was more advantageous to use water jets in combination with some form of mechanical assistance than it was to use water jets by themselves, so it is in the large volume removal of coal since, for a mining machine to be productive, output levels in the order of several tons per minute should be achieved. This suggests that water jets alone cannot be advantageously used to mine coal, providing that the large volume system in use at Kaiser and other places is not considered.

In the evaluation of a water jet machine design it must be borne in mind that most coal seams in the United Kingdom and elsewhere are relatively horizontal and do not have roof and floor members which are particularly resistant to water attack. Under such circumstances the use of large volumes of water is precluded and therefore, as a starting point for designing a water jet mining machine for such conditions a flow rate of some 50 gallons per minute was chosen. This is the level at about which many machines will produce water sprays to suppress coal dust particles generated during the mining process. The machine which was designed at the University of Missouri-Rolla was also built around the premise that as little as possible of the mining system should be changed in adapting this new technology. For example, it has been mentioned earlier that if a complete hydraulic mining and transportation system is included then, not only is the mining machine changed, but also the transportation system and the coal preparation plant must also be changed, requiring considerable investment. For this reason the machine design was built around pre-existing equipment to fit within the constraints of current longwall mining equipment using, to as great a
degree as possible, parts of this equipment. The most productive mining machine currently on hand is the longwall shearer, and this formed the basis for the design and while the detailed description of the results of this construction and the evaluation of field testing has been given elsewhere (Ref. 2), a brief summary will be included within this paper to make the paper more comprehensive.

The machine was designed around a modification of the British Jeffrey Diamond Supermatic Powerpack. The gear drives, the shearer drum and cutting arms were removed leaving the main motor and the haulage unit, out of which package a drive shaft protruded at each end. The intention of the modification was to take this drive shaft and gear connect it into the gearbox of a high pressure piston pump, located one at each end to give a total fluid output of 50 gallons per minute at 70 MPa. This high pressure water would be directed to the cutting head located at the relevant end of the face for advance in the particular direction required. The design developed was to use high pressure water jets to cut a slot at the top and bottom of the coal seam and also at the back. In this manner the jets could advantageously be used at their most effective in cutting.

A dual orifice jet was used in each nozzle not only to cut a deeper slot in the coal but also, by using an angled jet, this would infuse the coal pillar being mined and therefore weaken it. This would allow a lower haulage force to plow this coal cantilever once isolated over from the coal mass onto the conveyor belt. The machine used four oscillating arms to achieve this purpose in a conventional seam up to 6 ft. in height, one pair of oscillating arms to cut the bottom slot, one the top, and two to be located on the back of the unit to cut the back of the web.
It is perhaps germane to spend a short time discussing the advantages of using a dual orifice nozzle over the conventional single orifice, more particularly since it is understood that several German mining companies are now engaged in developing high pressure water jet assisted machines and these thoughts may assist them in this development. Where the water jet cuts out from a nozzle, the effect of the jet diminishes with distance as the central core is ablated by passage through air or by contact with the sides of the slot previously cut. The advantage to using a dual orifice diverging jet is that once the jet has made a pass which is at its widest at the back of the cut, then the unit will advance before the next cut and, therefore, there will be no contact between the coal and the jet until the back of the cut is reached. In this manner the jet is likely to be less diminished in force under this system than would be the case where a single orifice jet used where the jet will constantly be in contact with the sides of the hole since the jet will only cut a path up to 3-1/2 times the jet diameter. With a dual orifice diverging jet, not only will the jets cut out from the nozzle location, but all the material included between the two jet paths up to 5 cm will be removed by the effect of the jets as they impact, infuse, and rebound from the cutting surface. In this manner the jets have cut at distances up to 70 cm ahead of the cutting head (in field experiments) and isolated a cantilever of coal which, having little strength in tension, is easily broken off and pushed over onto the conveyor. Concurrently, the jets do have a component perpendicular to the line of advance, they are more and better able to force water into the cantilever of coal, infusing it, weakening it, and making it easy to break.

As a result of tests in the laboratory, it was determined that a pressure of 70 MPa would best be utilized in the field trials and accor-
ingly the system was designed around this operating pressure and flow rate. Following agreement with the U.S. Bureau of Mines a prototype Hydrominer was built and taken to a surface test location in north central Missouri. The test panel was a block of coal some 20 m long which had been uncovered in a stripping operation. The coal was of average quality for America, a little friable on the upper surface but generally competent over the major seam section with lenses of pyrite located in the seam up to approximately 5 cm thick and perhaps as long as 25 cm.

In this field trial, described elsewhere in more detail (Ref. 2), certain advantages to the Hydrominer became evident which had not originally been anticipated in the preliminary evaluation. Among these were the fact that the load on the haulage cable as the unit advanced was found not to vary as the web thickness was increased from a depth of 1/2 m to 1 m. Concurrently, it was found that the coal produced by the mining machine was larger in size than that of an equivalent shearer. The amount of water used by the machine is of the order of 20 litres per ton or less which lies within the recommended levels of water content. No dust was generated by the mining machine and, there would be no risk of spark ignition on the face. The results of the first field trial had successfully shown that a water jet system could be advantageously used in the mining of coal. During the tests it was demonstrated that the machine had a potential advance rate of 6 m/min. Concurrently, it was demonstrated that a web of 1 m could be taken. Thus, with trials of the first prototype, performance equivalence to a shearer was apparent.

Following these trials a second generation machine was developed and designed at the University, mainly by Dr. Clark Barker. This development has also been described at length elsewhere (Ref. 8).
machine was designed to solve the problems encountered with the Hydrominer (Version I) which had been tested previously.

The cutting arms were compartmentalized and the unit was made modular so that it could, with very simple modifications, be adapted to cope with seams of varying thickness and also so that the position of attack of the two compartments could be changed so that a better loading of the coal could be achieved off the solid (Fig. 5).

This unit has been preliminarily tested at the Surface Test Facility in Bruceton. However, quality of this first test panel was not satisfactory, and further trials at Rolla are currently anticipated before the unit is submitted to further field trials.

It is of interest that following the development of this machine the principal investigators on the contract visited the Central Mining Research Institute in Katowice and were introduced to the Polish long-wall hydraulic mining machine GIG-H3, which was developed in Poland in the early 1960's (Ref. 9). This unit was tested in two underground mines, at one of which, the Rymer Mine, the unit achieved advance rates of up to 8 m per minute at a web depth of up to .7 m. This was in the hard coal of Silesia and gives a strong indication that the performance of the Hydrominer in the field can be anticipated to be at least equivalent to that of a shearer in terms of advance rate while, as has already been shown by the tests in the surface mine, the machine is capable of taking over a meter web and, therefore, is perhaps capable of a higher productivity, in this manner, than the shearer.

The main disadvantage to the Polish equipment, which instead of using the high pressure, low volume flow as with the Hydrominer used a swinging monitor, equivalent to the monitors used in conventional hydraulicking and this gave a very high volume of water on the face.
The water jets were designed not only to cut the slot but also to blast off the coal from the face and, while able to do this, the very high quantity of water and spray in the mining area proved deleterious to working conditions. The jets were also of insufficient pressure to cope with hard inclusions within the coal seam. These had to be attacked by the conventional plow shape of the main body of the machine, and this, on occasion, proved problematic.

It is anticipated the Hydrominer II version which has been developed at the University of Missouri has demonstrated its ability to solve both these problems, insofar as the water volume is no more than that of conventional spray systems on shearers, and it has been demonstrated at the surface mine that, at 70 MPa it is possible to cut through hard inclusions in the coal without change in the machine parameters. It is perhaps interesting to comment that some of the coal balls which have given considerable problem to the operation of the longwall currently under test in Illinois (Ref. 10) were brought to Missouri and water jets were able to cut through these with relatively little difficulty. A water jet mining machine could therefore have advanced relatively slowly but continuously through the "inclusion" section without any wear on the machine. This was not the case with the shearer since the resistance of the coal balls led to a very rapid burn-off of the picks and in consequence the final solution was to use explosives to extract the coal ball section of the face leaving to a considerable delay and drop in coal production. The use of high pressure nozzles could also have another advantage. In a recent article in Gluckhauf (Ref. 11) it has been reported that pick costs in 1975 in one mine were as high as 2.8 mill DM. Such a cost would not be the case for the Hydrominer where the cutting action is remote from the machine itself.
During the course of the experiments in cutting coal it was found, as mentioned, that the water jets would infuse coal around the cutting area and that relatively large volumes of material could therefore be removed. This is in contrast to every other rock where the jets will only cut a very narrow slot under the point of impact. This factor can be advantageous in two applications of which are currently under investigation at the University of Missouri-Rolla.

The Detection of the Coal Shale Interface

A major problem in the steering of shearsers automatically is in the determination of the exact location of the interface between coal and overlying roof rock, particularly where some specified thickness of coal must be left between the cutting horizon and the overlying roof for support reasons. Currently, the major method whereby this is done is to use a nucleonic sensor. However, the University has been asked by the National Aeronautic and Space Administration to see whether a way could be found to use water jets to make this determination. It is the intention of this ongoing research program to use the ability of the water jets to infuse and cut out coal as a means of making this determination. The intention is to use a high pressure water jet, rotating on approximately a 5 cm radius, to cut a slot through the coal to the overlying rock. The water jet pressure is sufficient at 70 MPa that the water will not only cut the coal but also will infuse slightly along the bedding planes so that the coal included within this 5 cm circle will be removed due to its own weight and the infusion process. The coal section of the core length, will fall out leaving the overlying rock at the end of the hole (Fig. 6). It has already been determined that such rock will not be removed by the jet action but rather a slot will be cut.
around the profile. Thus, a small cylinder will be left in the roof, leading up to the overlying roof rock. The second stage of the process will be to identify the depth of this hole and this would appear to present very little problem insofar as there are now, for example, automatic focusing devices which one can purchase for cameras which can sense the distance to a surface relatively inexpensively and reliably, (Ref. 12) and these could be incorporated in the device to determine the depth of the hole.

The jet system will be mounted on the shearer, without the need to advance into the hole. Power will be drawn from a tap to the haulage motor hydraulics through an intensifier to the nozzle.

Several advantages can be foreseen for the new technique over that of the nucleonic sensing system. These include a) no machine contact is required with the coal b) no calibration due to changes in coal characteristics or the presence of dirt layers in the coal c) accuracy of measurement of less than 2 mm d) spot readings are given e) insensitive to falls of roof. The system also has the advantage that the accuracy of the reading may be manually verified after the machine has passed by inserting a ruler into the hole drilled.

A more rapid application of this phenomenon may, however, be in the long hole drilling of coal.

Long Hole Drilling

There are increasing numbers of applications where horizontal holes in coal are required. The most obvious of these are for methane drainage and for the passage of air through the coal seam for in situ gasification purposes. However, recent experiments carried out mainly by the U.S. Bureau of Mines have shown that there is some degree of difficulty in
maintaining the alignment of the drilling device within the coal as the hole length moves out towards 600 m (ref. 13). Concurrently, the in situ gasification of coal is normally carried out from vertical boreholes with the requirement that the hole be drilled out horizontally from these holes. Current equipment does not have the capability of making a very rapid transition from a vertical hole to a horizontal hole and typically turning radii of a minimum 30 m have been mentioned. Concurrently, the present method of drilling such holes requires a relatively high thrust across the drill bit, of the order of 1000 Kg, in order that the unit can advance and this becomes difficult to control as hole length increases.

In order to examine the potential for using high pressure water jets to solve these problems a contract has recently been initiated between the University of Missouri-Rolla and the Sandia Laboratories in Albuquerque, New Mexico. It is the intention of the contract to examine the potential of high pressure water jets as a system for solving this problem. The advantages which have been found in previous testing of water jet drills should hopefully allow a solution to these problems be found. The program will be carried out during the course of this summer (1978) and will seek to prove the following advantages to a water jet coal drilling system which have been found separately in the research programs described above.

1. The water jets will discriminately drill the coal more advantageously than the surrounding rock so that a water jet drilling system will be constrained to remain within the coal seam by the pressure and flow of the jet system used.
2. The contract is particularly aimed at in situ gasification where it is required that the hole remain in the coal seam, the weight of the drill system and the initial location of the drill will be such that the drill will remain in the bottom of the seam rather than wandering up through it.

3. The location will also be controlled since the thrust required to move the drill forward is relatively low, of the order of 100 kg, and there is normally no contact between the drilling device and the material being cut other than through the cutting jet streams, and the flow of debris out of the hole.

4. Because of the low thrust requirements and the small size, therefore, of the driving mechanism required, together with the small size of the drilling unit itself, it should be possible to turn the water jet system from the vertical to the horizontal plane within a turning radius of approximately 25 cm. This will allow use of pre-existing boreholes from the surface and will allow the water jet system to be installed with very little additional hole modification.

5. The hole diameter being drilled can be varied as a function of the jet cutting parameters and the jet can more easily cope with variations in hole section because of this parameterization so that it will follow the seam horizon if this wanders up and down while remaining on the bottom of the seam, whereas a conventional drilling system would not be able to discriminate between the coal and the shale that easily and would, therefore, tend to drill a more horizontal hole at times therefore passing from the coal into the surrounding rock.

A preliminary test of a water jet drill in a surface coal mine has tentatively confirmed these advantages in holes drilled to a depth of 6 m (Fig. 7).
Conclusions

At the present time the use of high pressure water jets in coal mining is still very much a research application. However, the results of the research to date have shown considerable potential benefits to the use of such systems, and funding has, therefore, been obtained to build prototype equipment for application in the field. This prototype equipment is now reaching the point of application and where such applications have been examined in small scale field programs, potential benefits to this high pressure water jet application have been demonstrated to hold true. There remain, of course, several problems which must be solved before high pressure water jet systems, either alone or in some combination with mechanical cutting devices, find their way onto the market. However, the effort which is not being made by various manufacturers would seem to indicate that this commercialization of the technique will come about. The advantages of high pressure water jet cutting will probably mean that initial applications will be made in seams where conventional mining equipment has some difficulty in operation, particularly in those coal seams with a high dust content or methane content, where the enhanced safety of jet cutting will lead to greater potential benefits. In other areas the potential of high pressure water jet cutting to solve existing problems in terms of drilling will also lead to their application, perhaps somewhat more quickly than with conventional mining equipment insofar as the hardware to be developed is much simpler and much smaller.

It is perhaps germane to mention that in the hole drilling application, for example, noise levels were monitored during the operation of some 82 db and the force required to drive the drill into the hole was transmitted through four 1/4 in. Allen screws, indicating a very low
level of effort. Thus, the total package has the potential for solving some of the problems currently encountered by drilling equipment in United States mines. The Federal agencies have become increasingly concerned about the environmental problems associated with pneumatic drilling and excavation equipment and one may, therefore, see a more rapid introduction of high pressure jet cutting equipment in these areas where, for example in the granite industry, the industry is faced with imminent closedown because of the noise and other pollution problems associated with the current methods of rock extraction.

Acknowledgements

The research described in this paper has been funded by the Department of Energy, the U.S. Bureau of Mines, and the U.S. National Aeronautics and Space Administration. Grateful thanks to these agencies is acknowledged. The research has been carried out with the considerable assistance of the faculty and staff of the Rock Mechanics & Explosives Research Center of the University of Missouri-Rolla and particular thanks are paid to Dr. Clark Barker, Mr. Ron Robison, Mr. John Tyler, Mr. Jim Blaine, and Mr. Ken Davis for their assistance in the construction of the equipment and to Mrs. Rotramel, Mrs. Snelson, and Mrs. Miloradovich for their assistance in the running of the contracts and the preparation of these and other documents.
REFERENCES


Fig. 1. Adjacent slots cut in Berea sandstone, illustrating the localized action of the cutting jet.

Fig. 2. Hole diameter for two nozzles and two rotation speeds as a function of advance rate.
Fig. 3. Water jet drilled hole - drilled at 225 in/min in Berea sandstone.

Fig. 4. Water jet drill mounted on the boom of a drilling jumbo.
Fig. 5. Second version of the Hydrominer.

Fig. 6. Water jet drilled hole through coal into sandstone, showing how the central core is removed in the coal but not in the rock.
Fig. 7. Hole drilled in coal, 16 m deep at 1.3 m/min and 15 cm in dimension. The approximately square shape is due to the jets cutting to a defined horizon in the coal.
PROGRESS IN THE WATER JET ASSISTED DRILLING OF ROCK

David A. Summers*
Ahmed A. El-Saie**

Introduction

Conventional uses of fluid in drilling oil, gas and geothermal wells are severalfold. Primarily the fluid acts as a transport medium to carry the broken rock from the drilling surface, back up out of the hole. At the same time the fluid is directed onto the cutting surface with sufficient velocity that it will remove the broken rock from under the bit teeth. A third function, of increased importance in geothermal work, is the cooling of the bit and the bearings as the penetration continues.

Early work on the additional benefits which could accrue if the jets could cut the rock was carried out by the Carter Oil Company (Ref. 1). Because of the problems, in the late 1940's, of attaining high pressure in depth, their research examined the potential benefits of adding an abrasive to the flow. The abrasive used was sand and some performance gain was achieved in the trials, but the rapid erosion of the nozzles stopped this development.

In the early 1960's tungsten carbide was developed as a nozzle material and abrasive fluid jets were rapidly adopted for penetrating casing and slitting boreholes for hydrofracing (Ref. 2).

As a result of this successful development, the Gulf Research Corporation began to investigate the use of abrasive particles as a means of enhancing the drilling rates for use in oil rigs. It was

*Dr. David A. Summers is a Professor of Mining Engineering and Director of the Rock Mechanics & Explosives Research Center, University of Missouri-Rolla, Rolla, Missouri 65401.
**Dr. Ahmed A. El-Saie is a Senior Research Engineer at Ingersoll-Rand Research, Inc., in Princeton, New Jersey 08540.
determined that, by increasing the fluid pressure to 10,000 psi and adding steel shot to the fluid, the penetration rate of the drill could be increased by a factor of up to five.

Laboratory test results were confirmed when the trials were repeated in the field and it was found possible to drill at rates of up to 80 ft/hr at depths of up to 14,000 ft with this method. Although the group appeared to solve many of the problems which have since bothered other investigators, the high cost of the experiments combined with the problems associated with the abrasives, led to the termination of the research. One problem which influenced the results was control of the mud weight, affected by the concentration of the abrasive steel shot. The steel shot could also instantaneously block the nozzle orifices and, when this occurred the drill steel became pressurized and stretched overloading the bit (Ref. 3).

The Exxon Research Corporation began field trials of a high pressure fluid system at about the time that the Gulf investigation was drawing to a close. High pressure flows were combined with conventional tricone bits and it was demonstrated that, in drilling of shallow deviated holes drilling rates of up to 200 ft/hr could be achieved in contrast to the conventional rate of 20 ft/hr (Ref. 4). This improvement was also found in straight hole drilling but the improvement was not as great as hole depth increased. Equipment problems particularly with the pumps, conventionally used for hydrofacing, slowed the development of the process. A series of four tests in depth were carried out in the mid 1970's but only one of these was carried out at the higher pressures of previous tests and this indicated, contrary to the findings of the Gulf group (who went to deeper levels), that as the depth of the hole increased, so the improvement in performance which could be obtained
by the addition of high pressure jets to the bits decreased and, at a depth of 6,000 ft there was no improvement. Since the addition of the jets is an expensive process, even though this continuing investigation was funded in the end by eight oil groups it was discontinued in 1976 (Ref. 5).

At about this time the Shell Research Corporation in the Netherlands, who has also been examining the advantages to be obtained by adding water jets to drilling moved the nozzles on the bits closer to the bottom of the bit and reduced the pressure 5,000 psi. This led to a break-through in 1977, when the Shell group became the first team to actually save money (some $140,000) in drilling a hole using high pressure water jet assistance on the bit (Ref. 6).

Current Research at UMR

In 1975 the University of Missouri-Rolla signed a contract with the U.S. Energy Research and Development Administration - Geothermal Division, to investigate the use of high pressure water jets as a means of enhancing the drilling rate in geothermal wells. Much of the experience at the University has been in the application of water jets at slightly higher pressure than are normally, to date, considered for use in geothermal operations and at somewhat smaller diameters. The first objective of the research was therefore to determine if such small jets would be effective in drilling holes in depth.

After preliminary experimentation to determine an optimum cutting geometry for the water jet nozzles, which resulted incidentally in achieving advance rates of up to some 300 in./min in sandstone, the water jet drill was tested in a triaxial chamber in which the rock could be pressurized and pressure could also be applied within the borehole created to simulate back pressure within the hole. The results of these
trials indicated that in relatively soft rock, such as sandstone, there was a considerable decrease in hole diameter as a result of applying stress to either the rock or the borehole of the order of some 40 percent. However, when the experiment was repeated in granite a diameter change of only some 12 percent was achieved. It was also noticed that the granite was broken out in larger fragments than the sandstone and penetration rates of up to 200 ft/hr could be achieved in the granite at jet pressures of approximately 15,000 psi, a pressure which had been achieved in field operations carried out by Exxon.

The results of this endeavor indicated that high pressure water jets at small diameter could practically operate in the configurations desired and it was therefore decided to examine the performance of the jets on large diameter bits. Because of the localized nature of the water jet cutting action, it is not practical to use water jets alone to remove all the material at the face of the drill and, as a result, it is necessary to combine the water jet cutting action with that of conventional roller bits.

In order to determine the practical effectiveness a new bit design has been developed which takes into consideration not only the use of high pressure water jets as a faster method of drilling but also the benefit which can be achieved by combining water jet and mechanical bit action together. The bit is shown in silhouette in Fig. 1 in order to more clearly show the relative jet locations. The jets are located so as first to drill an access hole ahead of the main body of the bit along the central axis, using high pressure water jet action alone and into this leading hole to insert a water jet nozzle system to direct jets under the quadra-cone bit teeth at the point of their contact with the rock. In this manner the water jet and rock bits will work together and
improve drilling rate. Where this has been tried in the field advance rate improvement by a factor of up to 8 has been achieved. The research is currently moving from the preliminary sandstone tests into dolomite and it is intended that the experiments will conclude in granite during the course of the summer of 1978.

While this research is continuing, a continued investigation has been made of the effect of stress on drilling rate and, because of the small size of the samples which were used in the triaxial chamber, the water jet drill was mounted on a drilling jumbo and taken 1,000 ft down into a lead mine in southeastern Missouri where, during the winter of 1977-78 it drilled over 100 holes in a barrier pillar and demonstrated not only that the water jet will drill effectively in these confined conditions at a much lower noise level than existing rock drills, but also that the effect of stress is as marked in the field as was found to be the case in the laboratory. For example, where a block of the rock was destressed there was a change in the hole diameter of approximately $\frac{1}{2}$ in. from that drilled by the water jets in a stress zone and that achieved by the jets in an area that had been destressed.

The research has also examined the potential benefits of adding abrasive to the water as had been proposed by Gulf and also the potential benefits to be achieved by cavitating the jet streams as has been proposed by Hydronautics (Ref. 7). It has been found that at pressures of up to 10,000 psi in the drilling of granite it is more effective to use abrasives in the fluid flow than cavitation of plain water jets since at this pressure the threshold velocity of the granite has barely been reached (Ref. 8). At pressures of above 10,000 psi it is more effective to use cavitating water jets in drilling through granite (Fig. 2). As the pressure increases plain water jets become more effective than abrasive
laden jets. It is postulated that the reason for this is that the abrasive wears a smooth surface on the rock, less susceptible to the fluid wedging of jet attack than the broken surface left by the plain or cavitated flow attack. This theory is substantiated by other experiments which have shown that, at a pressure of 8,500 psi, the jet attack on a smooth surface only becomes effective in cutting once a preliminary pass over the surface has created a broken surface.

Conclusions

Evidence developed at the University of Missouri-Rolla has shown that, at pressures currently available with commercial equipment, advance rates up to 200 ft/hr can be achieved in drilling granite.

This rate is, however, diminished by the application of the pressures to be found in a borehole at depths up to 6,000 ft. However, this reduction is to a much lesser extent in granite than has been observed in sandstone. It has also been shown advantageous to use abrasives and/or cavitation of the fluid flow in order to enhance drilling rates. At fluid pressures below 10,000 psi abrasive laden jets appear more effective while at fluid pressures above 10,000 psi cavitating jets would appear more effective.

Acknowledgements

This work was funded under U.S. Energy Research and Development Administration contract EY 76 S 02 2677.A002 with Mr. Cliff Carwile as the Technical Project Officer, Ms. June Wiinikka and Ms. Sheryl Povalish acted as Contracting Officers. We are pleased to acknowledge this assistance. The research was carried out with the assistance of Mr. J. Blaine, who made the nozzles, Mr. L.J. Tyler, and Mr. K. Davis of the Rock Mechanics and Explosives Research Center staff. We were also ably assisted by Mr. U. Larkin, Mr. L. Ashby, and Mr. J. Carter of the St. Joe 203
Research Department, this assistance and the help furnished by St. Joe under Mr. Casteel, Vice President - Mining of St. Joe Minerals is gratefully acknowledged.

References


Figure 1. Hydromechanical drill bit showing the jet locations relative to the bit teeth.

Figure 2a. Pressure = 51.7 MPa

Figure 2. Relative erosive capability of jets at various pressures, as a function of standoff distance.

Figure 2b. Pressure = 69.0 MPa

Figure 2c. Pressure = 13.80 MPa
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.
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 $y = Ax^B$. 

<table>
<thead>
<tr>
<th>Feed Rate (rpm)</th>
<th>A</th>
<th>B</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>120 rpm</td>
<td>4.12</td>
<td>-.32</td>
<td>.974</td>
</tr>
<tr>
<td>80 rpm</td>
<td>4.97</td>
<td>-.5</td>
<td>.931</td>
</tr>
<tr>
<td>40 rpm</td>
<td>5.32</td>
<td>-.603</td>
<td>.996</td>
</tr>
</tbody>
</table>
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 auxiliary 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 "0" 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)

<table>
<thead>
<tr>
<th>CONFINING PRESSURE</th>
<th>0 PSI</th>
<th>4000 PSI</th>
<th>6000 PSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>BACK PRESSURE</td>
<td>0 PSI</td>
<td>2.0 IN</td>
<td>1.050 IN</td>
</tr>
<tr>
<td></td>
<td>500 PSI</td>
<td>1.025 IN</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1000 PSI</td>
<td>.800 IN</td>
<td>.625 IN</td>
</tr>
<tr>
<td></td>
<td>1500 PSI</td>
<td>.875 IN</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2000 PSI</td>
<td>.750 IN</td>
<td>.575 IN</td>
</tr>
</tbody>
</table>
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>
<thead>
<tr>
<th>Jet Pressure</th>
<th>Diameter</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>10,000 psi</td>
<td>2.180</td>
<td>Back Pressure - 0 psi</td>
</tr>
<tr>
<td>9,000 psi</td>
<td>1.875</td>
<td>Confining Pressure - 0 psi</td>
</tr>
<tr>
<td>8,000 psi</td>
<td>1.725</td>
<td>Rotational Speed - 500 rpm</td>
</tr>
<tr>
<td>7,000 psi</td>
<td>1.650</td>
<td>Advance Rate - 40 in./min</td>
</tr>
<tr>
<td>6,000 psi</td>
<td>1.350</td>
<td>Rock - Berea Sandstone</td>
</tr>
<tr>
<td>5,000 psi</td>
<td>1.150</td>
<td>Nozzle - Type 22</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Back Pressure psi</th>
<th>ppm Nalco 254</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1.49</td>
</tr>
<tr>
<td>500</td>
<td>.75</td>
</tr>
<tr>
<td>1000</td>
<td>.71</td>
</tr>
<tr>
<td>2000</td>
<td>.73</td>
</tr>
</tbody>
</table>

* 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.

<table>
<thead>
<tr>
<th>Chemical</th>
<th>0</th>
<th>500</th>
<th>1000</th>
<th>1500</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nalco BX-254</td>
<td>2.00</td>
<td>1.05</td>
<td>.95</td>
<td>.95</td>
<td>1.00</td>
</tr>
<tr>
<td>Polyox</td>
<td>2.00</td>
<td>1.06</td>
<td>1.00</td>
<td>.94</td>
<td>.94</td>
</tr>
<tr>
<td>Polyhall 654</td>
<td>1.98</td>
<td>1.05</td>
<td>1.00</td>
<td>.98</td>
<td>.80</td>
</tr>
<tr>
<td>Alfonic 1214-60</td>
<td>1.95</td>
<td>1.02</td>
<td>.98</td>
<td>.95</td>
<td>.88</td>
</tr>
</tbody>
</table>

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.

Acknowledgments

This research is funded under contract E(11-1)-2677 by the Energy Research & Development Administration, under technical monitoring by Dr. Clifton Carwile. This support is gratefully acknowledged.

It is a pleasure to thank Mr. J. Blaine and Mr. C. Grisham who constructed the test equipment and Mr. A. Krause, etc. who assisted in the test program.