RI 9201

REPORT OF INVESTIGATIONS/1988

Techniques To Increase Water Pressure for Improved Water-Jet-Assisted Cutting

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BUREAU OF MINES

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNITED STATES DEPARTMENT OF THE INTERIOR
Donald Paul Hodel, Secretary

BUREAU OF MINES
T S Ary, Director

Library of Congress Cataloging in Publication Data:

Kovscek, P. D. (Paul D.)

Techniques to increase water pressure for improved water-jet-assisted cutting.

(Report of investigations; 9201)

Bibliography: p. 9

Supt. of Docs. no.: I 28.23:9201

1. Jet cutting. 2. Water-jet. 3. Mining machinery. I. Taylor, Charles D. (Charles Darrell), 1946- . II. Thimons, Edward D. III. Title. IV. Series: Report of investigations (United States. Bureau of Mines); 9201.

TN23.U43 [TN281] 622 s [622'.2] 88-600138

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

fpm	foot per minute	pct	percent
gpm	gallon per minute	psi	pound per square inch
in	inch	s	second

TECHNIQUES TO INCREASE WATER PRESSURE FOR IMPROVED WATER-JET-ASSISTED CUTTING

By P. D. Kovscek,[1] C. D. Taylor,[2] and E. D. Thimons[3]

ABSTRACT

High-pressure streams of water, known as water jets, can be used to improve the cutting efficiency of mechanical bits. During prior testing by the Bureau of Mines, the cutting performance of a longwall shearer, equipped for water-jet-assisted cutting, was evaluated. The performance of the shearer did not improve while using water jet assist because the pressure of the water delivered to the rock surface was inadequate.

The study, described in this report, resulted in a determination of the major cause of water pressure loss on the shearer, and an evaluation of the techniques for increasing the water pressure at the rock surface. The results show that the major pressure loss, which occurred between the nozzle and rock surface, is directly affected by the amount of fluid turbulence that develops just upstream from the nozzle. Preventing a sudden change in the direction of the flow channel can increase the stagnation pressure as much as 400 pct. Smoothing the surface of the flow channel in the shearer bit block would increase the stagnation pressure delivered to the rock surface by 35 pct.

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INTRODUCTION

Water-jet-assisted cutting is a rock fragmentation method that uses a drag bit and high-pressure streams of water. If the water impacts the rock 0.1 in or less from the bit tip (fig. 1), and supplies sufficient energy to the rock surface, forces on the bit tip will be reduced. During a laboratory study, a bit moving at 50 fpm was used to cut rock to depths up to 0.6 in. Use of a high-pressure water jet (10,000 psi) with the bit resulted in bit force reductions up to 45 pct (*1*).[4]

The Bureau of Mines equipped a longwall shearer so that high-pressure water could be delivered through a jet nozzle mounted in front of each bit block (*2*). The shearer cut a simulated coal face while using either low-pressure conventional type sprays or high-pressure water jets. The results indicated that use of the high-pressure jets did not reduce the forces on the cutting bits.

Other tests have shown that a minimum threshold energy must be provided before the bit forces are reduced (*3-4*). That is, the water energy density, as measured at the rock surface, must exceed a certain level before bit forces are reduced. An analysis of the shearer operating parameters showed that the water energy density supplied to the simulated coal face was much less than that supplied to the test rocks during the earlier laboratory tests. Therefore, to improve the performance of the shearer, the water energy density must be increased.

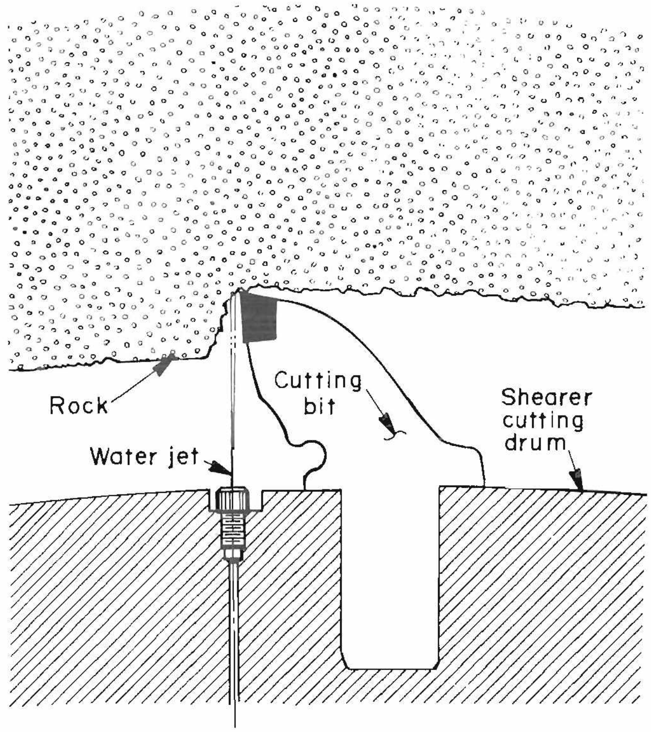

Figure 1.—Water-jet-assisted drag bit.

Water energy density delivered to a rock surface is a function of water pressure, waterflow rate, and bit speed. This study was concerned with determining how the water pressure delivered to the rock surface by the jet nozzles could be increased. Owing to the difficulty in supplying high-pressure water to a longwall face, it was not considered practical to increase the supply pressure to the shearer beyond about 6,000 psi. Therefore, to increase the water pressure, losses in the fluid delivery system would have to be reduced.

ACKNOWLEDGMENTS

The authors acknowledge the assistance of the following Boeing Services personnel, Pittsburgh, PA, who aided in the design and construction of test equipment: J. Leslie Thompson, senior project engineer; Allen A. Constantine, engineering technician; and Edward J. Uranker and George E. Mattish, mechanical technicians.

OBJECTIVE

The objective of this work was to determine if the water pressure delivered to a rock surface by jet nozzles could be increased by reducing losses in the water-delivery system. There was no technique to directly measure the water pressure at the rock surface while the bit was cutting. Therefore, without cutting, operation of the water jets was simulated using a test apparatus. With this apparatus the stagnation pressure at the location of jet impact was measured for nozzle-to-target distances between 1 and 5 in. The effects of various flow conditions on stagnation pressure losses were studied, and techniques for reducing those losses were evaluated.

[4]Italic numbers in parentheses refer to items in the list of references preceding the appendix at the end of this report.

WATER DELIVERY SYSTEM–PRESSURE LOSSES

PRESSURE LOSSES IN CUTTING DRUM

Pressure losses occurring within the cutting drum affect the performance of the water-jet-assisted cutting system by reducing the water pressure delivered to the nozzle inlet. When water enters the cutting drum it passes first through the rotary union, then enters the flexible and solid piping which carries the water to the bit block. From the bit block the water enters the jet nozzle (fig. 2). Pressure losses in the cutting drum were determined for

1. Water flow through the rotary union, and

2. Water flow between the rotary union and the nozzle.

During testing, input pressure to the drum was varied from 800 to 6,200 psi.

Rust and corrosion from the inside surface of the cutting drum frequently plugged the water-jet nozzle orifices, making it difficult to accurately measure the pressure drop in the drum. Therefore, rather than trying to keep all nozzles open at the same time, a measurement technique was used that required no more than six jet nozzles operating.

The cutter drum contained six segments, each supplied by individual hoses from the rotary union. The total waterflow rate through the rotary union, during shearer tests with 32 nozzles operating at 6,200 psi, was approximately 42 gpm. Each of the six hoses to the bit blocks was disconnected at the rotary union and replaced with a 0.055-in orifice spray nozzle that provided 7 gpm

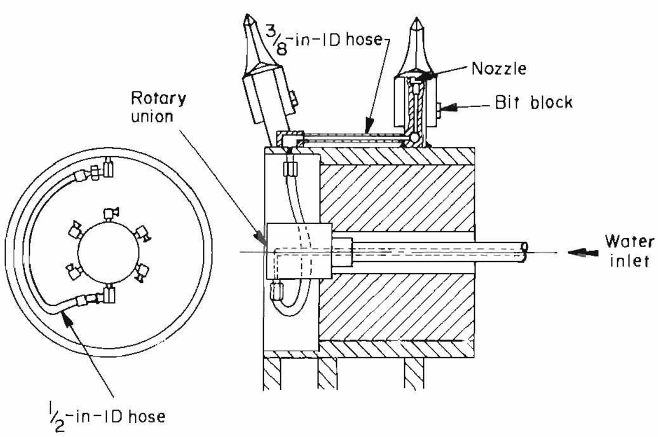

Figure 2—Water passage through cutting drum.

flow rate at 6,000 psi. The total flow rate through the rotary union remained the same as during the shearer tests. Pressure transducers were installed to measure the pressure on each side of the rotary union.

After calculating the water pressure loss due to flow through the rotary union, one segment of the drum was connected to the rotary union by a hose. Water passed through all six water jet nozzles in that segment. One pressure transducer was installed where the hose connected to the rotary union, and another at the inlet to one of the operating nozzles. The pressure loss measured was due to the waterflow through the piping and bit block. The total pressure loss within the shearer drum was calculated by summing the pressure losses due to the waterflow through the rotary union, piping, and bit block.

PRESSURE LOSS BETWEEN NOZZLE INLET AND ROCK SURFACE

In addition to the pressure loss that occurs within the cutting drum, pressure is also lost after the high-pressure stream of water jet leaves the nozzle. This loss is primarily due to the breakup of the solid water stream into droplets that rapidly lose their velocity as they travel through the air (see appendix). The total pressure loss that occurs between the time the water leaves the nozzle and impacts the rock is difficult to determine because there is no way to directly measure the water pressure at the rock surface.

Fluid stagnation pressure is defined as the maximum sustained pressure developed at the location of water jet impact. If a pressure transducer is placed at the target, or location of water jet impact, the stagnation pressure can be measured directly. By simulating flow conditions for a water-jet nozzle on a longwall shearer, stagnation pressure measurements can be used to estimate the water pressure striking the rock surface during longwall cutting. Other studies (*5-6*) have measured water stagnation pressure to evaluate nozzle performance. The test apparatus used for this study was designed specifically to measure stagnation pressure while simulating waterflow through the longwall shearer bit block and jet nozzle. The nozzle to target (standoff) distances were typical of the nozzle to rock distances expected during mining with a longwall shearer. For example, standoff distances for the Bureau longwall shearer ranged from 2.5 to 4 in (equivalent to 106-169 nozzle diameters). A Partek[5] pump was used to supply water at 6,000 psi for all stagnation pressure tests. Each

[5]Reference to specific products does not imply endorsement by the Bureau of Mines.

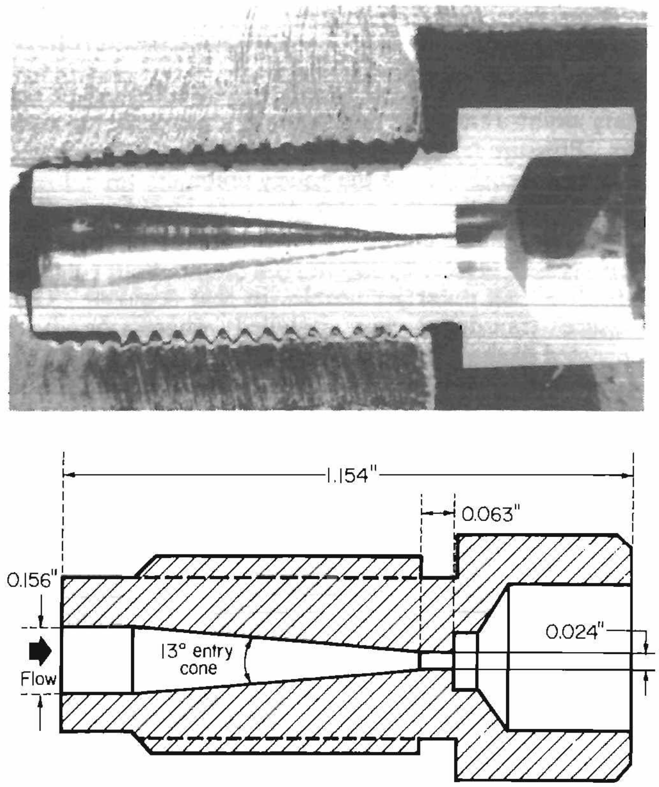

Figure 3.—Cross-sectional view of Leach and Walker type nozzle.

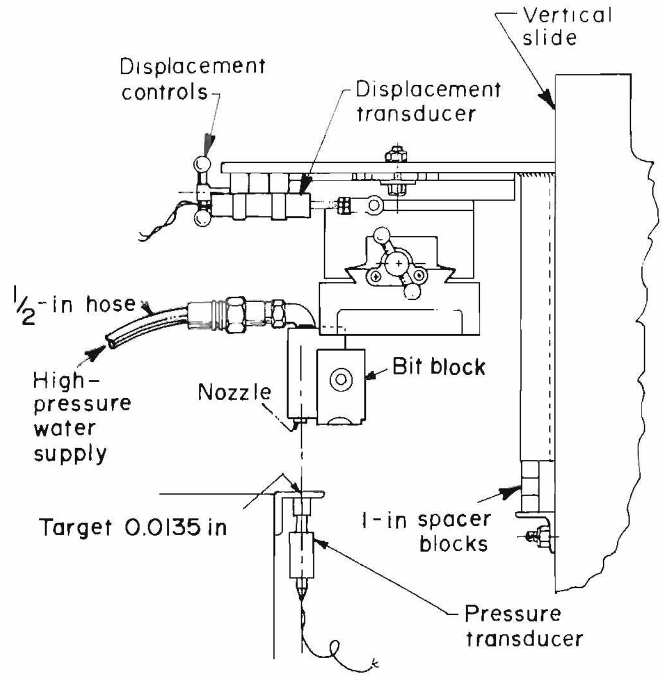

Figure 4.—Test apparatus with bit block.

TABLE 1. - Discharge coefficients for stainless steel nozzles

Nozzle	Coefficient of discharge
A	0.92
B	.95
C	.94
D	.99
E	.94
F	.97
G	.95

water-jet nozzle used for a stagnation pressure test had the same size and design as the nozzles used for the shearer tests. The nozzles were made entirely of stainless and had the Leach and Walker configuration (*5*) with a 0.024-in-diam orifice. Figure 3 shows a cross-sectional view of one of these nozzles. The Leach and Walker nozzle is specifically designed to provide the efficient transfer of fluid energy from the nozzle to the rock surface (*7*).

Fluid flow through most nozzles, including the Leach and Walker nozzle, results in frictional losses, and a reduction in the diameter of the fluid flow stream after it leaves the nozzle. The coefficient of discharge for a nozzle is a relative indicator of the friction loss, and the amount of contraction that occurs in the water stream. The greater the contraction of the fluid stream, the smaller the value of the coefficient of discharge. Consequently, the waterflow and energy delivered to the bit tip is less for a nozzle having a lower coefficient of discharge.

Prior to the stagnation pressure tests, the coefficient of discharge was measured for each of the nozzles to be tested. Seven identical nozzles, identified by letters A through G, were examined. The coefficient of discharge for each of the seven nozzles is given in table 1. No coefficient of discharge value was less than 0.92, indicating that all nozzles performed similarly and friction losses were small.

To simulate operation of a jet nozzle on the shearer drum, one shearer bit block was removed from the cutting drum and mounted on the test apparatus (fig. 4). The distance between the nozzle and target was varied by moving the bit block and nozzle on a vertical slide. The standoff distance was set at 1 in by direct measurement. To obtain standoff distances of 2, 3, 4, and 5 in, 1-in spacer blocks were installed under the vertical slide assembly.

A second bit block was removed from the shearer drum and cut to expose the waterflow channel (fig. 5). As can be seen, the bit block was drilled to provide a 4.5-in-long flow path upstream of the nozzle. The inside diameter changes abruptly from 0.25 to 0.156 in, approximately 1.5 in from the nozzle. A closer examination of the flow channel showed that the surface was rough. Abrupt changes in flow channel diameter and a rough surface can cause flow turbulence, which decreases stagnation pressure.

Past work has shown the stagnation pressure increases when the flow path just upstream of the nozzle is made smoother and uniform in size (*8-9*). However, neither the size nor surface finish of the flow channel could be changed in the shearer bit block. To evaluate the effects of providing a smooth and uniform flow path just upstream from the nozzle, straight sections of tubing, 2 to 4 in long, were inserted in the end of a nozzle holder, specially

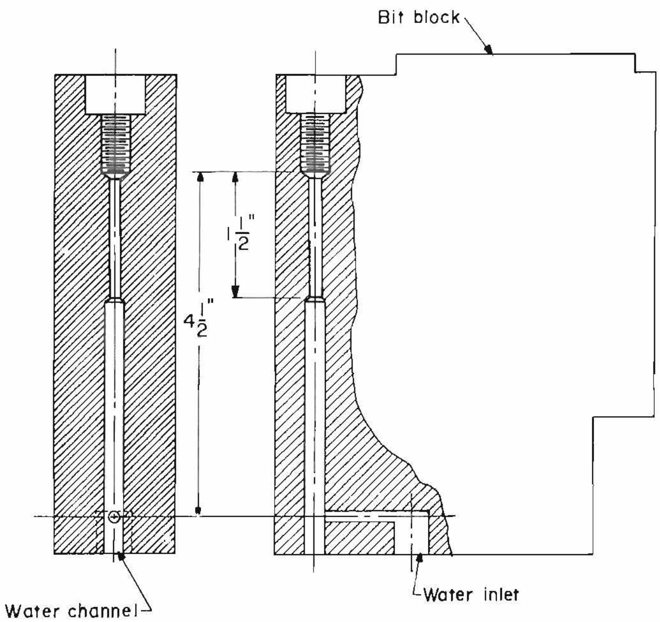

Figure 5.—Bit block flow passage.

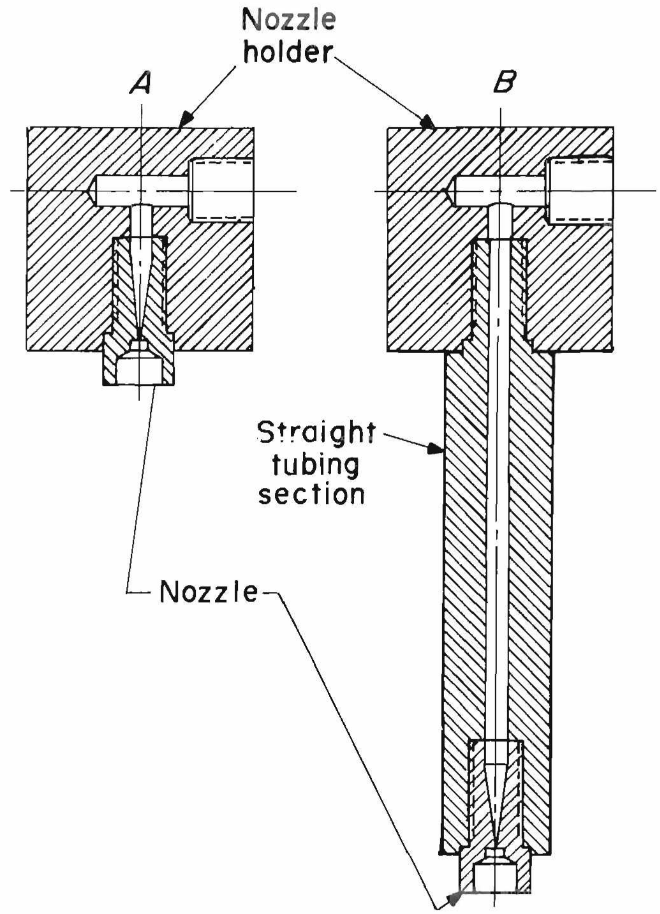

Figure 6.—Nozzle holder with (*B*) and without (*A*) straight tubing.

designed for the test apparatus. The nozzles could be inserted in the ends of the straight tubing or directly into the nozzle holder (fig. 6). The inner diameter of the tubing was the same (0.156 in) as the inlet diameter to the jet nozzle. In figure 7, the nozzle holder, with tubing, is shown installed on the stagnation pressure test apparatus.

During testing, the water jet was directed at a target (figs. 4 and 7) that consisted of a 0.0135-in tungsten carbide orifice installed in a flat plate. A strain-gauge pressure transducer was installed immediately beneath the orifice to measure the stagnation pressure. Instrumentation was installed to measure the water pressure at the nozzle, water-jet traverse displacement, and water pressure at the target face. Signal conditioners powered and amplified the monitored events, and supplied an analogous voltage of the event to an X-Y plotter, FM magnetic tape recorder, and strip chart recorder. The target hole pressure (Y) and displacement (X) on the X-Y plotter were used to obtain the peak pressure and stagnation pressure profile as the water jet was traversed across the target hole. Figure 8 is a block diagram of the instrumentation system. The nozzle supply and target hole pressures were monitored in real time with digital voltmeters.

Before making the stagnation pressure measurements, each nozzle was visually aligned with the target hole. The initial alignment of the water stream with the target hole was performed at a water pressure of 70 psi. Using a lower water pressure allowed better visual alignment of the jet with the target hole. After the jet was aligned, the water pressure was raised to 6,000 psi. The jet stream was traversed across the target hole in orthogonal directions to obtain a pressure profile.

Figure 9 gives a profile for a nozzle inserted in a 4-in piece of straight tubing and set at a 1-in standoff distance. The maximum sustained pressure, determined from the

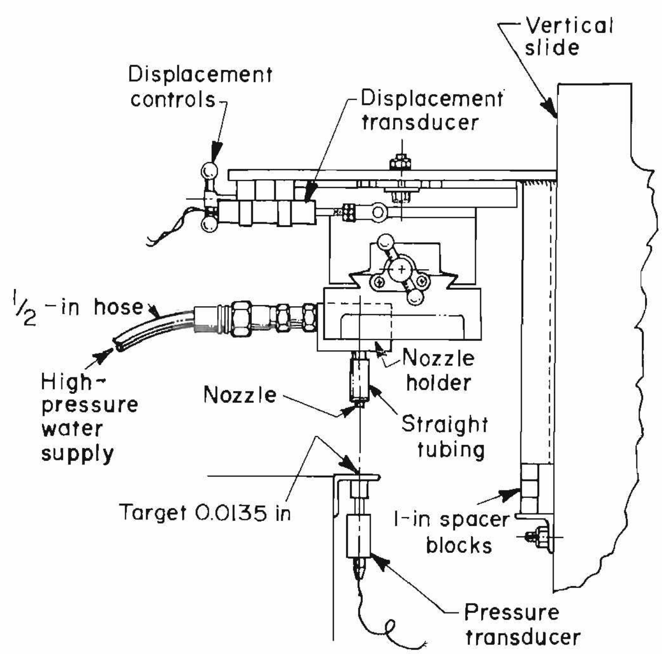

Figure 7.—Test apparatus with nozzle holder.

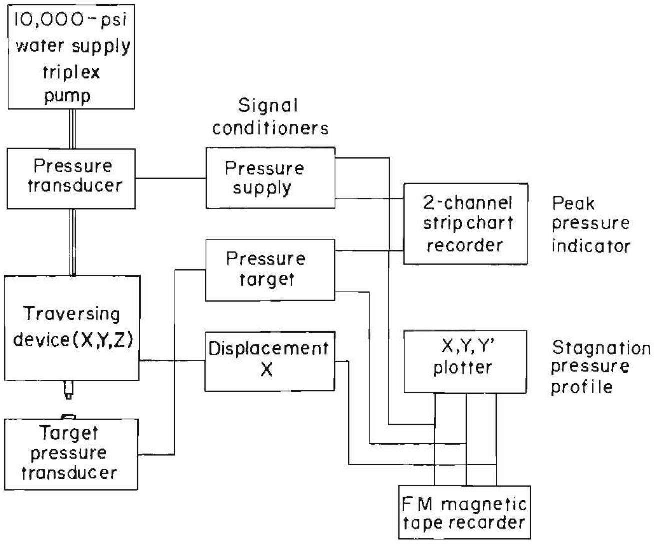

Figure 8.—Block diagram of instrumentation system.

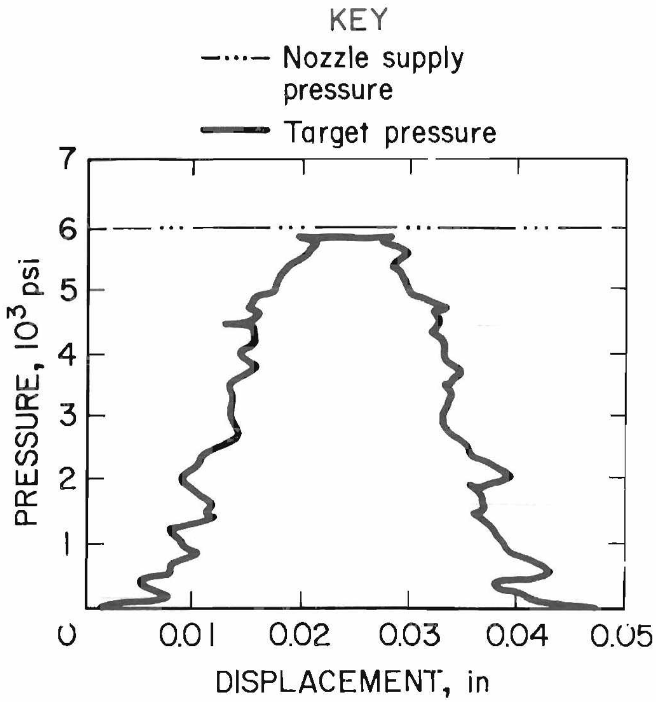

Figure 9.—Example of stagnation pressure profile at 1-in standoff distance.

profile, was recorded as the stagnation pressure for a given test.

The stagnation pressure for two nozzles was measured before the inner surface of each nozzle was polished. Other research has shown that nozzle internal surface finish can have an effect on nozzle stagnation pressure (*10*). Two nozzles were evaluated before and after the inner surface was polished to determine the effect of polishing on stagnation pressure. A tool that conformed to the shape of the nozzle inlet cone section was fabricated and used with a commercial polishing agent.

RESULTS

Table 2 shows the pressure supplied to the cutting drum and the corresponding pressure loss that occurred in the drum. The loss, as a percentage of the drum supply pressure, varied from about 8 to 10 pct. Input versus output water pressures for the cutting drum are plotted on figure 10. At a 6,000-psi drum inlet pressure, the outlet pressure was 5,500 psi. The average pressure measured at the bit block was 91 pct of the pressure supplied to the drum.

The stagnation pressure profile obtained for each nozzle test was used to determine the stagnation pressure. All tests were conducted at a water pressure of 6,000 psi.

Four of the nozzles (A, B, E, and G) were tested with the bit block. The dotted line in figure 11 is plot of standoff distance versus the average stagnation pressure measured for the four nozzles. The solid line in figure 11 shows the average stagnation pressures for the same four nozzles tested with a 4-in straight tube. The data used to construct both lines are given in table 3. At each standoff distance, the stagnation pressures were less when the nozzle was used in the bit block. The average stagnation pressure, for all standoff distances, was 35 pct greater when the nozzle was mounted in the straight tubing.

Two nozzles (A and G) were inserted directly into the nozzle holder and stagnation pressures were measured.

TABLE 2. - Pressure loss in shearer cutting drum

Drum supply pressure, psi	flow, gpm	Pressure loss psi	Pressure loss pct
780	15.6	80	10.2
1,280	20.2	120	9.4
2,290	27.6	200	8.7
3,280	33.6	280	8.5
4,400	39.1	360	8.2
5,270	43.2	450	8.5
6,190	47.9	480	7.8

TABLE 3. - Nozzle stagnation pressure, for bit block and 4-in straight tubing, pounds per square inch

Nozzle-to-target distance ... in ..	2	3	4	5
BIT BLOCK				
A	4,300	3,650	2,950	2,850
B	4,250	3,100	2,200	1,050
E	4,500	3,650	3,100	2,500
G	4,650	3,600	2,900	1,600
4-IN TUBING				
A	4,950	4,375	4,100	3,875
B	4,775	4,250	3,375	2,600
E	5,100	4,550	4,200	3,750
G	5,225	4,800	4,325	4,125

After placing a 4-in piece of straight tubing in the nozzle holder, the stagnation pressure readings were taken using the same two nozzles. Figure 12 shows how the stagnation pressures for the two nozzles compared with and without the straight tubing. The dashed line shows the average stagnation pressures without straight tubing, and the solid line shows average stagnation pressures when the 4-in tube was used. At a 4-in standoff distance, the stagnation pressure was 4 to 5 times greater when the 4-in tubing was used. The data for this test are given in table 4.

To study the relative effects of the tube length on stagnation pressure, 2-, 4-, and 6-in lengths of straight tube were used with the nozzle holder. Nozzles A, B, C, E, and G were used for these tests. At a nozzle supply pressure of 6,000 psi and a constant standoff distance of 4 in, the average stagnation pressure increased with increasing tube length, although the pressure increase above 4 in was small (fig. 13); data are given in table 5.

The effects of nozzle polishing on stagnation pressure are shown on figure 14. The results, for nozzles F and G, indicate that polishing had a negligible effect on increasing nozzle stagnation pressure; data are given in table 6.

TABLE 4. - Comparison of nozzle performance with and without 4-in straight tubing, pounds per square inch

Nozzle-to-target distance .. in ..	1	2	3	4	5
NO TUBING					
A	4,500	2,600	1,700	1,200	850
G	3,900	1,750	950	600	450
4-IN STRAIGHT TUBING					
A	5,850	4,950	4,375	4,100	3,875
G	5,850	5,225	4,800	4,325	4,125

TABLE 5. - Effect of straight tubing length on nozzle stagnation pressure, pounds per square inch.

Straight tubing length .... in ..	0	2	4	6
A	1,700	3,900	4,050	4,200
B	550	3,100	3,650	3,700
C	700	3,300	3,900	3,900
E	1,075	3,550	4,100	3,950
G	550	2,700	3,600	3,900

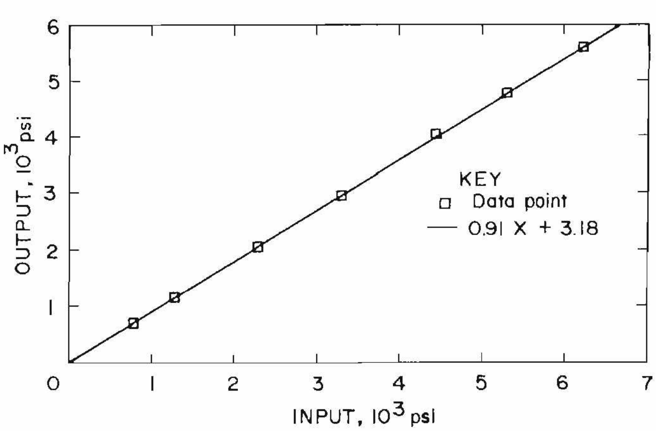

Figure 10.—Cutting drum input and output pressure.

TABLE 6. - Effect of nozzle surface polishing on stagnation pressure, pounds per square inch

Nozzle-to-target distance .. in ..	1	2	3	4	5
INTERIOR SURFACE POLISHED					
F	5,725	4,650	3,800	2,850	2,350
G	5,725	4,700	3,975	3,300	2,850
INTERIOR SURFACE NOT POLISHED					
F	5,800	4,700	3,930	3,230	1,800
G	5,850	5,225	4,800	4,325	4,125

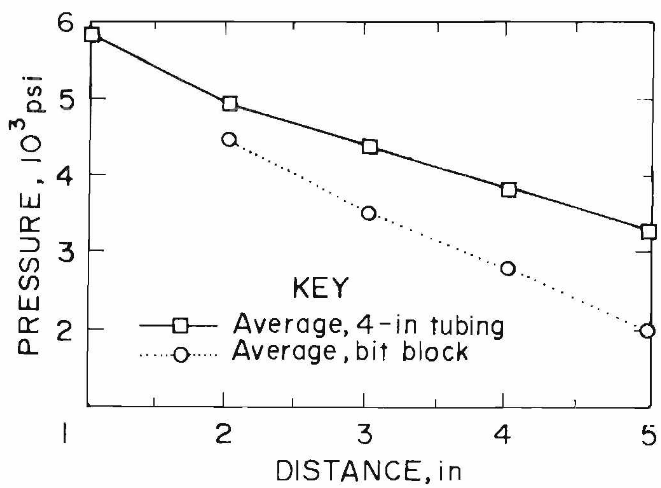

Figure 11.—Stagnation pressures, bit block and 4-in tubing.

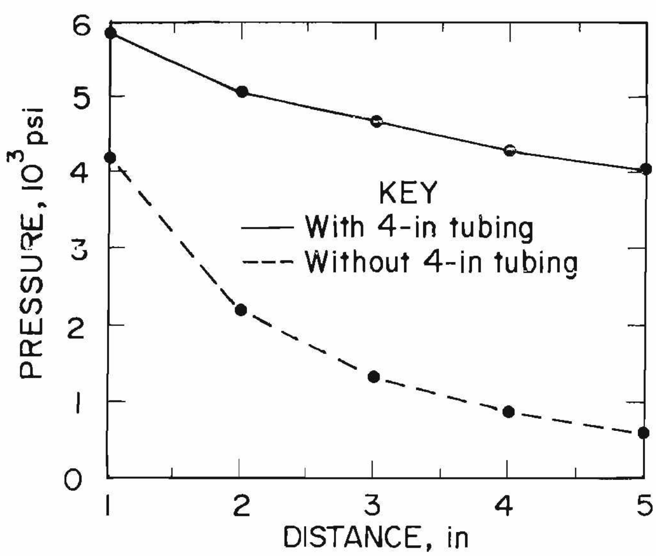

Figure 12.—Stagnation pressures, with and without 4-in straight tubing.

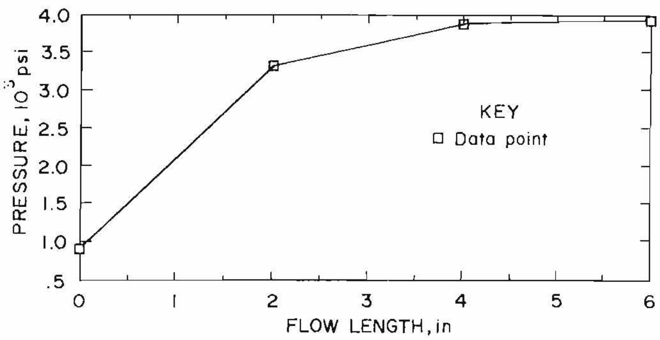

Figure 13.—Effect of straight tubing length on stagnation pressure.

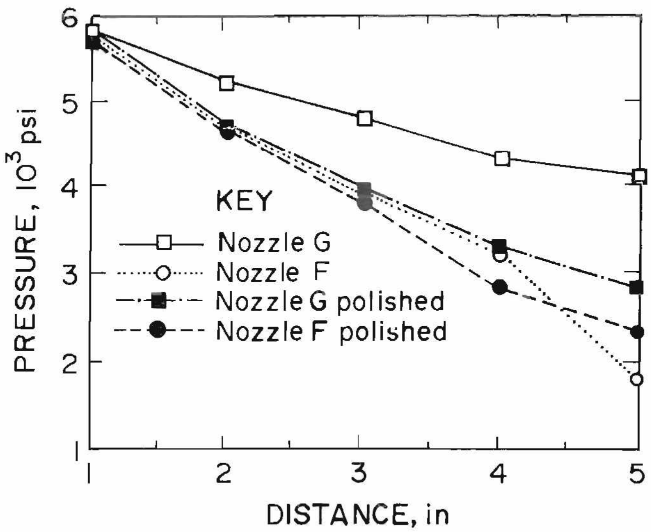

Figure 14.—Effect of nozzle polishing on stagnation pressure.

DISCUSSION

Water-jet-assisted cutting makes use of the combined energy from the bits and high-pressure water jets. Pressure losses between the nozzle and rock surface can significantly reduce the effectiveness of the water jets. These losses can be reduced by decreasing the fluid turbulence that occurs just upstream of the nozzle. Test results showed how turbulence, caused by waterflow through the bit block, reduced nozzle stagnation pressure. If the flow direction changed by moving through a 90° bend just upstream of the nozzle, an even greater reduction in stagnation pressure occurred.

Straight, smooth sections of tubing placed just upstream of the nozzle reduced turbulence. Stagnation pressure increased as the length of straight pipe increased, but no significant increases for tubing lengths greater than 4 in occurred. The results indicate that the stagnation pressure, supplied by the water-jet nozzles mounted in the shearer cutting drum, could be increased if the flow turbulence in the bit blocks was reduced. This could be accomplished if the holes drilled in the bit block for the water channels were smooth, and had a uniform diameter equal to the nozzle inlet diameter. The channels should be straight and approximately 4 in long.

Stagnation pressure could also be increased by moving the nozzle closer to the rock surface or increasing the supply pressure to the shearer. However, it was not considered practical to move the nozzle closer to the rock because of the construction of the bit block and possible damage to the nozzle during operation of the shearer. Techniques to bring the water through the bit to reduce the standoff distance are being investigated by the Bureau.

Other nozzle types are also being studied by the Bureau. Currently the Leach and Walker type nozzle is accepted as one of the most efficient nozzles for use with water-jet-assisted cutting. Nozzles having the Leach and Walker design have been used to erode a rock surface at distances up to 1,000 nozzle diameters (*8*). However, to be effective during use with a longwall shearer the water jet standoff distance has to be less than 3.5 in.

Roughness within the nozzle can cause turbulence that results in reduced stagnation pressure (*6, 9, 11*). Nozzle D was cut in half so that the interior surface could be examined closely. Concentric rings caused by machining could be seen (fig. 3) in the nozzle entry. Although the nozzles were polished in an attempt to remove some of these rings, stagnation pressure did not increase. Additional polishing may have improved nozzle performance, but the polishing performed was intended to simulate what would be commercially practical for a stainless steel nozzle.

CONCLUSIONS

This study investigated the sources of pressure loss within a shearer water delivery system. Less than 10 pct of the supply pressure (6,000 psi) was lost because of flow of water through the shearer drum. Most of the pressure loss, which occurred between the nozzle and rock surface, was due to flow turbulence just upstream from the nozzle. Different flow path designs upstream of the nozzle were tried to determine how they affected stagnation pressure. Using a 4-in straight flow path rather than a 90° bend increased the stagnation pressure at the target location 400 pct. Reducing flow turbulence in the shearer bit block can increase stagnation water pressure 35 pct.

Although it did not have a significant effect on stagnation pressure during these tests, additional polishing of the nozzle interior surface, may further reduce turbulence. If the water must pass through a sharp bend upstream from the nozzle, wire screen placed in the flow channel will reduce turbulence.

Measurement of pump and nozzle pressures are not good indicators of the water pressure delivered to the rock surface during water-jet-assisted cutting. A test apparatus was used to measure the stagnation pressures for Leach and Walker type nozzles while simulating operating conditions on a longwall shearer. The techniques and apparatus described provide a good way to estimate the stagnation pressure provided through high-pressure nozzles during water-jet-assisted cutting.

REFERENCES

1. Hood, M. Water-jet-Assisted Cutting. Paper in Proceedings: Bureau of Mines Open Industry Meeting, Pittsburgh, PA, June 21, 1984, comp. by C. D. Taylor and R. J. Evans. BuMines IC 9045, 1985, pp. 3-20.

2. Kovscek, P. D., C. D. Taylor, H. Handewith, and E. D. Thimons. Longwall Shearer Performance Using Water-Jet-Assisted Cutting. BuMines RI 9046, 1986, 15 pp.

3. Brook, N., and C. H. Page. Prospects of Rock Cutting by High Speed Water Jets. Paper III-B.1 in Sixth International Mining Congress (Great Britain, 1970) Int. Min. Cong. 1970, pp. 1-8.

4. Franz, N. C. The Interaction of Fluid Additives and Standoff Distances in Fluid Jet Cutting. Paper A5 in Third International Symposium on Jet Cutting Technology (IIT Res. Inst., Chicago, IL, May 11-13, 1986). BHRA Fluid Engineering, Cranfield, Bedford, England 1976, pp. 67-75.

5. Leach, S. J., and G. L. Walker. The Application of High-Speed Liquid Jets to Cutting; Some Aspects of Rock Cutting by High Speed Water Jets. Proc. R. Soc. London, Phil Trans. A, v. 260, 1966, pp. 295-308.

6. Gayson, K. P. Nozzle Performance Trials, April to September 1981. Nat. Coal Board Min. Res. and Dev. Establ., Tech. Memo. No. TU(82), MRDE/U.S. Dep. Energy Collaboration Agreement Contract No. DE AC01 78ET13339, 31 pp.

7. McCarthy, M. J., and N. A. Molloy. Review of Stability of Liquid Jets and the Influence of Nozzle Design. Chem. Eng. J., v. 7, 1974, pp. 1-20.

8. Barker, C. R., and B. P. Selberg. Water Jet Nozzle Performance Tests. Paper A1 in Fourth International Symposium on Jet Cutting Technology (Univ. of Kent, Canterbury, England, Apr. 12-14, 1978). BHRA Fluid Engineering, Cranfield, Bedford, England, 1978, pp. A1-A20.

9. Saunders, D. H. Some Factors Affecting Precision Jet Cutting. Paper F1 in Third International Symposium on Jet Cutting Technology (IIT Res. Inst., Chicago, IL, May 11-13, 1976). BHRA Fluid Engineering, Cranfield, Bedford, England, 1976, pp. F1-F14.

10. Selberg, B. P., and C. R. Barker. Dual-Orifice Waterjet Predictions and Experiments. Sec. in Erosion and Useful Applications, ASTM STP 664, W. F. Adler, ed., ASTM, 1979, pp. 493-511.

11. Jackson, M. K., and T. W. Davies. Nozzle Design for Coherent Water Jet Production. Paper in Second U.S. Water Jet Symposium (Univ. Missouri-Rolla, May 24-26, 1983). Univ. MO-Rolla, 1983, pp. 47-73.

12 Yanaida, K., and A. Ohashi. Flow Characteristics of Water Jets in Air. Paper in Fifth International Symposium on Jet Cutting Technology (Hanover, Federal Republic of Germany, June 2-4, 1980). BHRA Fluid Engineering, Cranfield, Bedford, England, 1980, pp. 33-44.

13. _______. Flow Characteristics of Water Jets in Air. Paper A3 in Fourth International Symposium on Jet Cutting Technology (Canterbury, England, April 12-14, 1978). BHRA Fluid Engineering, Cranfield, Bedford, England, 1978, pp. 39-54.

14. Shavlovsky, D. S. Hydrodynamics of High Pressure Fine Continuous Jets. Paper A6 in First International Symposium on Jet Cutting Technology (Coventry, England, April 5-7, 1972). BHRA Fluid Engineering, Cranfield, Bedford, England, 1972, pp. 81-92.

15. Lohn P. D., and D. A. Brent. Nozzle Design for Improved Water Jet Cutting. Paper A3 in Third International Symposium on Jet Cutting Technology (Chicago, IL, May 11-13, 1976). BHRA Fluid Engineering, Cranfield, Bedford, England, 1976, pp. 33-46.

16. Sterling, M. S., and W. T. Abbot. Mechanisms of Water Jet Instability. Paper in First U.S. Water Jet Symposium (Golden, CO, Apr. 7-9, 1981). CO Sch. Mines Press, Golden CO, 1981, pp. I-4.1—I-4.6.

APPENDIX.–INTERPRETATION OF JET STREAM FLOW REGIONS

Preliminary comparisons of nozzle performance were also made by visually observing the water stream pattern. High contrast black and white photographs were taken of the stream pattern using a flash duration of 1/17000 s. Figure A-1 shows two different stream patterns which were both produced using nozzle C operating at 6,000 psi. To produce the pattern shown in figure A-1*A* the nozzle was inserted into a 4-in-long straight section of tubing. The stream pattern shown in figure A-1*B* was produced by using the same nozzle, but inserting it directly into the apparatus nozzle holder. In figure A-1*A* the central portion of the water stream is better defined and longer than the central portion of the stream in figure A-1*B*.

Past research (*12-13*)[1] has shown that central core formation is an important factor in determining the performance of the nozzle. However, the appearance of the jet pattern will vary with the water pressure. As water pressure increases the formation of more and faster moving water droplets around the core makes visual observation more difficult, and, therefore, the observed length of the core is not always a good indicator of nozzle performance.

A waterjet exiting into ambient air has been characterized as containing three regions (*11-15*). These regions are initial (core) region, main region, and final region.

A diagram of the jet stream structure is given in figure A-2. A pressure profile through a single plane in the jet stream shows how the pressure varied. These profiles were obtained by measuring stagnation pressure as the operating nozzle was moved across the target face of a pressure transducer at varying standoff distances. These pressure profiles have shown that the dissipation of the jet stream in air is related to the transfer of water energy as measured by stagnation pressure.

The initial region is identified as the area of the jet stream where the jet center line pressure is equal to the nozzle pressure. The distance the jet stream remains coherent is related to the jet formation in the initial region. As core length increase, the length of the coherent jet stream increases.

The main region is identified by the gradual decrease in the center line pressure. Within this region, jet flow disturbances are amplified and propagated. The air surrounding the jet stream resists the flow of water and acts to pull of ligaments of water (*16*). The outer layer of water slows, and air and water intermixing occurs. The main region jet stream is further dispersed until the air at the center line makes up 50 pct of the total volume (*11*).

In the final region the jet coherence rapidly decreases, and the center line jet pressure decreases rapidly.

[1]Italic numbers in parentheses refer to items in the list of references preceding this appendix.

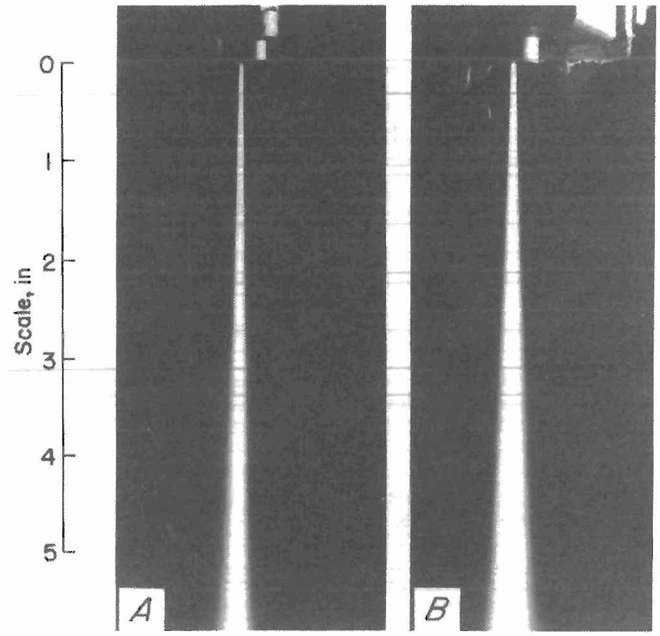

Figure A-1.—Visual flow patterns with (*A*) and without (*B*) 4-in straight tubing.

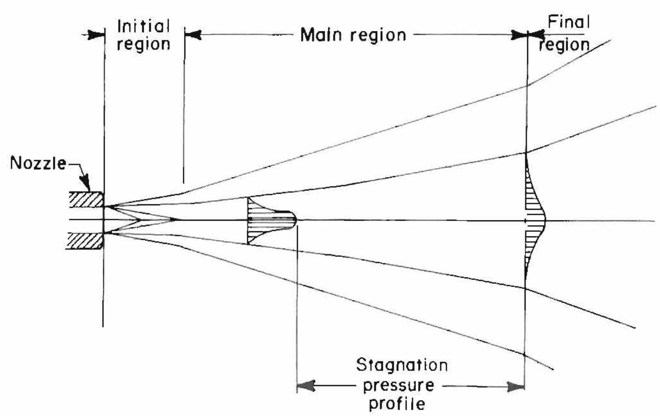

Figure A-2.—Water jet flow regions.

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INT.-BU. OF MINES,PGH.,PA. 28768