DOE/ET/12463-1

APPLICATION OF WATER JET ASSISTED DRAG BIT AND PICK CUTTER FOR THE CUTTING OF COAL MEASURE ROCKS

Final Technical Report

Contractor—Colorado School of Mines
Excavation Engineering and Earth Mechanics Institute

April 1, 1980

Contract No. FG01-77ET12463

U. S. Department of Energy
Assistant Secretary for Fossil Energy
Office of Coal Mining

DISCLAIMER

DISCLAIMER

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

Price: Printed Copy A05
Microfiche A01

Printed in the United States of America
USDOE Technical Information Center, Oak Ridge, Tennessee

DOE/ET/12463-1
Distribution Category UC-88

APPLICATION OF WATER JET ASSISTED DRAG BIT AND PICK CUTTER FOR THE CUTTING OF COAL MEASURE ROCKS

Final Technical Report

By

David Ropchan
Fun-Den Wang
John Wolgamott

Colorado School of Mines
Excavation Engineering and Earth Mechanics Institute
Golden, Colorado 80401

Prepared for the
United States Department of Energy
Carbondale Mining Technology Center
Under Contract No. ET-77-G-01-9082

April 1, 1980

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT'D.)

LIST OF TABLES

LIST OF FIGURES

FIGURE NO. PAGE

LIST OF FIGURES (CONT'D.)

LIST OF FIGURES (CONT'D.)

FOREWORD

This report was prepared by the Excavation Engineering and Earth Mechanics Institute, Colorado School of Mines, Golden, Colorado. The project was originally with U.S.B.M. under Contract No. G0274009. Shortly after the contract began, reorganization placed the project with DOE under Contract No. ET-77-G-01-9082. It was administered under the techpnial direction of the Twin Cities Mining Research Center with Mr. David P. Lindroth as Technical Projet Officer and Mr. Larry L. Rock as Contracting Officer.

This report is a summary of the complete project activities from June 1977 to November 1978.

ABSTRACT

A laboratory investigation was made of the effects of high pressure water jets on the cutting forces of drag bit cutters in sedimentary rocks. A hard and soft sandstone, shale and limestone were tested with commercially obtainable conical and plow type drag bits on the EMI linear cutting machine. About 1,200 cuts were made at different bit penetration, jet orientation,and water pressure to determine the reduction of cutting forces on the bit from the use of the water jet. Both independent and interactive cutting was used. The greatest reduction in cutting forces were with both of the sandstones; the drag forces were reduced about 30 percent and the normal forces about 60 percent at 5,000 psi water pressure with the nozzle behind the bit. The method was less effective in the shale, except at 10,000 psi water pressure the reduction in drag force was about 55 percent. Of the rocks tested, the limestone was least affected by the water jet. The cutting forces for the plow bit showed continuous change with wear so a machined conical bit was used for most of the testing. Tests with the plow bit did show a large reduction in cutting forces by using the water jet with worn bits. An economic analysis of equipping a drag bit tunnel boring machine indicated that the water jet system could reduce costs per foot in sandstone by up to 40 percent.

1. INTRODUCTION

This investigation examined the feasibility of using high pressure water jets to assist drag bit cutting of sedimentary rocks. On the basis of the results of other test programs using water jets to cut rock, this technique might improve the ability of coal mining excavation machinery using drag bit cutters to mine harder sedimentary formation as may be required in development work.

Increased reliance on coal as a domestic energy source will require improvement in underground mining technology to improve productivity. One important area where productivity can be increased is in the penetration rate of mining machines, especially in development work where harder rocks, such as sandstone, limestone, and shale, may be encountered. Most coal excavation machines use a drag bit (or pick) cutting action to break the material. Drag bit cutting has been shown to require less specific energy than disc cutting (1)[1]; furthermore, drag bits have a simple, sturdy construction and are economical to produce and easy to replace. In medium-to-hard sedimentary rock, however, the increased shock loading and abrasion make the drag bit uneconomical.

The purpose of this research was to develop and test a method for improving the cutting efficiency of the drag bit in harder sedimentary rocks using high pressure water in a fine jet to assist in breaking the rock. Investigations were conducted in the laboratory using a linear rock cutter with a commercial high-pressure (10,000 psi) water pump system and drag bits in common use on domestic coal mining equipment.

The parameters studied included two bit types, four rock types, three water jet positions relative to the bit, variation of jet pressure and orifice

---

[1] Underlined numbers in parenthesis are references in Section 8.

diameter, and variation of bit spacing and penetration. About 1,200 cuts were made on the four rock types tested: Dakota sandstone, a hard sandstone from Germany, Lyons limestone, and Lyons shale. Results are shown in graphical form and a summary of all the data is included in Appendix C.

A preliminary economic analysis was made to determine the potential economic benefit of the water jet assisted drag bit cutting.

2. BASIS OF WATER JET ASSISTED CUTTING

Investigation into the use of high pressure water jets to assist in cutting rock have been made at the CSM Earth Mechanics Institute where high pressure jets were used with rotating disk cutters, and in South Africa where jets were used in conjunction with a drag type of cutter (2). In the case of assisting rotating disk cutters, high pressure jets have been used to cut slots between of the cutters to provide a relief cut for the rock to break to. In Hood's work with water jet assisted drag cutters, pressures of about 7,250 psi were used in norite. The water was used to assist the drag cutter without cutting an independent slot in the rock. Hood found that by aiming two jets into the high stress zone near the corners of the chisel-type bit, he could double the depth of cut over that of the unassisted bit with the same driving force. The cutting mechanism for single point drag bits, as used in the present investigation, is somewhat different. As discussed by Roxborough (1) and others (3), (4), (5), the cutting mechanism for drag bits in brittle materials is considered to be a spalling action that takes place ahead of the bit. This spalling is initiated by the combined thrust, normal, and side forces exerted by the bit on the rock (Figure 2-1). For a water jet to be of benefit in assisting the drag bit, the water should assist this spalling action.

Three basic orientations of the water jet relative to the cutting point of the drag bit (Figure 2-2) were considered: (1) the jet mounted ahead of the bit oriented to cut a vertical slot in line with the cutting edge or point of the bit, (2) the jet mounted at the side of the bit aimed at the cutting point of the bit, and (3) the jet mounted behind the bit aimed at a flat angle to hit at the bottom of the cutting point. The purpose of the first orientation was to cut a relief slot ahead of the drag bit to see what effect

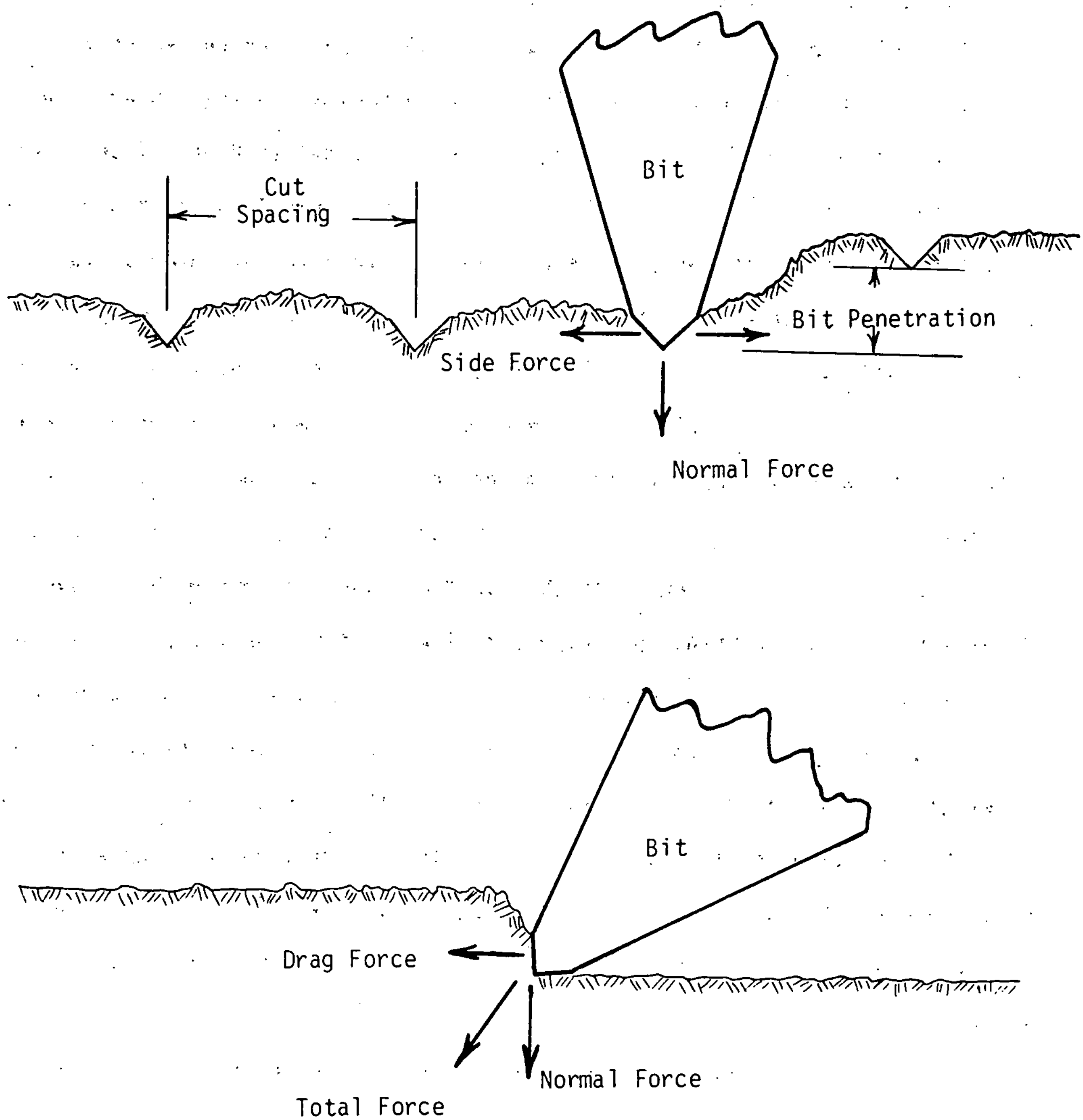
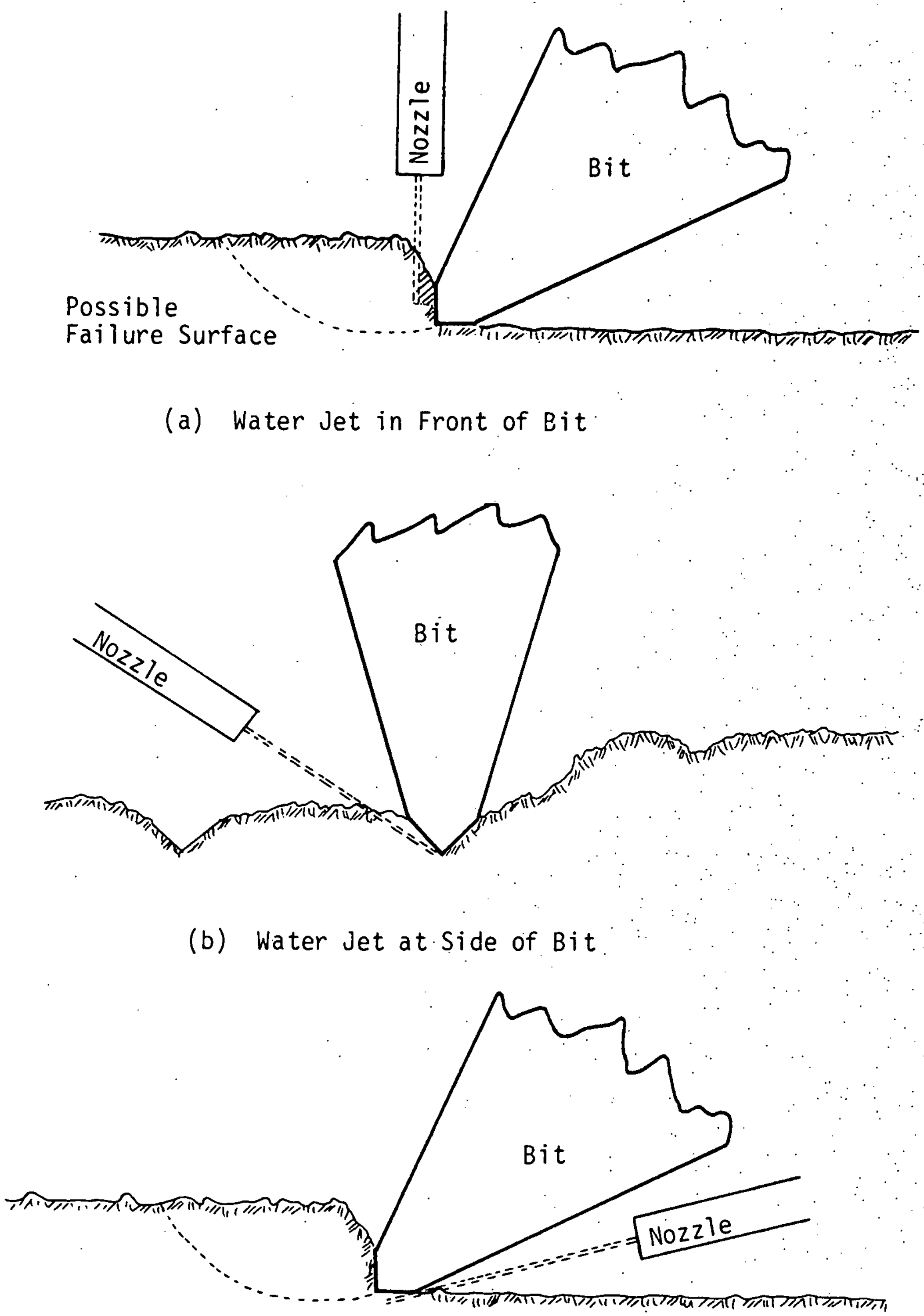


Diagram of Cutting Forces

FIGURE 2-1



(a) Water Jet in Front of Bit

(b) Water Jet at Side of Bit

(c) Water Jet Behind Bit

Positions of Water Jet Relative to the Drag Bit

FIGURE 2-2

this would have on reducing the forces necessary to produce cutting. The second orientation was intended to place the impact of the jet just below the cutting point of the bit with the added feature of cutting a low angle slot parallel to the bit path to promote spalling of the rock. The third orientation was intended to hit the rock with the jet just below the cutting point in the high stress zone of cutting.

Although the placement of the jets was of primary importance in the test program, the water pressure (and horsepower) used, size of the nozzle orifice, and the nozzle standoff distance were also important parameters in evaluating the assistance the jets provided to the drag bits. The depth of the water jet cut for any specific rock type is dependent on the standoff distance and the water pressure. The width of the cut is dependent on the width of the jet stream, which is, in turn, controlled by the orifice diameter.

3. EQUIPMENT

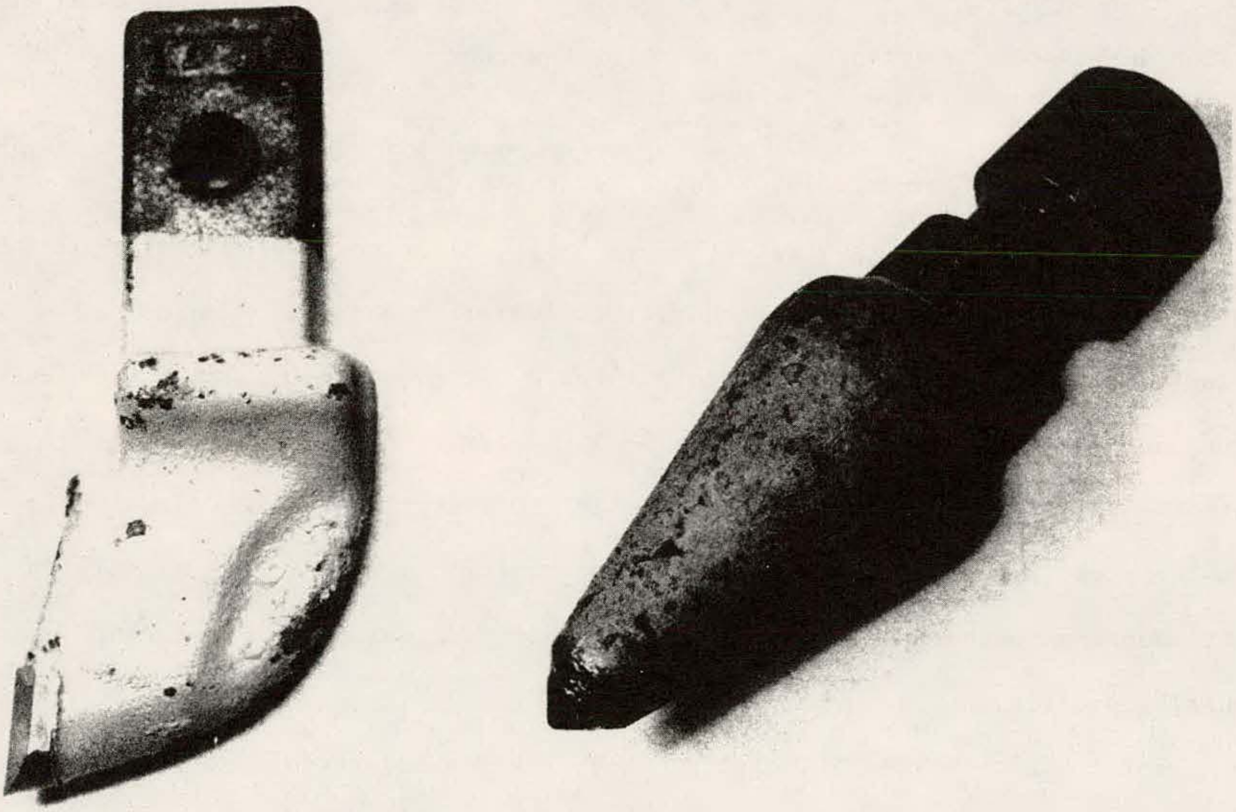
The equipment used in the test program consisted of four major units: (1) the drag bits and their mounting blocks, (2) the linear rock cutting machine, the main frame and prime mover for controlling the bit-rock interaction in simulating insitu cutting of the rock, (3) the instrumentation to monitor the forces required to cut the rocks, and (4) the high pressure water jet system to assist in fragmenting the rock.

3.1 Drag Bits

Two types of commercially obtainable drag bits, commonly used in the coal industry were used for the tests (Figure 3-1). Although several variations of bits exist on the market, two styles predominate: the pointed conical or plumb bob type, and the plow or wedge type. A Carboloy CC-40 point attack bit was used for the conical bit (Figure 3-2). A tungsten carbide insert is attached at the tip. This bit is designed for mounting at a 45 degree angle to the rock surface (Figure 3-3) and is designed to freely rotate axially in its mounting so that the tip is self-sharpening and maintains a constant cutting profile.

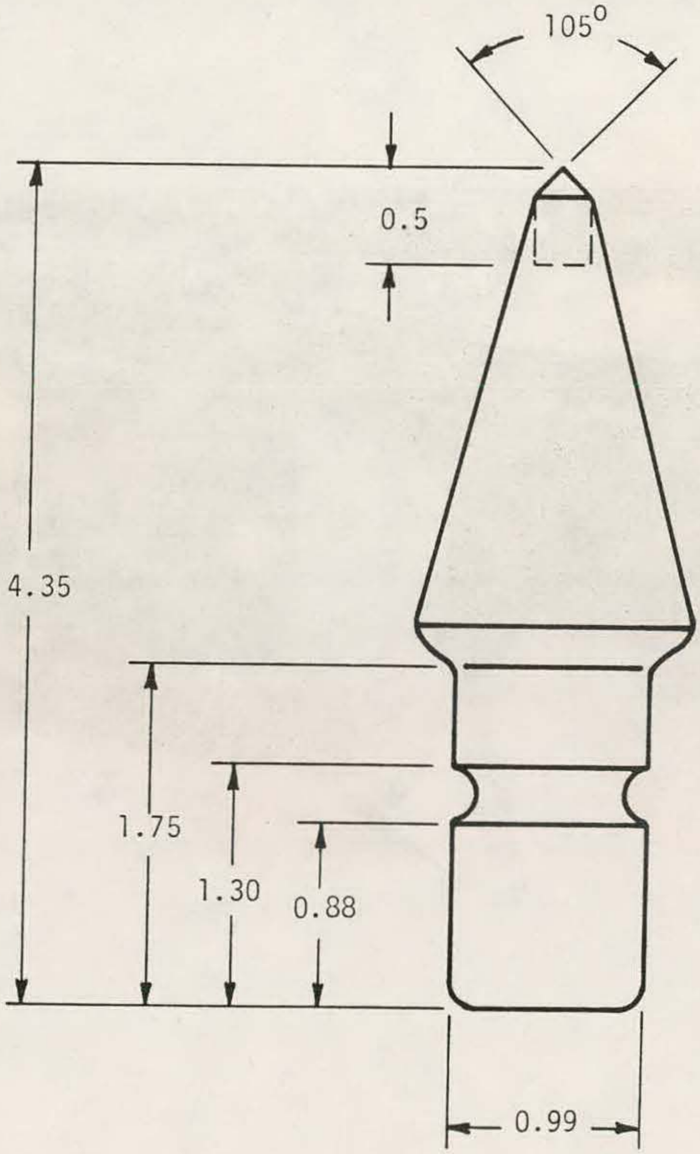
For the plow style, a Carboloy CCH-66 bit was selected (Figure 3-4). The bit was mounted with its cutting edge almost perpendicular to the rock surface (Figure 3-5). The cutting tip of the bit is a wedge shaped carbide insert having a 5 degree rake angle and a 15 degree back clearance angle.

Mounting blocks for each bit were designed to match the support characteristics of commercial bit holders. These blocks were then rigidly attached to the underside of the load cell on the linear rock cutter used to measure the normal and drag forces on the bit.



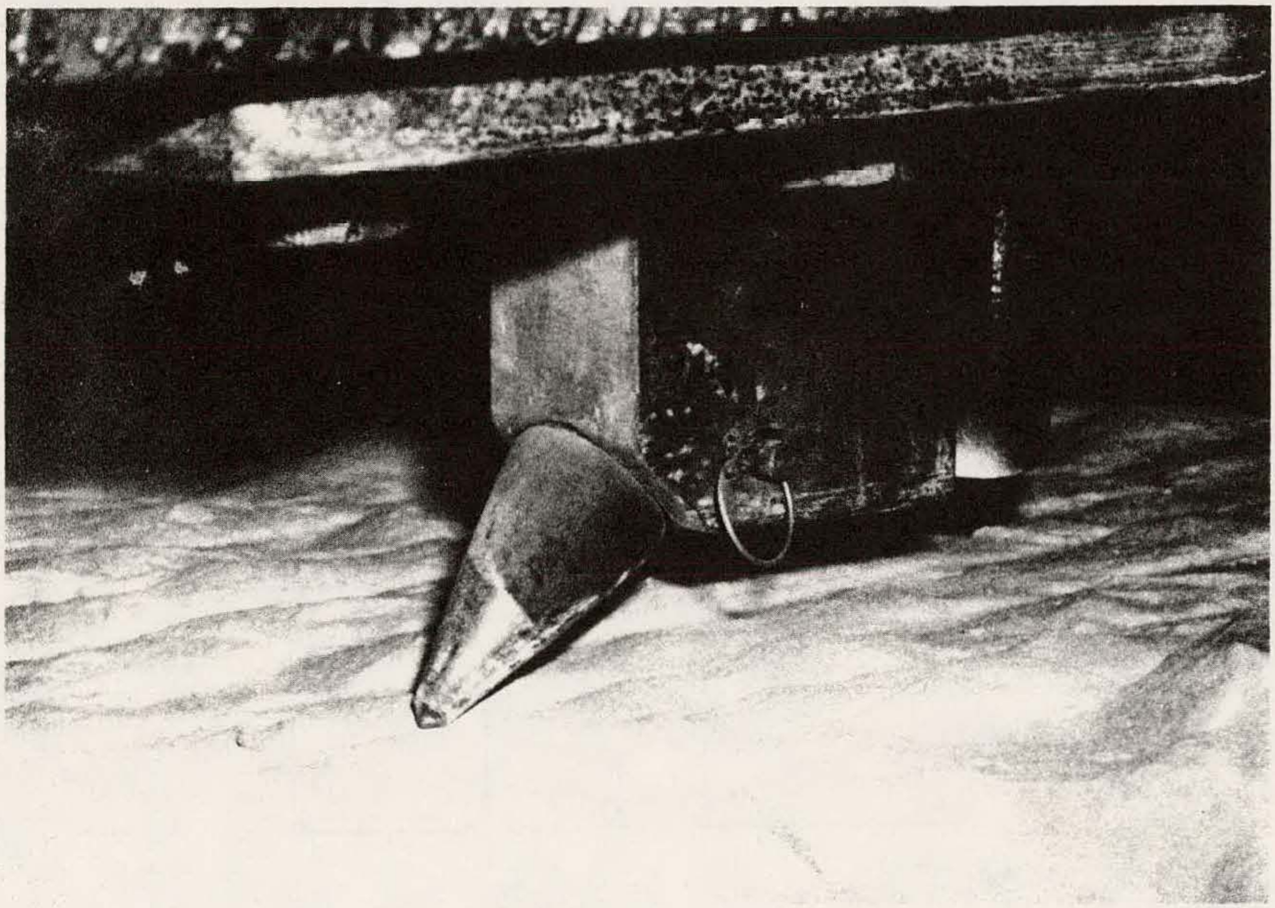
Two Pick Styles Used

FIGURE 3-1



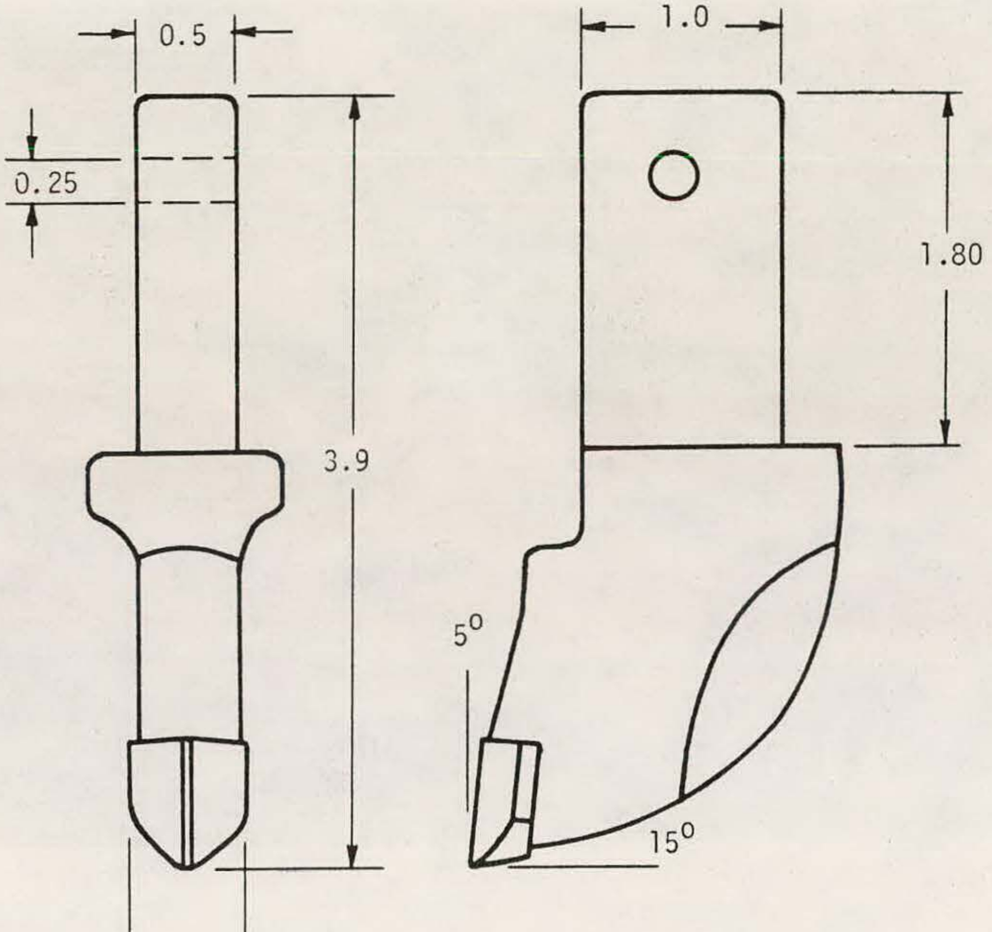
Conical Bit Dimensions

Figure 3-2



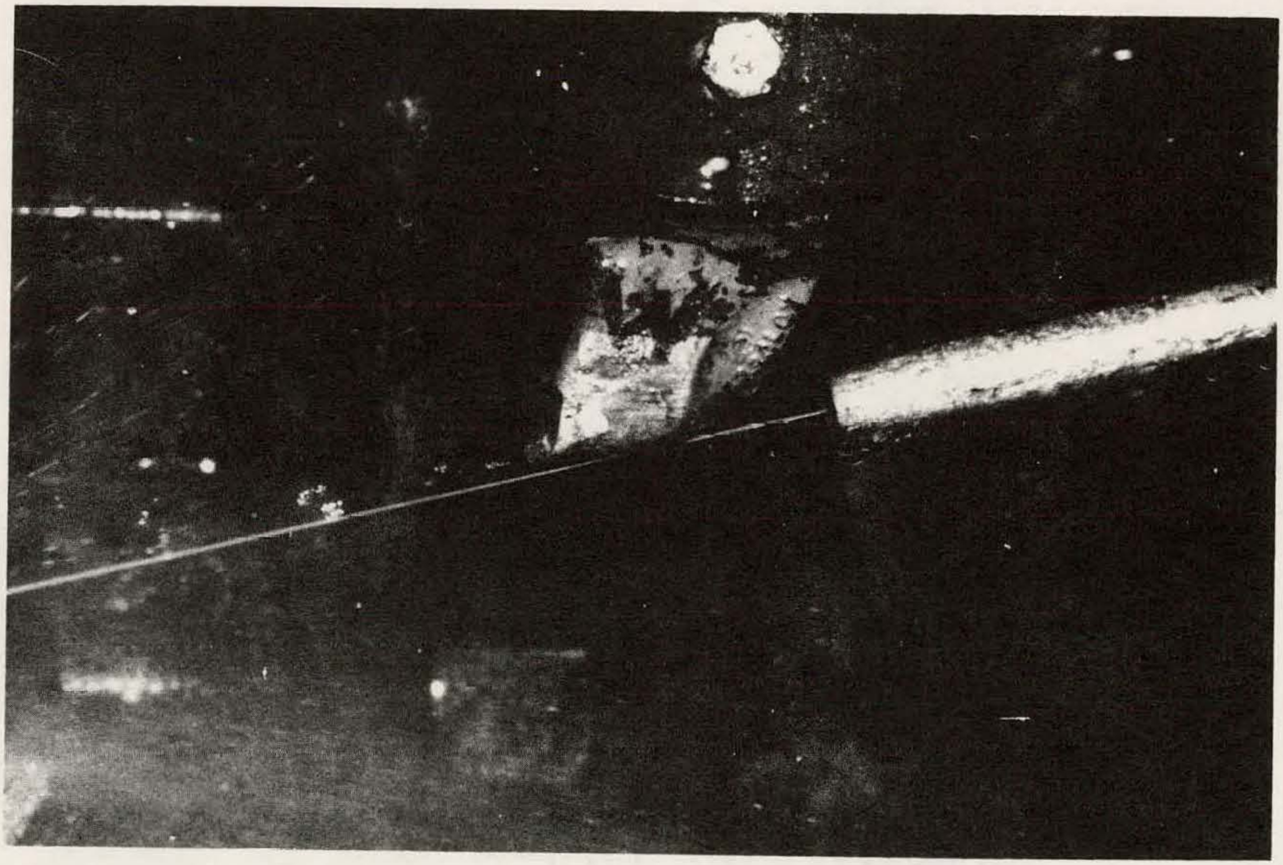
Mounted Conical Bit

FIGURE 3-3



Plow Bit Dimensions

Figure 3-4



Mounted Plow Bit

FIGURE 3-5

3.2 Linear Rock Cutter

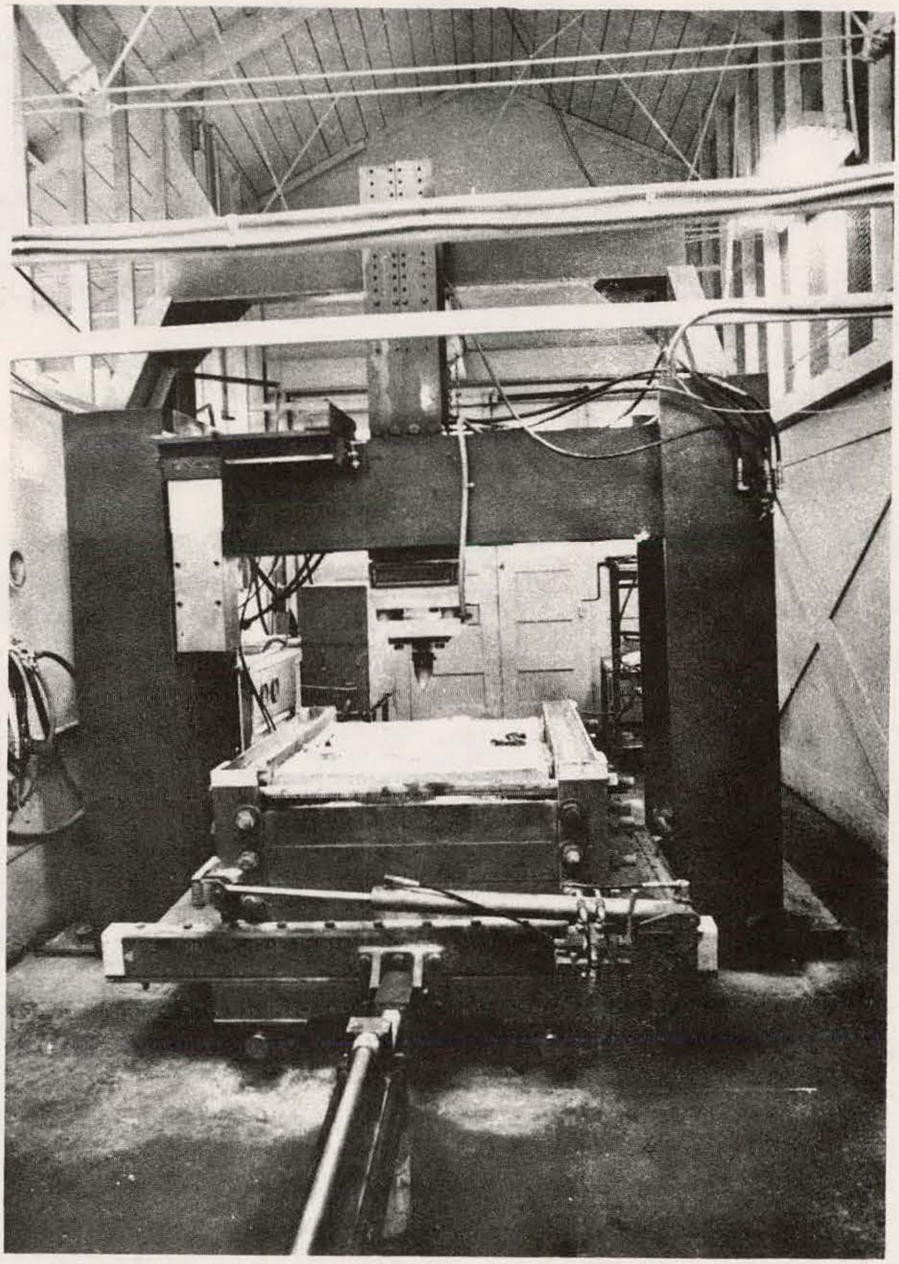
This unit supports the rock sample and the cutting tool and controls the interaction between them. The unit is designed to test full sized rock cutters under actual loading conditions and can withstand large dynamic loads with minimal deflection or vibration (6). A stationary overhead frame holds the cutting tool while the rock sample below is driven horizontally into the tool.

The main frame consists of large, welded and bolted steel beams. The cutting tool is suspended under the large boxed crossbeams (Figure 3-6) and can be raised or lowered by a hydraulic ram that is mounted to the top of and runs through the beam. Steel plate spacers were placed between the cutter mounting and the cross beam so that a constant cutter height could be maintained. Calibration experiments showed that a 25,000 pound load on the cutter produced less than 0.01 inch deflection on the frame. The sample box, fabricated from I-beams, is positioned horizontally beneath the cutter and moves horizontally on two 3-inch-diameter steel rails anchored to the floor. Four linear bearings provide a rigid, low-friction mount.

Horizontal thrust is provided by a servo-controlled hydraulic ram that can provide 30,000 pounds of force at 40 inches-per-second feed rate over a 5 foot stroke. To index the cutting paths, a pair of 2-foot-stroke double-acting cylinders move the rock holder box sideways.

3.3 Force Monitoring System

This unit consists of a load cell, signal conditioners, and a digital integrator that determine the average values for the normal, drag, and side forces on the cutter. The triaxial load cell (Figure 3-7) consists of two thick aluminum plates separated by four prestressed, hollow aluminum cylinders on whose circumferences are mounted six dual-element strain gages. The gages



Linear Rock Cutter

FIGURE 3-6

PAGES 15 to 22

WERE INTENTIONALLY

LEFT BLANK

4. TEST PROCEDURES

Procedures for testing rocks in the linear cutting machine, established from several years of experience with rolling disc and water jet cutters, were modified somewhat for these tests of drag bit cutting.

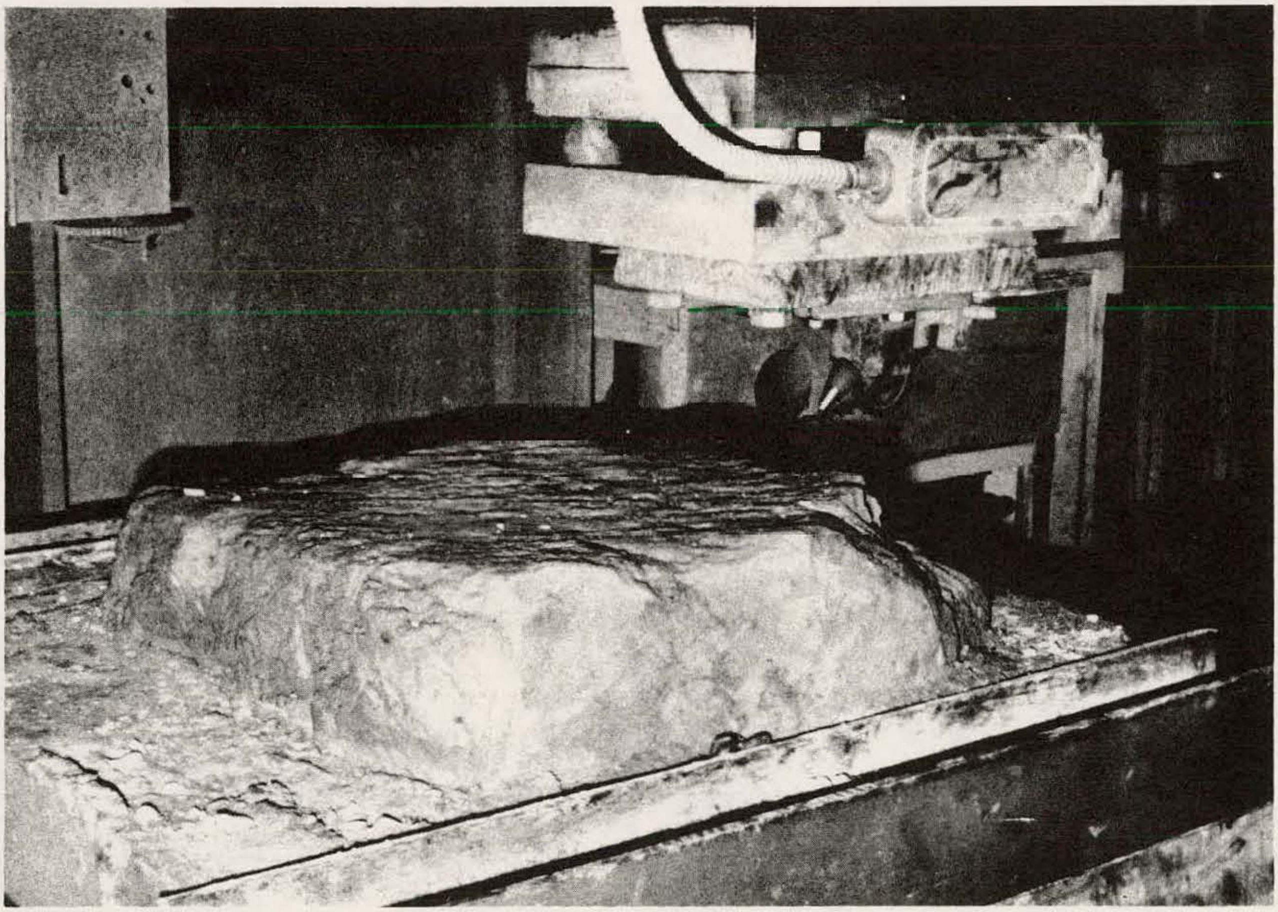
4.1 Sample Preparation

The rock samples were sized to fit the 36 inch by 42 inch sample holder before being cast into the holder with concrete. The height of the samples ranged between 12 to 36 inches with the top surface having a reasonably flat, clean face exposed for cutting (Figure 4-1). For most of the samples, the shaping was done by drilling and splitting with wedges. The sandstone from Germany had wire sawed surfaces. A loop of chain was cast into the concrete to facilitate ease of handling, and the concrete was cured for at least two weeks before testing.

4.2 Calibration

To calibrate the force measuring system, a hydraulic ram was used to load the bit. The ram was placed between the bit and the upper end of a support pole. The lower end of this pole was supported at the floor and moved to vary the direction of load on the bit. Measurement of the angle of inclination of the pole permitted calculation of the three principal forces on the bit. By loading the bit with the ram to known values and reading the corresponding output from the strain gage bridges on the cutting head load cell, the force measurement system could be calibrated. The sensitivity of the load cell is about 5 percent of full range up to 5,000 pounds. Below 1,000 pounds, sensitivity was reduced by about 10 percent.

An independent check of the calibration method was to test each axis of the cutting machine separately. To test the vertical thrust, the hydraulic ram was placed between the cutter and the rock so that there were no lateral



Rock Sample in Position

FIGURE 4-1

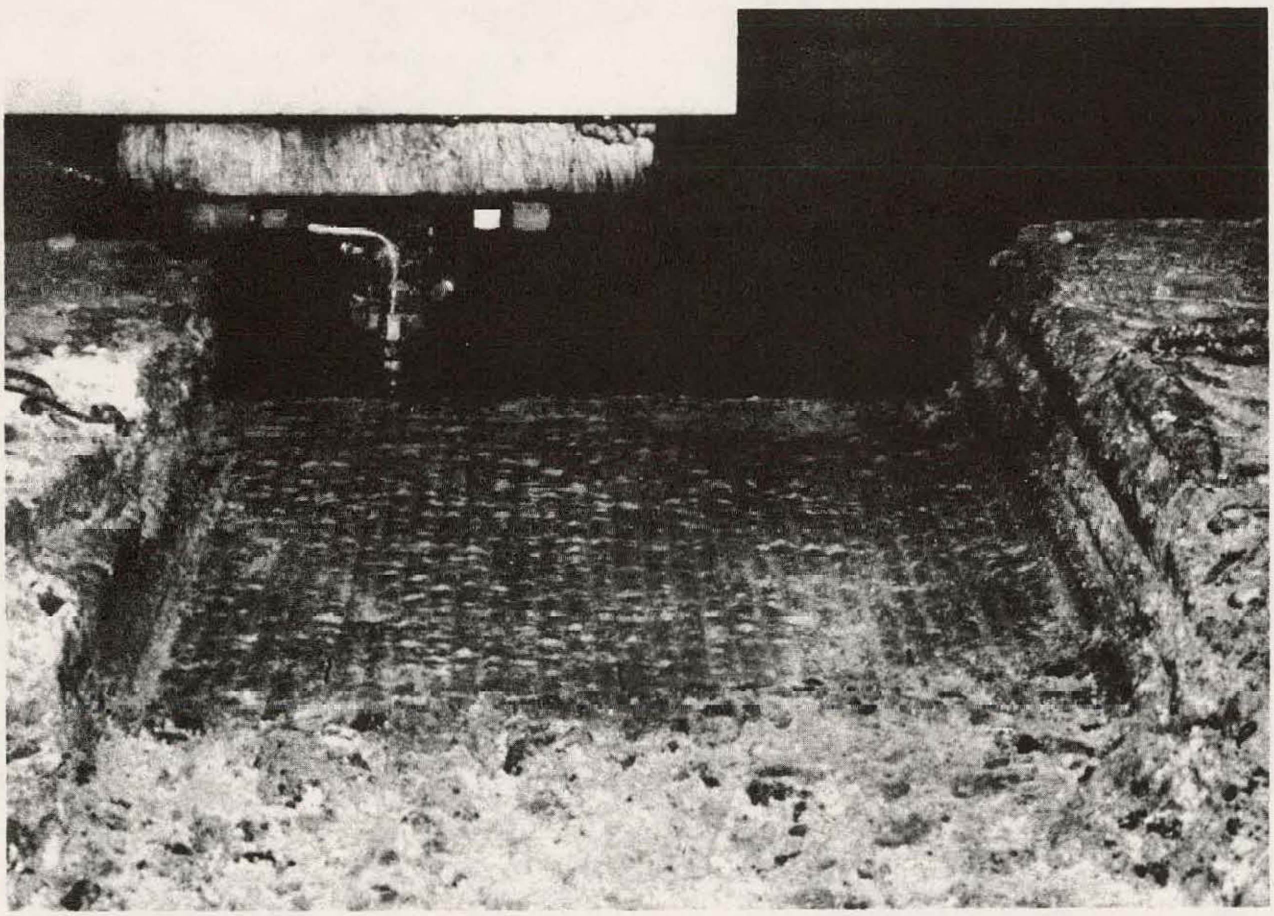
loads on the bit. To test the horizontal thrust, the ram was placed between the bit and a T-beam placed between the overhead frame side supports. For side loads, the ram was placed between the bit and the side supports,

Agreement between the two techniques and the repeatability of each technique was within 5 percent. The calibrated sensitivity of the load cell did not vary more than 5 percent over the course of the test program.

4.3 Cutting Machine Operation

In all the tests, the bit was held at a set penetration depth into the rock, and the thrust and drag forces resulting from moving the bit across the rock were monitored. This approach probably is close to the actual cutting of a large multitool-faced machine. The individual force on an individual bit can vary greatly as a machine operates, while the penetration rate remains fairly constant because of the overall stiffness of the system.

The high bit-rock stresses produced by drag bit cutting in brittle materials cause both chipping of the material and also promote microcracks in the visually intact rock. These microcracks will affect the cutting forces on the bit and are dependent on the type of bit, spacing between cuts, and penetration depth. To reduce variability in the results from the effects of these cracks, the rock surfaces were conditioned with a series of cuts before a test run was made. For the independent cut tests (no interaction between cuts), the bit was set for 0.1-inch penetration and traversed across the rock sample in a 0.5-inch spacing pattern until a fairly uniform surface was obtained (Figure 4-2). The majority of the tests designed to measure the effect of interaction between parallel cuts were at a spacing of 1.5 inches and a penetration of 0.5 inch. In conditioning the rock surfaces for these tests, a minimum of two series (passes) of cuts were made across the width of the sample.



Conditioned Rock Surface

FIGURE 4-2

4.4 Water Jet Operation

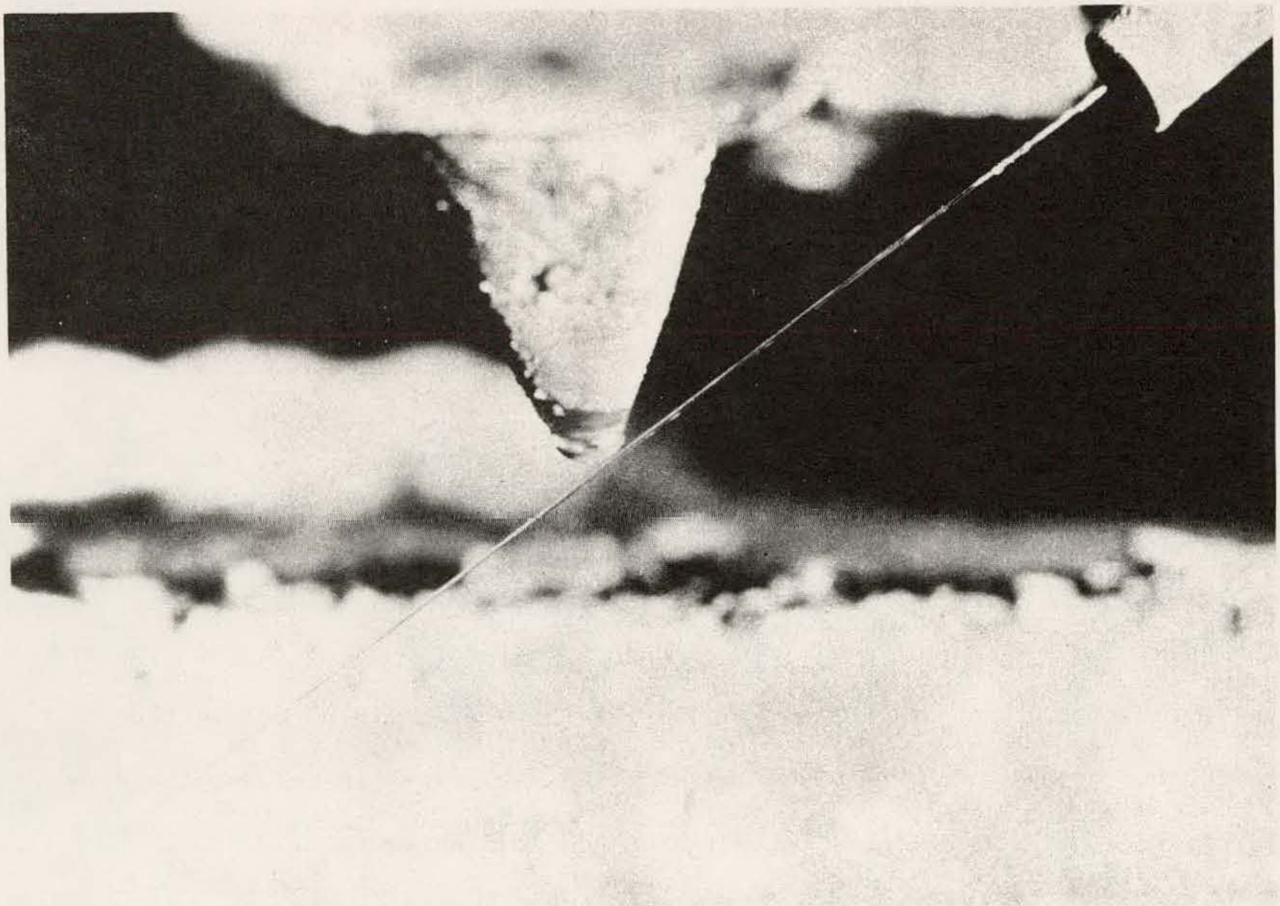
The water jet nozzle assembly was mounted on the bit mounting plate in a manner to allow changes in the orientation of the water jet relative to the cutting surface of the bit. This was done by using slip-type swivel joints to allow exact positioning of the nozzle (Figure 4-3). For each orientation, the jet was positioned and tested under pressure so that the water jet alignment with the drag bit could be checked.

In making the water jet assisted cuts, the rock was positioned in front of the bit and nozzle. Then the water jet was turned on and the rock pushed toward the bit. Upon completion of the cut, the jet was turned off and the rock pulled back. The rock sample was then shifted laterally to the desired spacing between cuts and the procedure repeated.

4.5 Data Collection and Analysis

As discussed in Section 3.3, the data for the normal, drag, and side forces on the bit was collected and electronically analyzed to provide a total force per cut for each of the three directions. For the purposes of analysis, the total force on the bit was considered to be the resultant of the drag and the normal forces on the bit. The side forces were monitored during the tests, but because of the low values and high variations in values, the side forces were not considered in calculating the load on the bit.

An example of data is shown in Figure 4-4. The values for the individual cuts show considerable variation over the range of cuts. A scatter of 10 or 20 percent in the data was not uncommon. To analyze the data for each series of passes over the sample, the mean and standard deviation of the forces were calculated (a pass being one series of cuts across the face of the sample). Figure 4-5 shows the results of 4 passes of test No. 39 with the mean and standard deviation of the drag and normal forces. For this test, the plotted



Jet Alignment

FIGURE 4-3

Example of Test Data for Multiple Cuts for Test No. 39, Pass 3

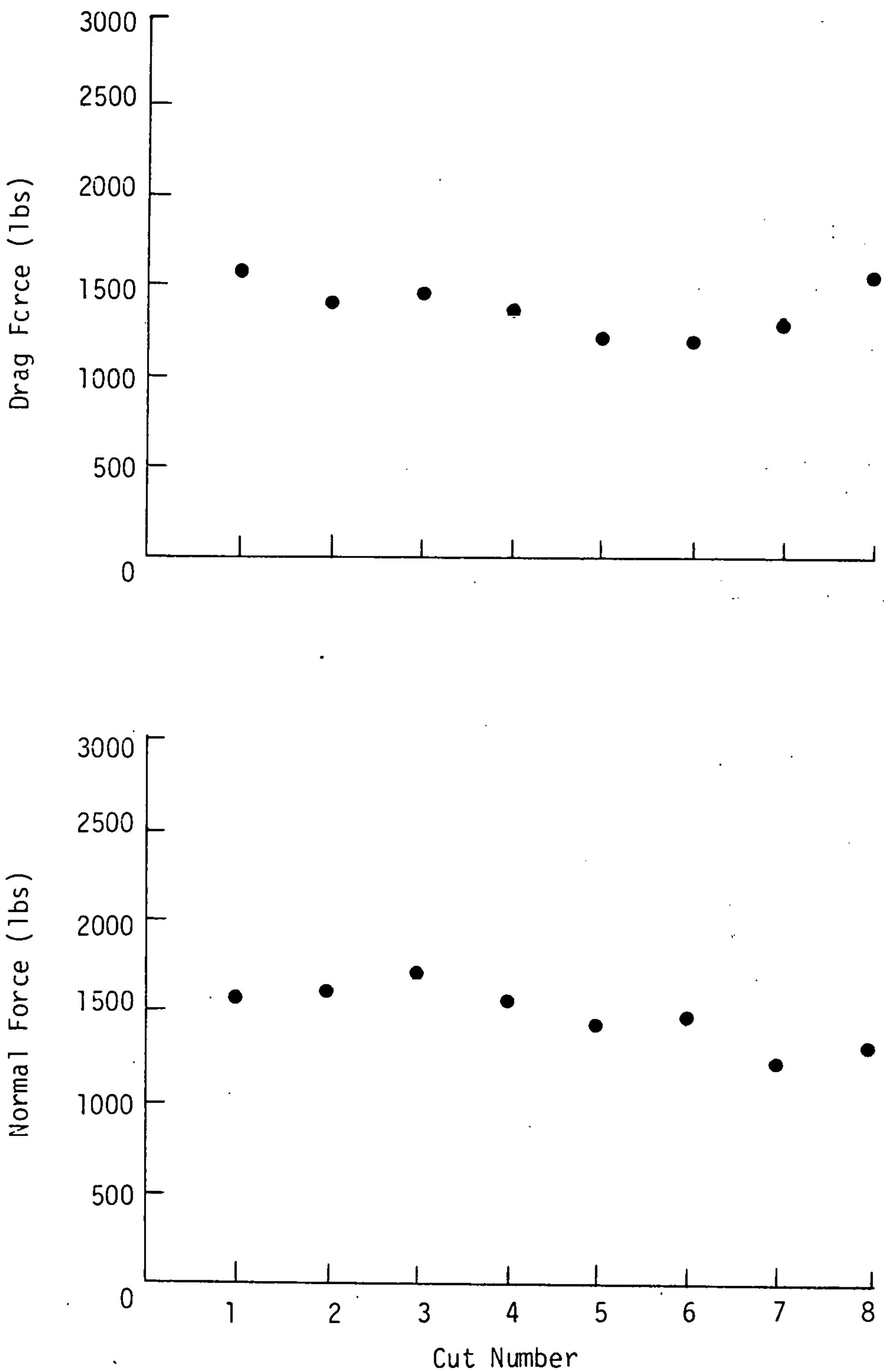


FIGURE 4-4

Summary of Test Data Over Four Passes for Test No. 39

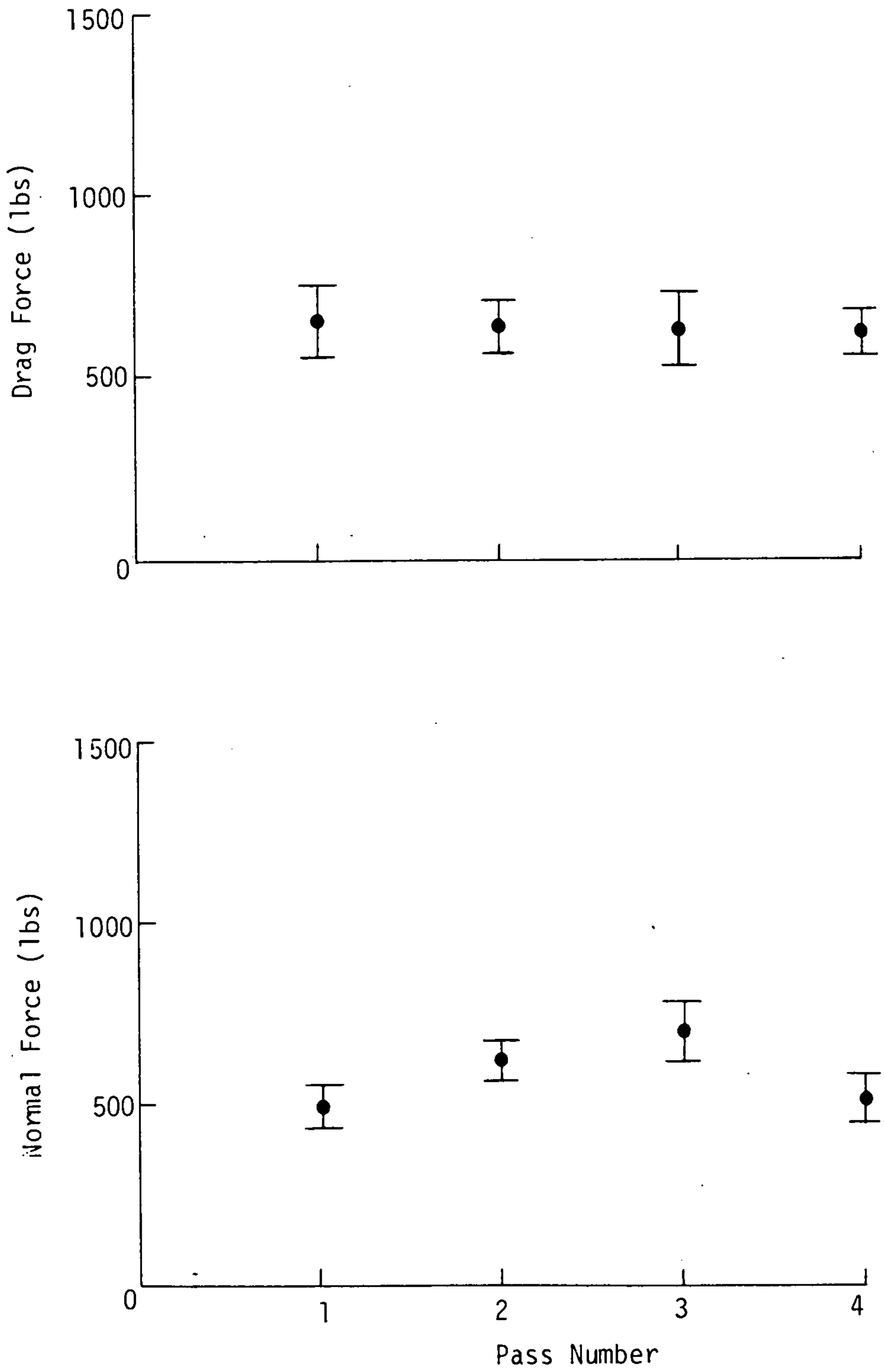


FIGURE 4-5

values would represent averages of 30 individual cuts. As each cut was approximately 1.5 to 2 feet in length, the cutting force value was the average of about 50 feet of cutting.

5. TEST RESULTS

5.1 Summary

The use of high pressure water jets in this study to assist drag bits in cutting rock was of varying effectiveness, depending on rock type. The cutting forces in both the hard and soft sandstones were reduced from 30 to 70 percent with the water jet assist. The tests on shale indicated that at 10,000 psi with a low angled jet behind the bit, the cutting forces could be reduced more than 50 percent. For limestone, the jets were not very effective at the jet pressures and configuration tested. For a single jet at 5000 psi pressure, the total cutting force was reduced only about 16 percent. For two jets at 10,000 psi, the reduction was about 27 percent. The single jet at 10,000 psi was not effective.

Because the study of every variation of all the parameters would have meant conducting several thousand tests, the results from these tests probably do not represent the optimum in every case; however, the results from the 1,200 cuts made indicate that water jets can significantly reduce the cutting forces on drag bits.

The conical pick type of bit was used for most of the testing, as it showed more consistent normal and drag forces with wear less than the plow style. The continuous rise in cutting forces with wear on the plow bit would have made it more difficult to analyze the effect of water jet assistance on cutting performance. The most effective location for the jet was at a low angle behind the bit aimed just below the cutting point.

5.2 Preliminary Investigations

Before using the water jet to assist the drag bits, some preliminary tests were made to determine the relation between nozzle standoff of the jet (distance from cutting surface) and depth of cut, effect of cutting speed of the drag bit alone on the cutting forces, and the effect of wear of the drag bit on cutting forces.

5.2.1 Nozzle Standoff

The penetrating action of drag bits occurs by the bit imbedding itself in the rock and spalling the rock upward and outward. Because there is no fixed distance between the cutting point of the bit and the resulting broken material, the nozzle of the water jet must be far enough away from the bit point to be protected against damage from this broken rock. Tests were conducted to measure the effect of this standoff distance of the nozzle on the depth of cut by the water jet.

Samples of Dakota sandstone were prepared with flat sawn surfaces and passed under the jet nozzle at different standoff distances. The nozzle was kept perpendicular to the rock surface. No tests were made at oblique nozzle angles. In tests of both 0.012-inch and 0.025-inch nozzle orifices at 10,000 psi water pressure, no significant change in depth of cuts occurred over a range of 2 to 10 inches of standoff distances. The variation in depth of cut was about 0.050 inch for both orifices. The depths for the 0.025-inch orifice ranged from about 0.10 to 0.15 inches, and for the 0.012-inch orifice, below 0.05 inches.

5.2.2 Cutting Speed

Although other investigators report no differences in cutting forces over a reasonable speed range (1), (4), tests were made with the conical pick to determine if the cutting forces were influenced by the cutting speed. Independent cuts were made in soft sandstone at 0.2-inch penetration and at velocities of 1, 2, 5, and 10 inches per second. As shown in Figure 5-1, there was a dip in cutting forces between 3 and 4 inches per second cutting velocity.

5.2.3 Bit Wear Tests

During the preliminary testing and equipment checkout, it was noticed that the plow bit showed a great variation in cutting forces for consecutive tests where there was no change in parameters. This was traced to wear of the cutting face. The Dakota sandstone used in the initial tests was very abrasive, and the plow bit showed signs of dulling after only a few feet of cutting (Figure 5-2).

Results of tests on both plow and conical bits in soft sandstone at 0.4 inch penetration are presented in Figure 5-3. For the conical bit, drag forces decreased 25 percent and normal forces decreased 50 percent after a new bit had cut about 5,000 feet. For the plow bit, drag forces increased 500 percent and the normal forces increased almost 800 percent after a new bit has cut about 5,000 feet. When new, the plow bit required only 1/4 the drag force and 1/2 the normal force as the conical bit. However, after 5,000 feet of cutting, the plow bit required twice the drag force and three times the normal force on the conical bit.

Although the drag bit exhibited continuous change in cutting force with wear, the conical bit demonstrated more uniform cutting forces after the first 2000 feet of cutting. The different cutting force pattern for the conical bit may be due to the fact that this type of bit is designed to rotate in its holder and be self-sharpening. It was found that the cone angle of the carbide insert in the tip of the bit remained at 105 degrees during wearing of

Variation in Cutting Forces with Cutting Speed for Conical Pick in Dakota Sandstone, Independent Cut Spacing, Bit Penetration: 0.2 Inches

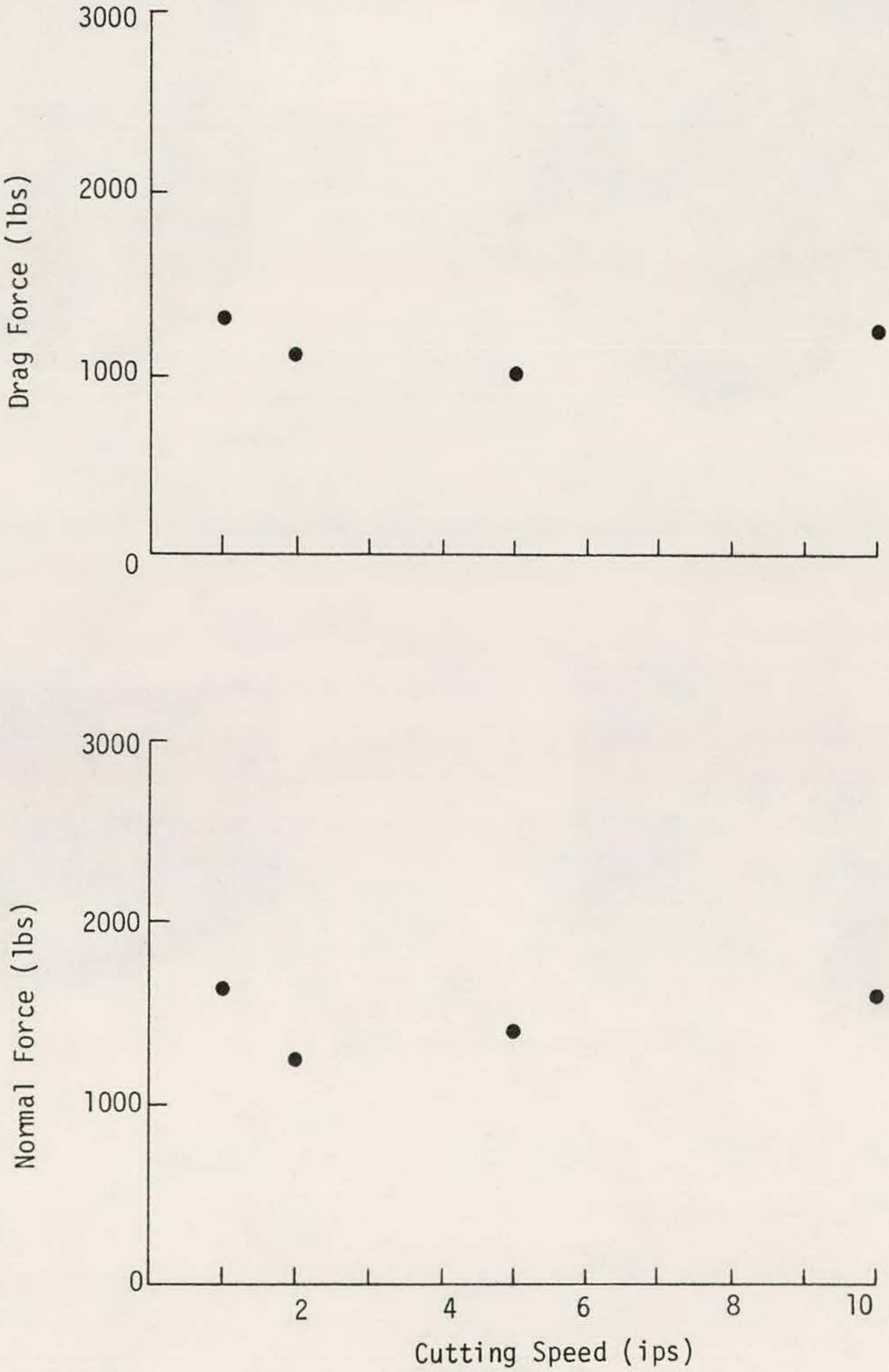
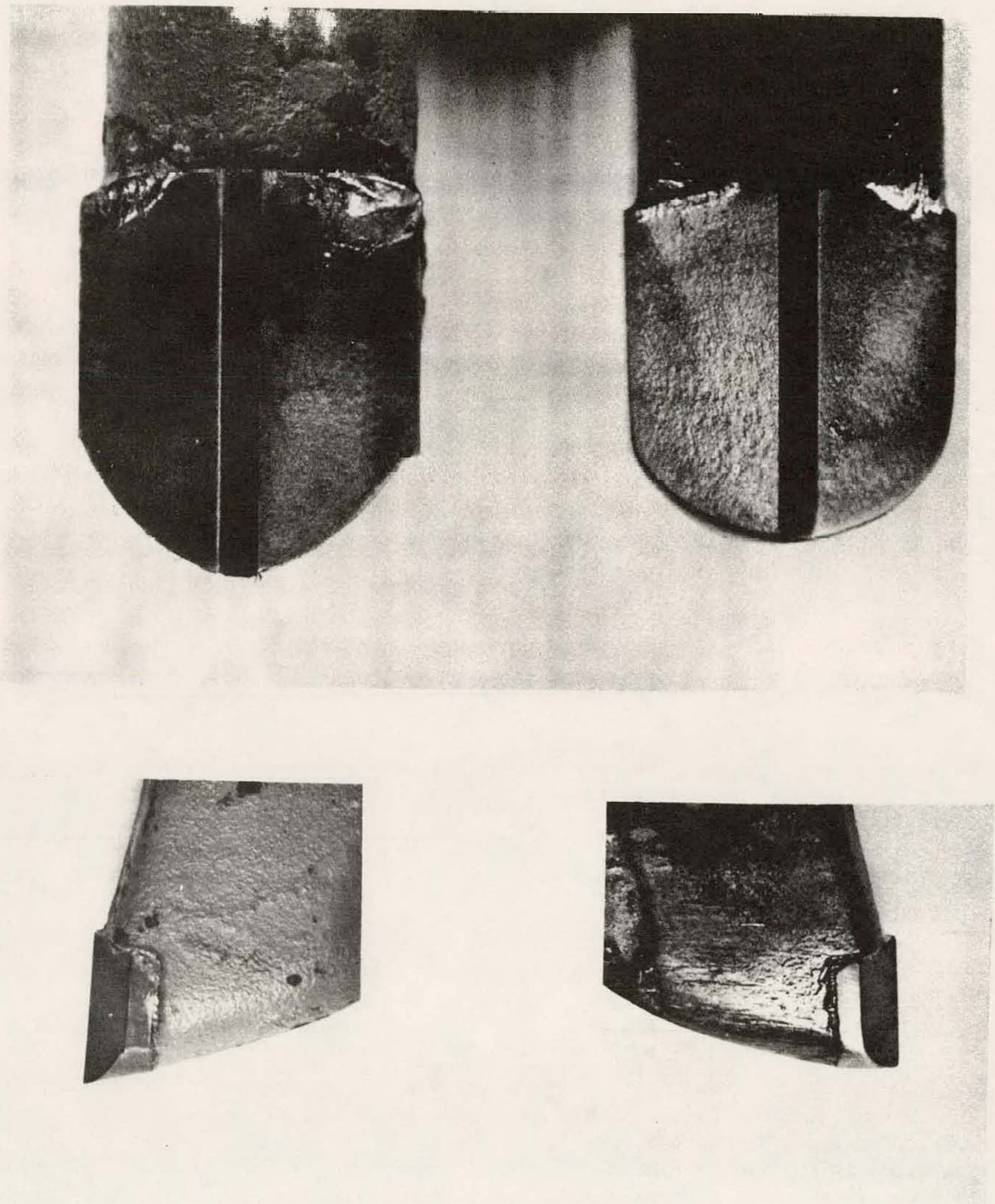


FIGURE 5-1



Plow Bit Wear

FIGURE 5-2

Variation in Cutting Forces with Bit Life for Conical and Plow Bits in Dakota Sandstone, Independent Cut Spacing, Bit Penetration: 0.4 Inches

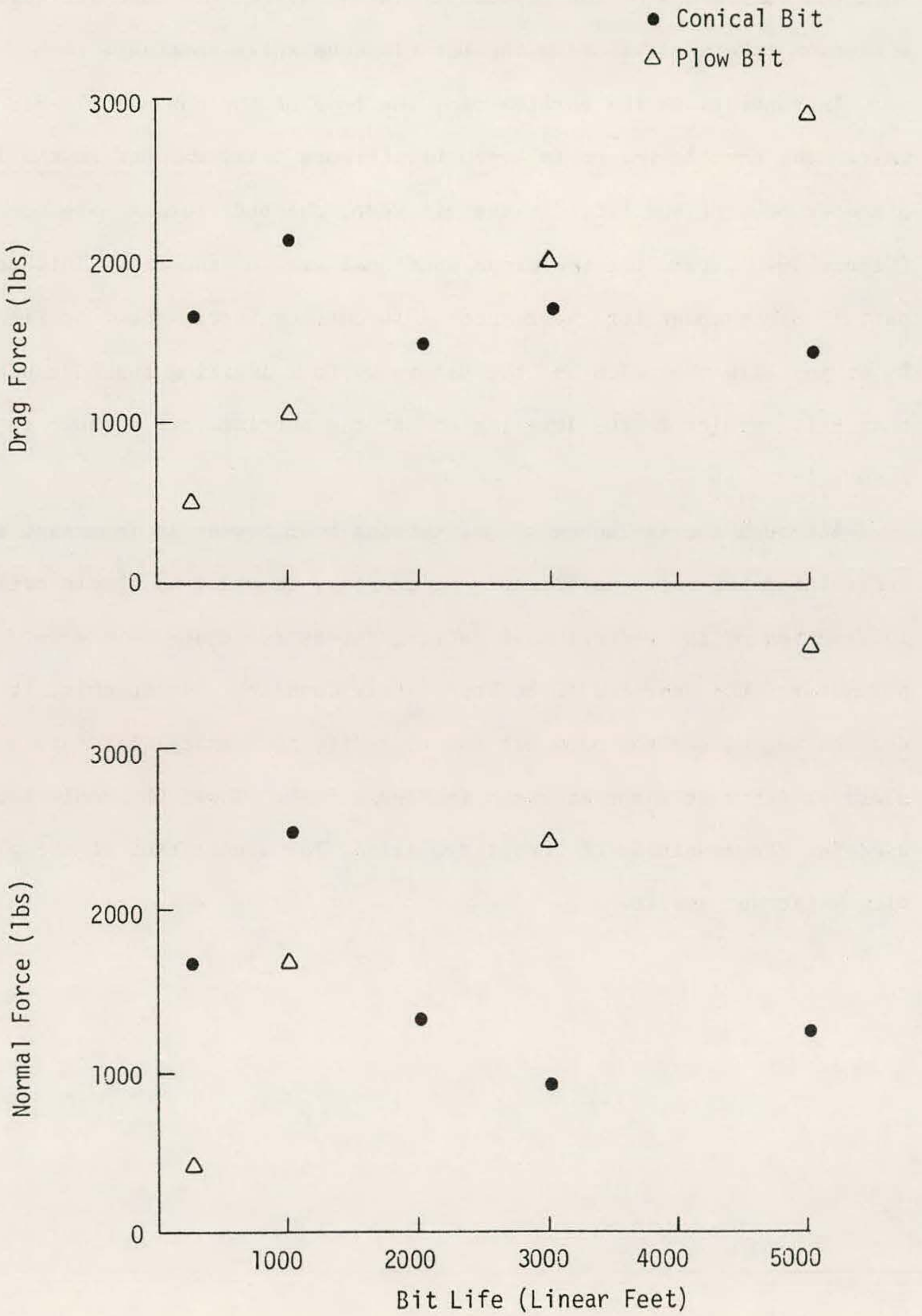
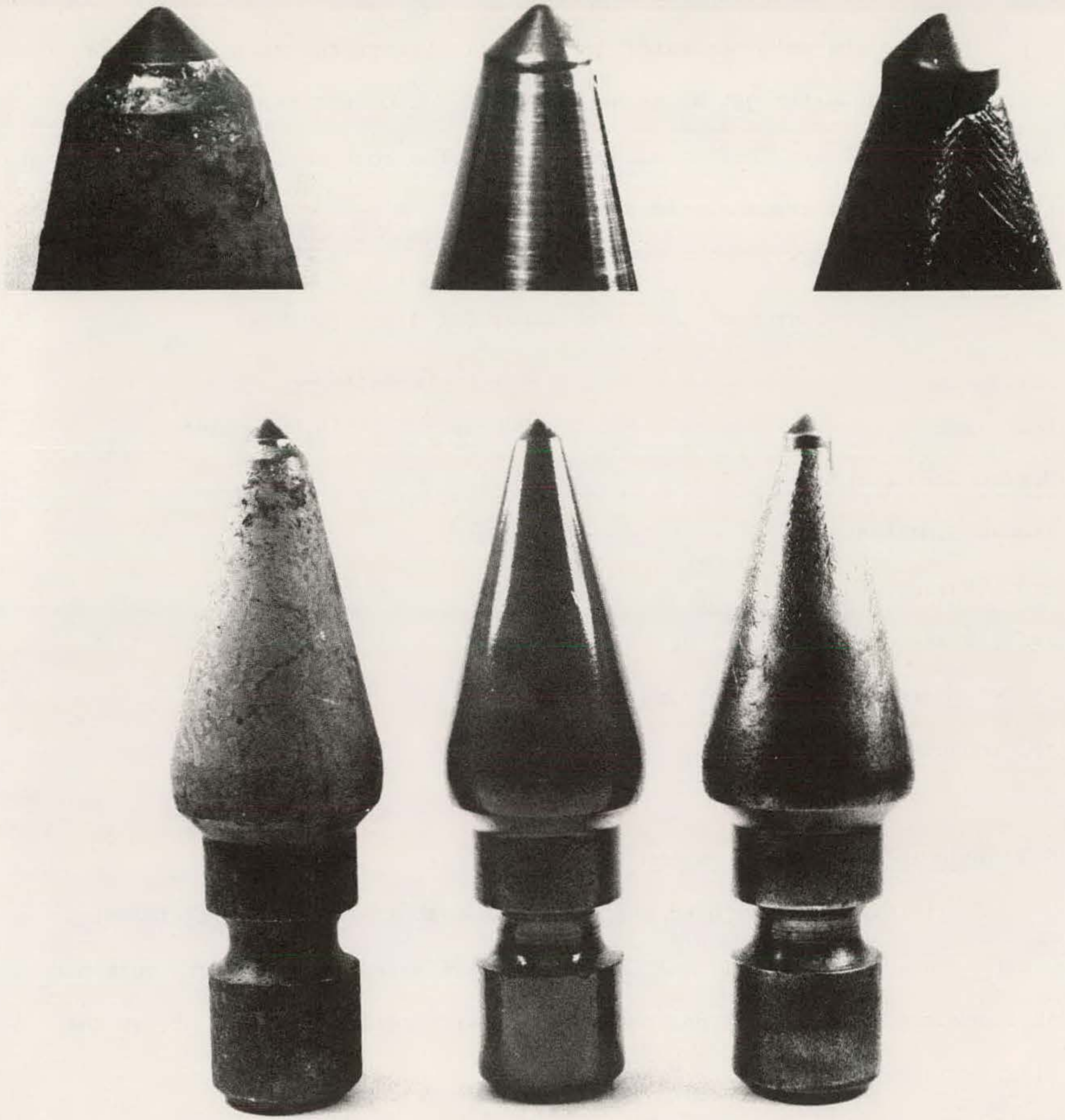


FIGURE 5-3

the tip, even though the longitudinal axis of the bit was at a rake angle of 45 degrees to the rock surface. The looseness of fit required for the bit rotation combined with the elasticity in the system may have increased the effective rake angle to keep the bit tip cone angle constant.

In contrast to the carbide tip, the body of the conical bit did exhibit wear. The carbide insert in a new bit (Figure 5-4A) was set in the larger diameter nose of the bit. As the bit wore, the body became more streamlined (Figure 5-4C), reducing the cross sectional area of the bit. This wear pattern may account for the reduction in cutting forces shown on Figure 5-3. It is possible that with use the bit tends to a limiting the wear pattern and that this results in the leveling off of the cutting forces shown in Figure 5-3.

Although the influence of jet cutting on bit wear is important in determining the total performance of the bit, in order to obtain reliable information on the reduction of cutting forces for changes in other parameters, the wear had to be kept fairly constant. To do this, it was decided not to use the plow bit and to modify the conical bit into a shape close to its wear shape as shown in Figure 5-4B. Thus, the conical bits were used for the remainder of the study, except for a wear test of the plow bit with water jet assist.



A
New Bit

B
Machined Bit

C
Worn Bit

Conical Bit Wear

FIGURE 5-4

5.2.4 Water Jet Tests on Rock Samples

Prior to the combined water jet drag bit tests, the rocks used were tested with the water jet alone at 5,000 and 10,000 psi pressures through a 0.025-inch orifice. The jet was vertical to the rock surface. The depths of the cuts produced are shown in Table 1.

TABLE 1

Depths of Cuts With Water Jet Alone (inches)

	Pressure	
Rock Type	5,000 psi*	10,000 psi**
Dakota Sandstone	0.12	0.80
German Sandstone	0.01	0.11
Lyons Shale	0.01	0.01
Lyons Limestone	0.01	0.01

*10-inches-per-second traverse velocity

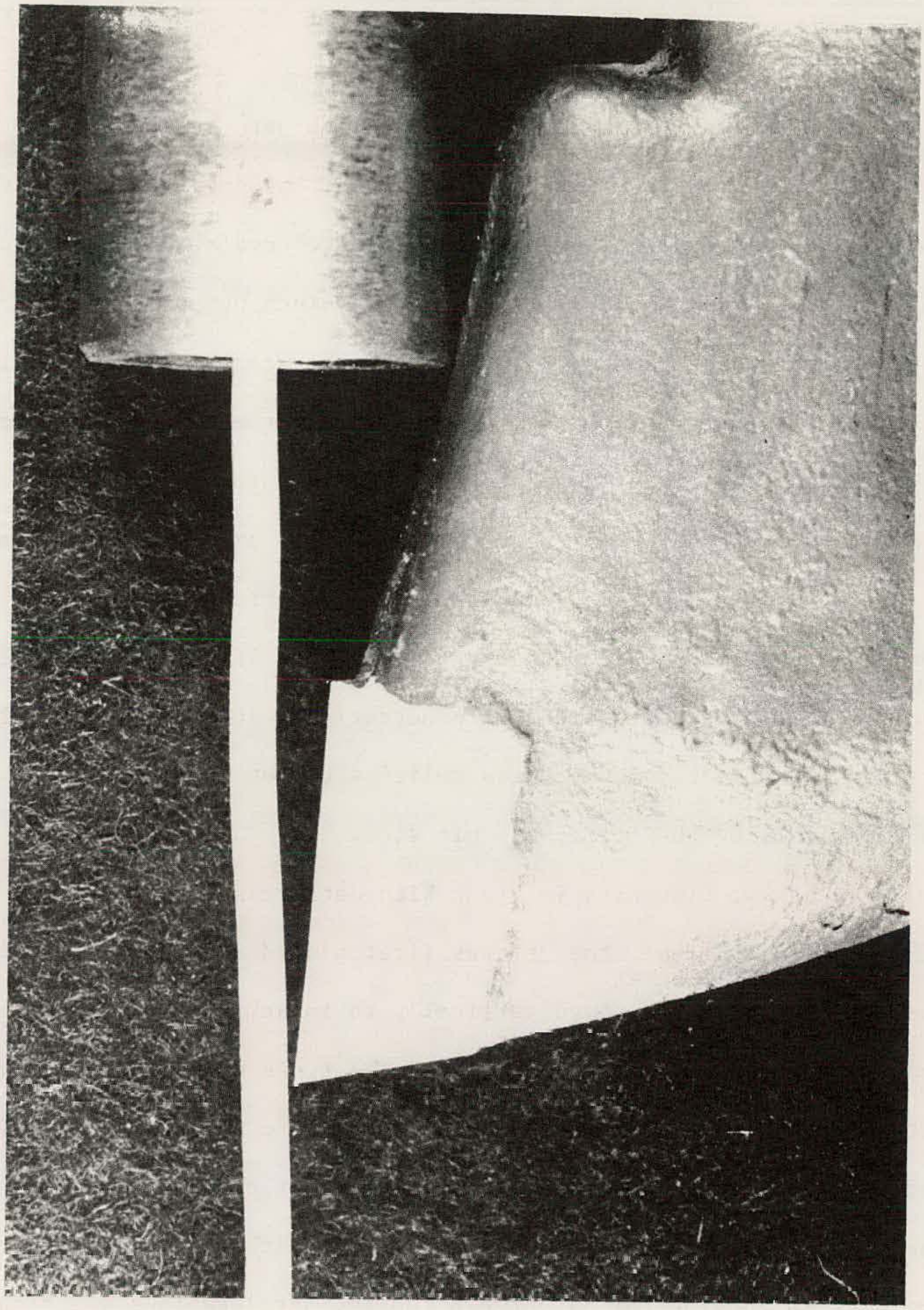
**2-inches-per-second traverse velocity

5.3 Independent Cuts in Dakota Sandstone

The initial testing used the water jet with the conical pick to cut Dakota sandstone, a fairly soft sandstone (see Appendix A). Tests were made at pressures up to 10,000 psi and with jet orientation in front of, at the side, and behind the bit.

5.3.1 Jet In Front With Bit Penetration Varied

In the first test, the nozzle was placed so the jet would strike vertically 0.1 inch in front of the bit in the highly stressed rock zone ahead of the bit point (Figure 5-5). A 0.025 inch diameter orifice was used in the nozzle and the water pressure was 8,300 psi. Cuts were made at 0.2, 0.4, 0.6, and 0.8-inches penetration, first without jet assist and then with jet



Jet in Front of Bit

FIGURE 5-5

assist. The results (Figure 5-6) indicate the jets reduced the normal force about 57 percent at 0.2 inch bit penetration, but only about 37 percent at 0.6-inch penetration. The drag forces were reduced about 32 percent at 0.02-inch penetration and about 24 percent at 0.4-inch penetration. At higher bit penetration depths, the jet did not reduce the drag forces. This is probably due to the inability of the jet to penetrate to the highly stressed zone ahead of the bit at the greater depths. Higher water pressure might improve the depth of cut, but one other factor is the larger amount of rock fragments that pile up ahead of the bit at deeper cuts. These frequently tend to deflect and absorb energy from the jet reducing its cutting effectiveness. The decreasing reduction in normal force with bit penetration depth is probably also related to decreasing effectiveness of the relief slot cut by the jet as the bit point cuts farther below the bottom of this slot.

5.3.2 Jet at Two Distances in Front With Jet Pressure Varied

In the second test, the jet was first placed at 0.1 inches and then 0.4 inches ahead of the bit aimed vertically to impact the rock in the vertical plane of the cutting point of the bit. The tests were made at a constant penetration of 0.2 inches, and the water pressure was varied from 2,500 to 10,000 psi. As displayed in Figure 5-7, the jet closer to the bit was more effective at reducing normal and drag forces, although at higher pressures the difference in cutting forces between the two jet locations was significantly less. The large reductions in the normal forces probably are partially the result of the shallow depth of cut. The test illustrates that the more effective location for the jet in front of the bit is closer to the cutting point. This correlates with what Hood found in his work.

Variation in Cutting Forces with Bit Penetration Both With and Without Water Jet Assist Using the Conical Bit in Dakota Sandstone

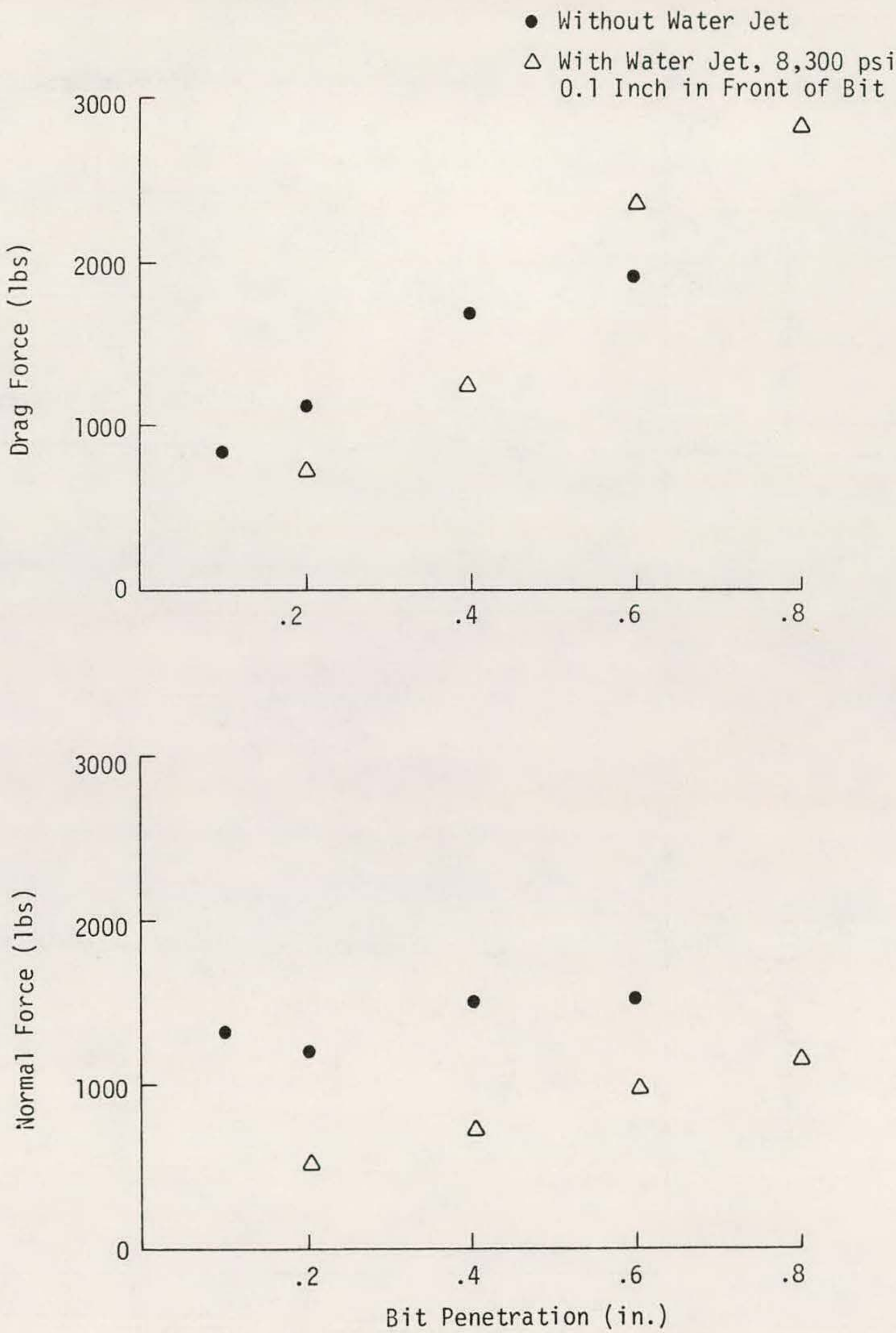


FIGURE 5-6

Variation in Cutting Forces with Water Jet Pressure for Jet Locations 0.1 and 0.4 Inches in Front of Conical Bit, Dakota Sandstone, Independent Cut Spacing, Bit Penetration: 0.2 Inch

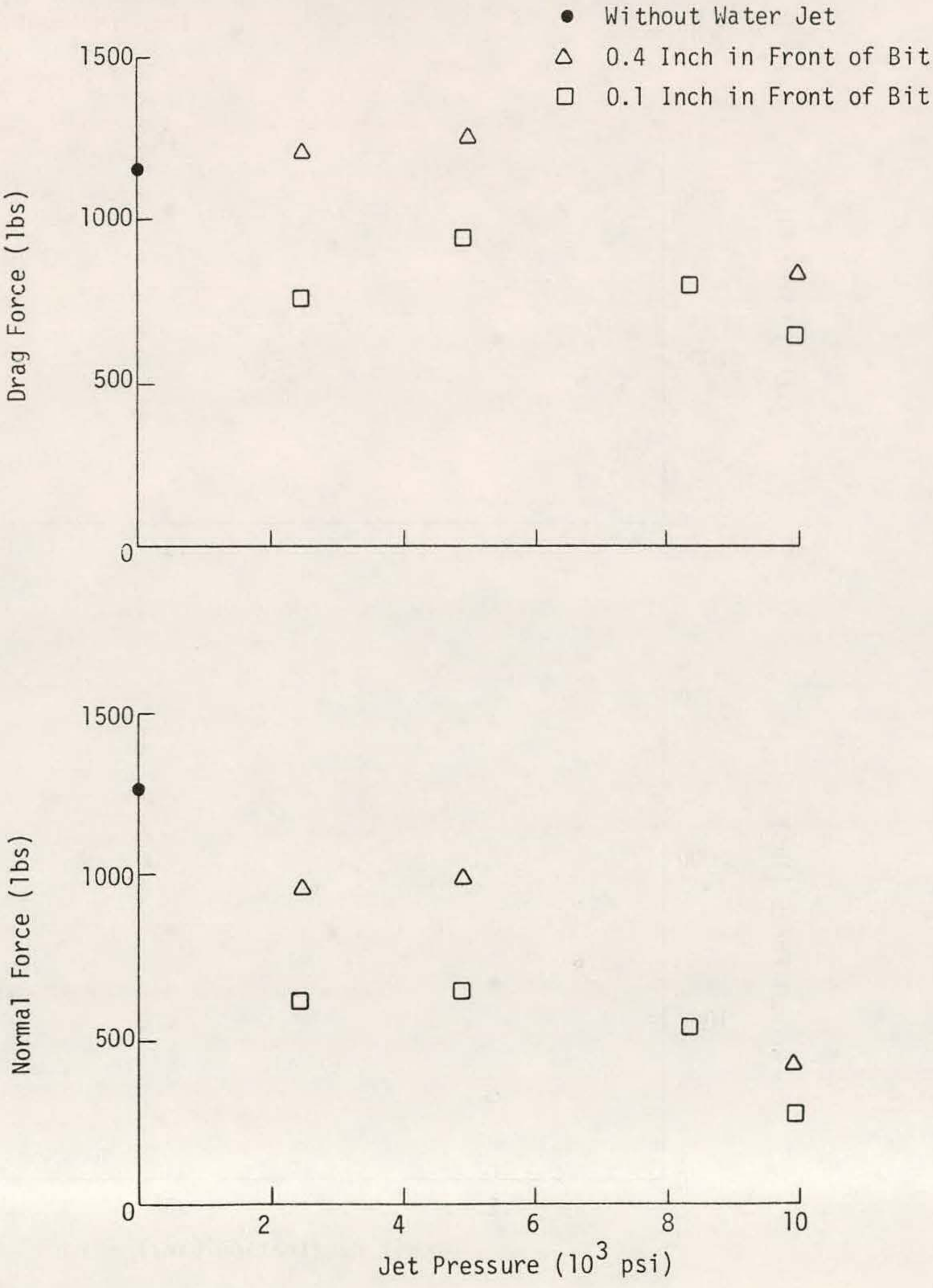


FIGURE 5-7

5.3.3 Jet From Side

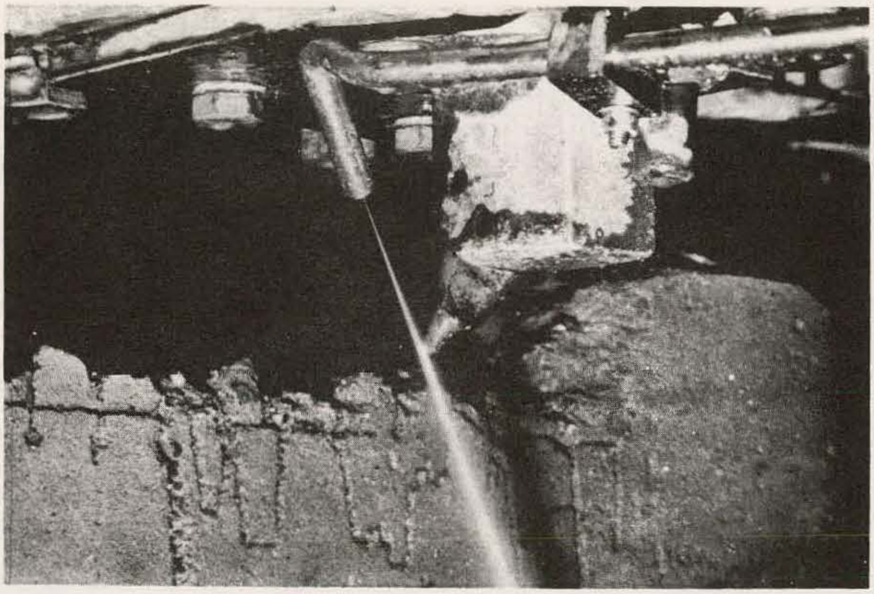
The nozzle was moved to the side of the bit to see if better reduction of cutting forces could be achieved. Of the several orientations tried, the position shown in Figure 5-8 with the jet stream at a 45-degree-rake angle to the rock surface and at a 45-degree-side angle to the bit worked the best. However, even this orientation was not as effective as having the jet in front of the bit. The jet was constantly deflected and diffused by fragments of broken rock thrown up by the pick. Because of this interference, the jet did not cut the rock in a manner to reduce the cutting forces on the bit.

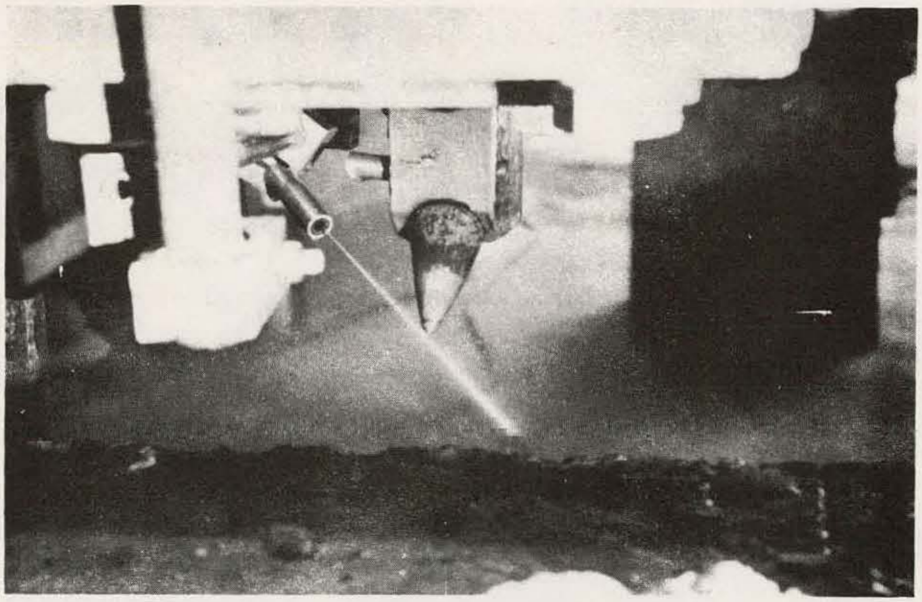
5.3.4 Jet from Behind With Bit Penetration Varied

The nozzle was placed behind the bit at a low angle to impact the rock just below the cutting point of the bit (Figure 5-9) Independent cuts were made at penetrations from 0.1 inches to 0.6 inches with 10,000 psi water pressure, using an 0.025 inch diameter orifice. The drag forces were reduced about 50 percent by the action of the jet, and the normal forces were reduced 60 to 70 percent (Figure 5-10). The dramatic reduction in cutting forces through the range of penetrations tested would indicate that the water jet may be assisting fracture in the sandstone when it is aimed at or very near the highly stressed zone around the cutting tip.

5.3.5 Comparison of Jets Ahead and Behind Bit

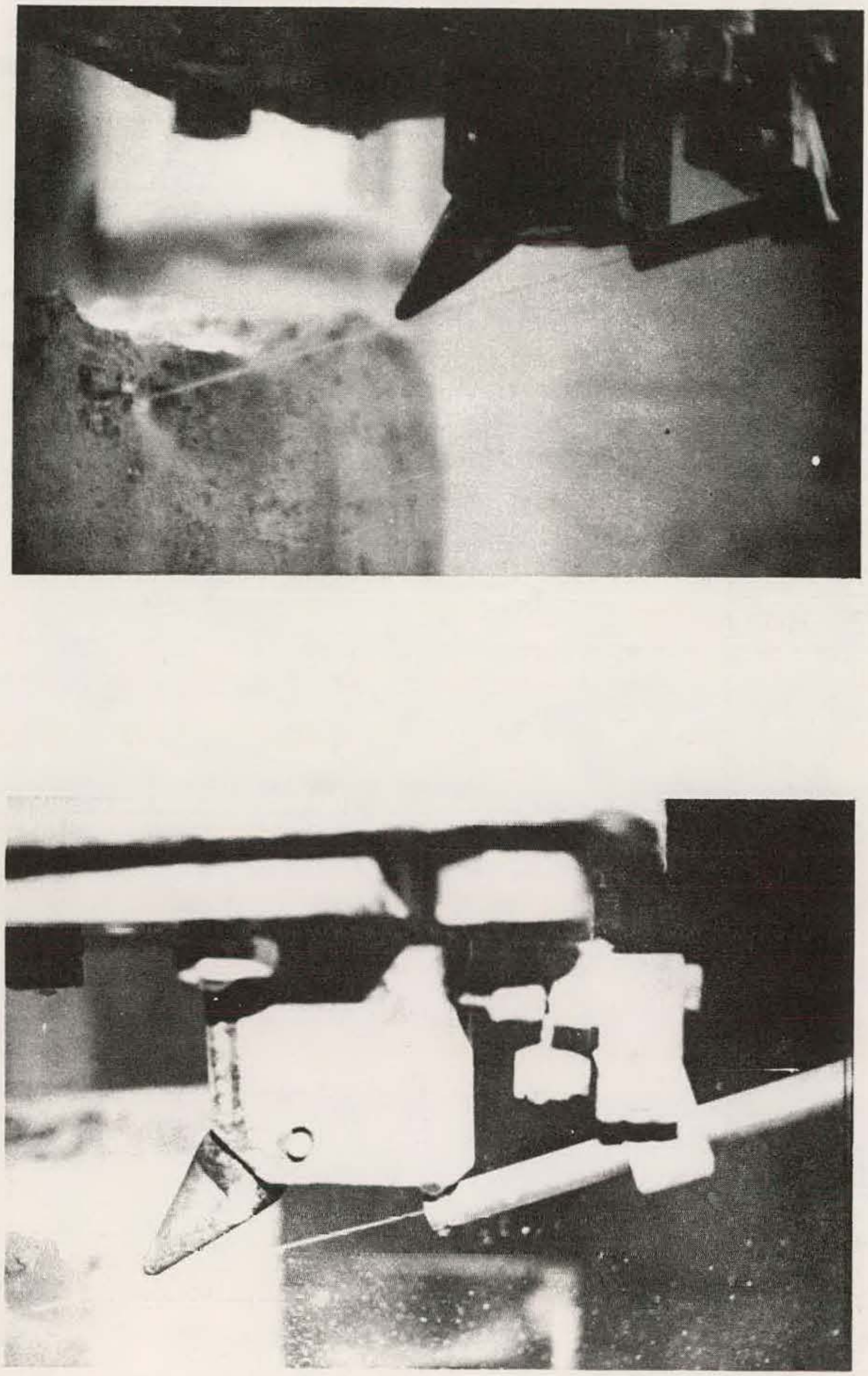
Tests were made at 0.4 inch bit penetration over a water pressure range of 2,000 to 10,000 psi to evaluate the difference in cutting forces between a jet 0.1 inch ahead of the bit and a jet at a low angle behind the bit. The jet behind the bit was much more effective at reducing both normal and drag forces (Figure 5-11). The reduction of drag forces for the rear nozzle location ranged from 40 to 60 percent over the pressure range tested. The normal forces for the same locations were reduced 50 to 90 percent over the





Jet from Side

FIGURE 5-8



Jet from Behind the Bit

FIGURE 5-9

Variation in Cutting Forces with Bit Penetration Both With and Without Water Jet Assist from Behind Conical Bit in Dakota Sandstone, Independent Cut Spacing

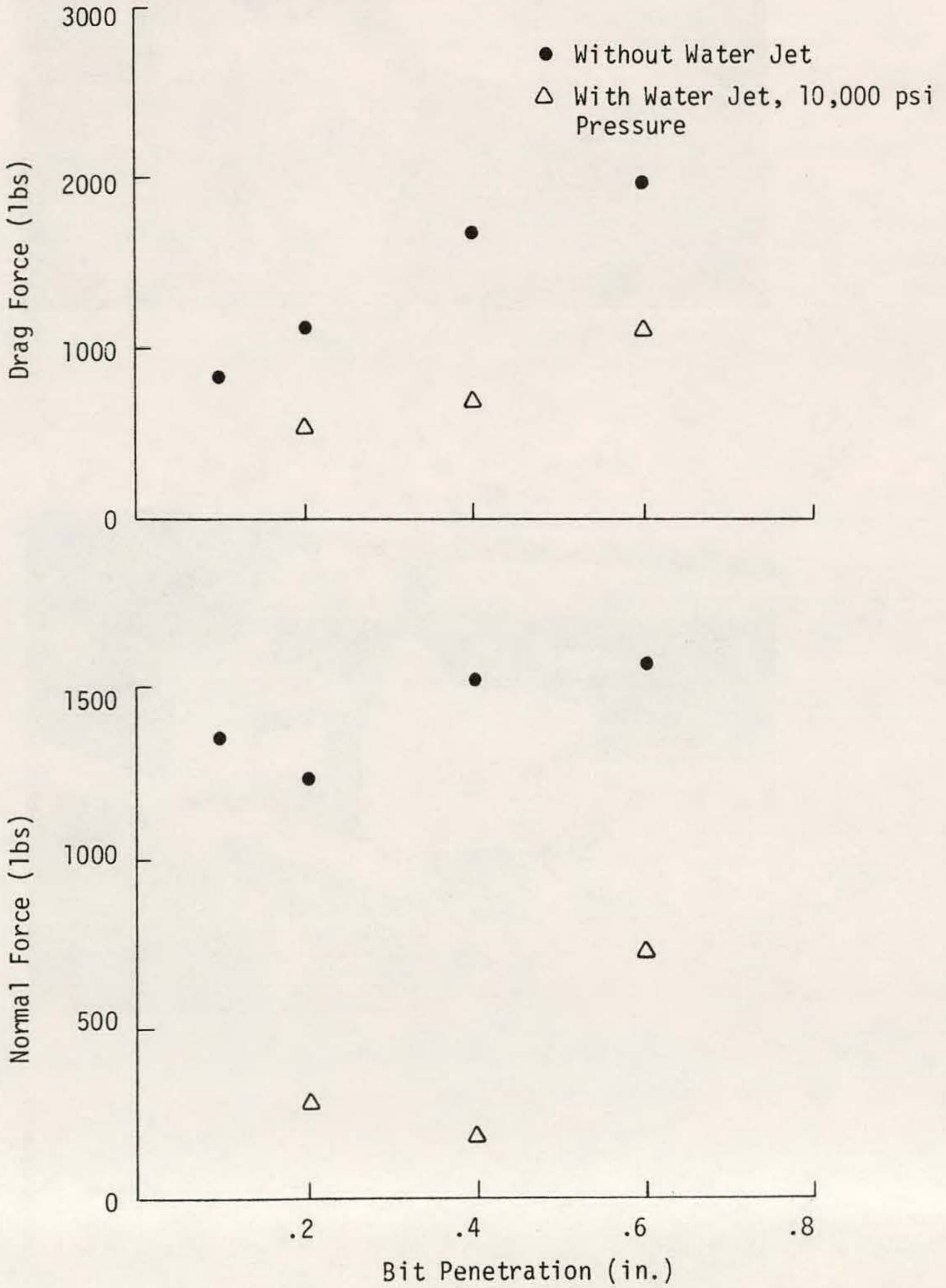


FIGURE 5-10

Variation of Cutting Forces with Water Jet Pressure for Jets Ahead and Behind a Conical Bit in Dakota Sandstone, Independent Cut Spacing, Bit Penetration: 0.4 Inch

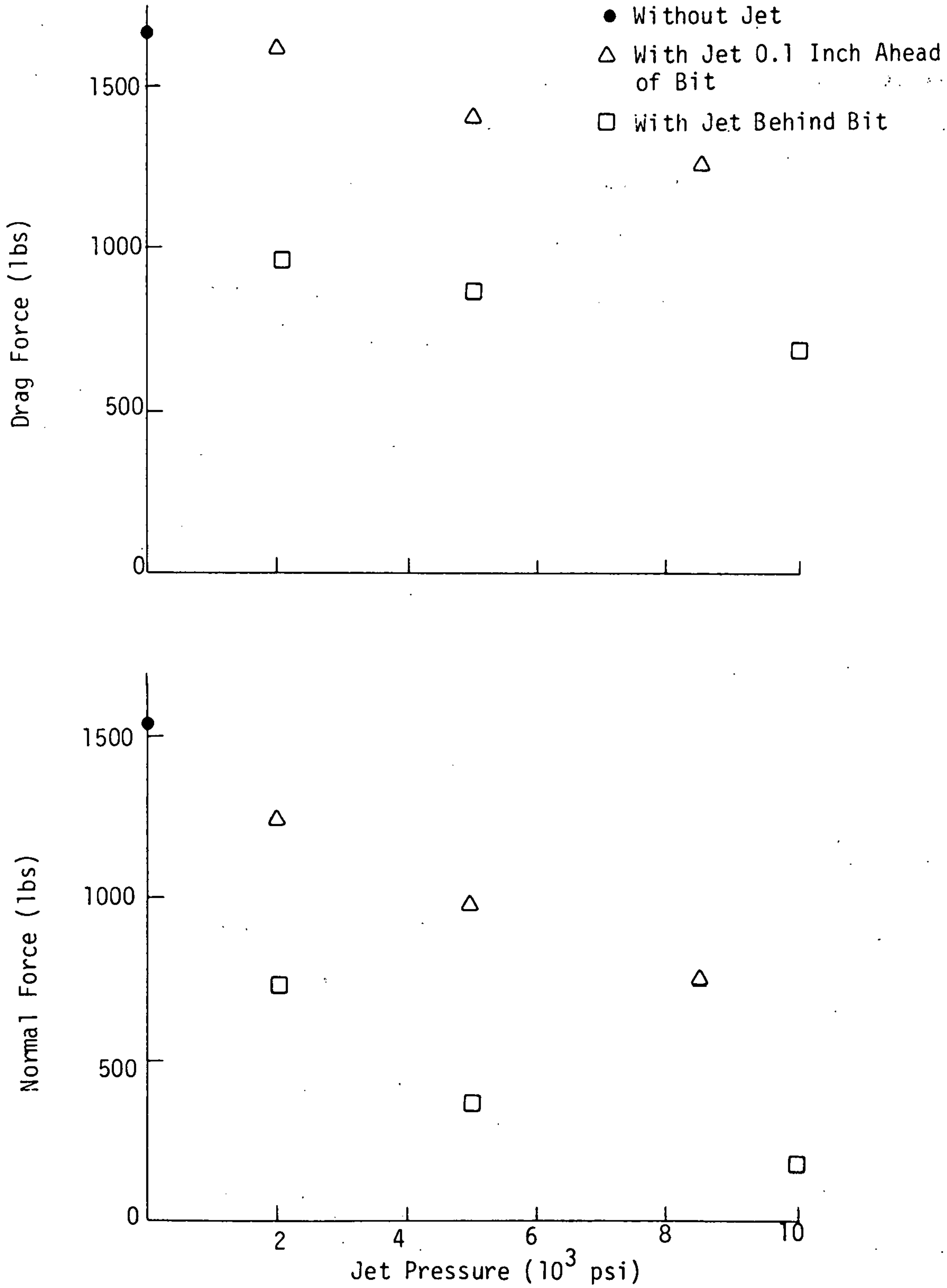


FIGURE 5-11

same water pressure range. The pattern of force reduction with pressure increase for both the leading and trailing jets indicates that the more energy that is directed at the rock from the water jet, the lower the bit cutting forces will be. In contrast, Figure 5-7 indicates that the relation between water pressure and cutting force has a maximum value. There was, however, a considerable spread in the data for the 2,500 and 5,000 psi tests in the 0.2-inch penetration tests, and this may have created a false picture of the relationship between jet pressure and cutting force in this case.

With the nozzle behind the bit, the water jet left a shallow slot in the bottom of the bit groove. This was not observed with the jet in front of the bit, even at 10,000 psi. The effectiveness of the nozzle in the rear may be the result of a hydrofracturing mechanism, and also the fact that the jet can strike the high stress zone around the bit unobstructed by solid rock or rock chips.

5.4 Interacting Cuts

Drag bits are usually mounted on excavating machinery in a manner to produce overlapping or interacting cutting patterns. An important parameter in designing this machinery is the proper spacing of bits for optimum penetration and rock removal. Thus, the tests on interacting cuts with the water jet were intended to demonstrate the effectiveness of the method under conditions more representative of actual machine cutting.

The high pressure water jet was effective in reducing the cutting forces in interacting cuts in both the (soft) Dakota sandstone and a (hard) sandstone from Germany. The jet was also effective in shale, but only at high (10,000 psi) pressures. The jet was least effective in limestone. The nozzle was mounted behind the conical bit in all the tests, as the independent cut testing indicated that this was the most effective location.

5.4.1 Dakota Sandstone

Cuts were made at a 1.5-inch spacing at bit penetration of 0.3 to 1 inch without jet assist and with 5000 psi water pressure in the jet. The drag force was reduced an average of 25 percent (Figure 5-12) and the normal force was reduced an average of 50 percent. This resulted in a 30 percent reduction of the total cutting force over the range of bit penetrations tested (Figure 5-13). The total force angle (the angle the total force makes with the horizontal) decreased with deeper bit penetration, both for jet assisted and unassisted cutting. The jet assisted cutting had smaller force angles at all cutting depths and also exhibited a more rapid change in the angle with increasing depth of cut.

5.4.2 Lyons Limestone

Because the test of cutting the limestone with just the water jet indicated that even at 10,000 psi the water jet would not cut more than 0.01-inches deep, testing the limestone with different depths of cuts with the drag bit probably would not indicate much change of cutting forces as a result of the water jet. Instead, it was decided to vary the water jet horsepower to evaluate the effect of changing horsepower at a constant depth of cut. The cuts were made at a bit penetration depth of 0.5 inches and a spacing between cuts of 1.5 inches. The nozzle was positioned at a flat angle behind the bit, as was shown in Figure 5-9. The orifice diameter and water pressure were varied to achieve different jet horsepower as shown in the following table:

Variation in Cutting Forces with Bit Penetration With and Without Water Jet Assist Behind a Conical Bit in Dakota Sandstone, Cut Spacing: 1.5 Inches

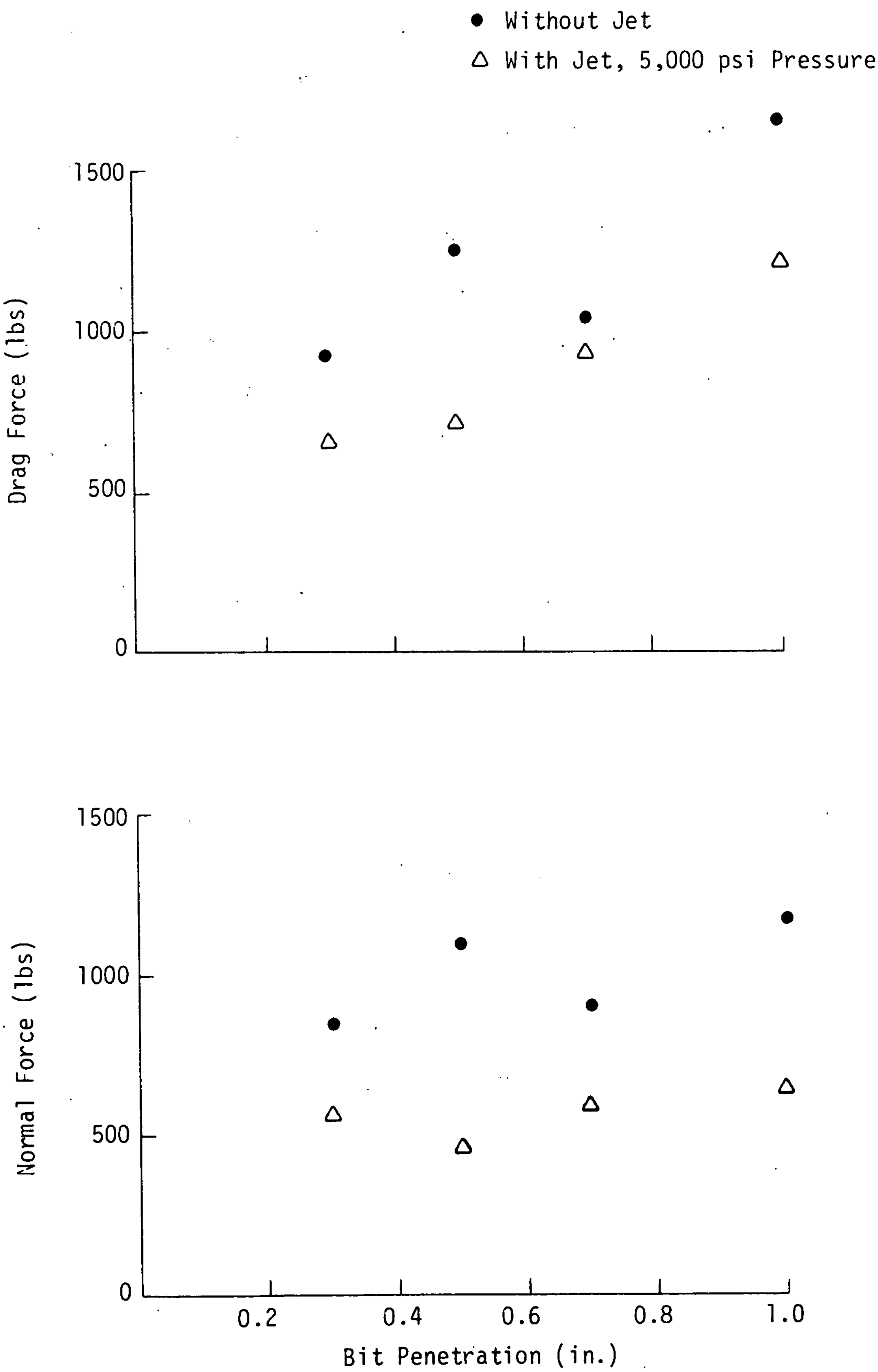


FIGURE 5-12

Comparison of Total Force and Total Force Angle Between Unassisted and Water Jet Assisted Cutting with a Conical Bit in Dakota Sandstone, Cut Spacing: 1.5 Inches

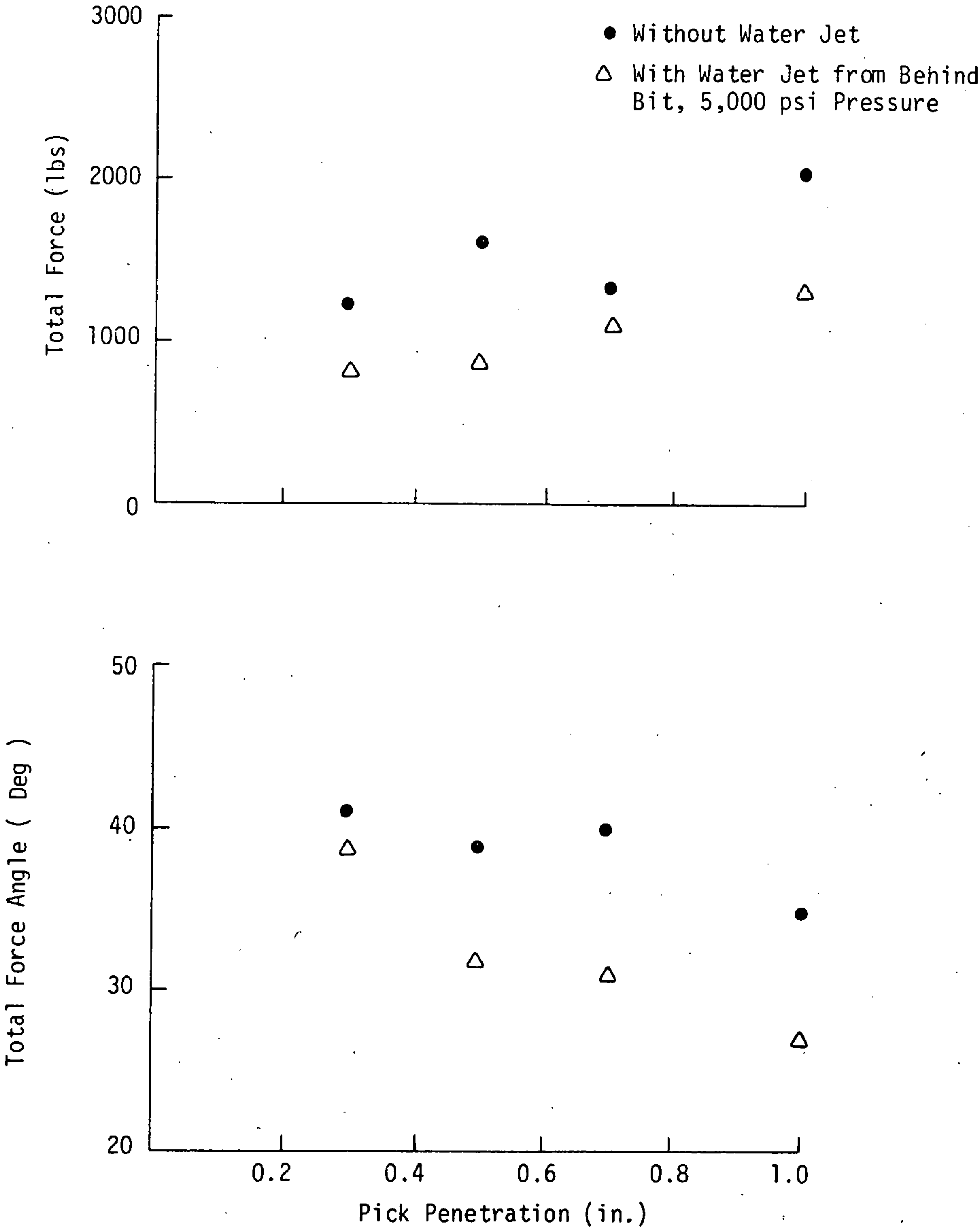


FIGURE 5-13

TABLE 2

Jet Horsepower Variation for Lyons Limestone

Number of Jets	Water Pressure (psi)	Nozzle Orifice (in.)	Jet Horsepower
1	5,000	0.25	3.08
1	10,000	0.25	8.71
1	10,000	0.35	17.10
2	10,000	0.25	17.42

The results of the test (Figure 5-14) indicate that increasing the horsepower did not have a consistant effect on the cutting forces. The data for the unassisted cuts displayed a wide range of values. The band of values includes most of the values shown for the jet assisted cuts. It may be that there is sufficient variability in the hardness of the rock that the values shown for jet assist really do not indicate any significant change produced by the water jet. Higher pressures would probably be needed in the limestone to make any significant reduction in cutting forces. Other researchers (8) have suggested that water pressure should at least be equal to the uniaxial compressive strength for any impact on cutting forces.

5.4.3 Lyons Shale

The shale tested with the water jet alone normal to the bedding was not significantly cut by the jet. The shale has pronounced directional properties, however, and it was possible the jet could help in cutting the shale if placed at the correct orientation. The sample was placed in the cutting machine so the drag bit would cut parallel to the bedding.

Large slab-like pieces were produced in cutting the shale instead of the fairly small uniform chips from the sandstone and limestone. Because of this, the interactive cuts had a variable spacing to preserve the same relative

PAGES 55 to 62

WERE INTENTIONALLY

LEFT BLANK

forces. A comparison of some of the test results (Table 4) indicates the water jet is generally more effective at reducing normal than drag forces. Also, with both hard and soft sandstone, increasing the water pressure produces a greater reduction in normal than drag forces. For the interactive cuts, the water jet reduced drag forces in both sandstones about the same amount (30 percent). Higher pressure in the harder sandstone did not increase the reduction in drag.

TABLE 4

Percent Reduction in Cutting Forces (F_D and F_N) by Using Water Jets

Rock Type	Pressure (psi)	Depth of Cut (in.)	Independent Tests		Interactive Tests	
			F_D (%)	F_N (%)	F_D (%)	F_N (%)
Dakota SS	5,000	0.4	50	75	30	45
	10,000	0.4	60	90	-	-
German SS	5,000	0.4	-	-	27	18
	10,000	0.5	-	-	30	63
Lyons Shale	5,000	0.5	-	-	0	0
	10,000	0.8	-	-	55	60
Lyons Limestone	5,000	0.5	-	-	0	0
	10,000	0.5	-	-	20	28

The water jet was effective on the shale but only at higher (10,000 psi) pressure, and only when directed into the bedding planes. The water jet was least effective on the limestone.

The different responses of the four rock types to the water jet indicates that where the high pressure jet is most effective, water may be acting to open up developing fractures and planes of weakness produced by the drag bit with a hydrofracturing mechanism. The preliminary tests of using the water jet to cut a kerf in the rocks demonstrated that the sandstones would cut fairly easy. This is possibly due to the mechanical construction of the sandstones having relatively large grains held in place with a fine-grained or amorphous matrix. On the other hand, the limestone (and shale when the jet was perpendicular to the bedding) was hardly cut at all. The uniform, fine-grained, hard construction of these materials did not present paths for the water to penetrate. The water jet was effective on the shale when directed along the bedding planes, which in a shale, by definition, are weaker than the rock itself.

The reduction in drag forces may be the result of the water helping to develop and propagate fractures ahead of the bit. The reduction in normal forces may be from the undercutting of the point of the bit by the water jet. Without the jet assistance, the bit point will tend to dig down into the rock, thus increasing the normal force on the bit. The action of the water jet when directed from behind at a low angle just under the point may be to undercut the rock just below the point sufficiently to prevent the point from digging in. This, combined with the possible lubricating effect from the water, could have a tendency to let the bit slide forward, thus reducing the normal force. The reduction in the normal force is also coupled to the reduction in drag forces in that the easier the rock spalls ahead of the bit, the flatter the angle between the horizontal and the resultant force on the bit.

The reduction of forces by using the water jet assist with the plow style of bit is probably from the same phenomena as occurred with the conical bit. The wider path the plow bit makes through the rock results in a larger crushed zone at the point of the bit. This may be allowing the water more paths to open up fractures resulting in the significant reduction in cutting forces observed.

An important benefit May be the cooling and lubricating action the water has on the bit. Although no specific measurements were made in these tests, the water, through these effects, should help to prolong bit life. Also, the fog produced by the high pressure water impacting the rock was effective in preventing dust particles from being emitted from the cutting. This could be a significant benefit, as reduction of airborne dust underground is important. This same effect would tend to reduce the sparking tendency of the bit.

6. ECONOMIC EVALUATION

The cutting forces on the drag bit can be significantly reduced by the use of the water jet. For this technique to be of commercial use, however, it must result in a savings in dollars per cubic yard of rock excavated over competing methods. The economic feasibility is as important to the utilization of the technique as is the mechanical practicality.

The technique would be economically beneficial if the added cost of the addition and operation of the water jet system to a tunnel boring machine (TBM) was more than compensated by the additional cutting efficiency from use of the water jets. In other words, the water jets must produce a reduction in cost per foot of advance (or per cubic yard) that more than compensates for the increased cost per hour of operation from adding the water jet system to the machine. The estimated capital cost of the water jet system for a 15-foot-diameter TBM is shown in Table 5. The estimate is based on jets for a 75-bit pattern on the cutting head of the machine. The bits would be spaced 1.5 inches apart out to 75 inches on the head; the remaining bits would be spaced 0.5 inches apart. The water system would require 80 gpm at 5,000 psi. The 75 jets would consume about 230 horsepower.

As the most consistant force reduction data came from the tests on the two sandstones, the economic analysis is based on these tests. The German sandstone, because it was harder, is possibly more representative of field conditions. Figure 6-1 shows that at the same bit penetration and water jet pressure the reduction in torque on a simulated cutting head for both the Dakota (soft) and German (hard) sandstones was of approximately the same magnitude (35 to 45 percent).

Figure 6-2 illustrates the effect of the water jet on thrust and torque

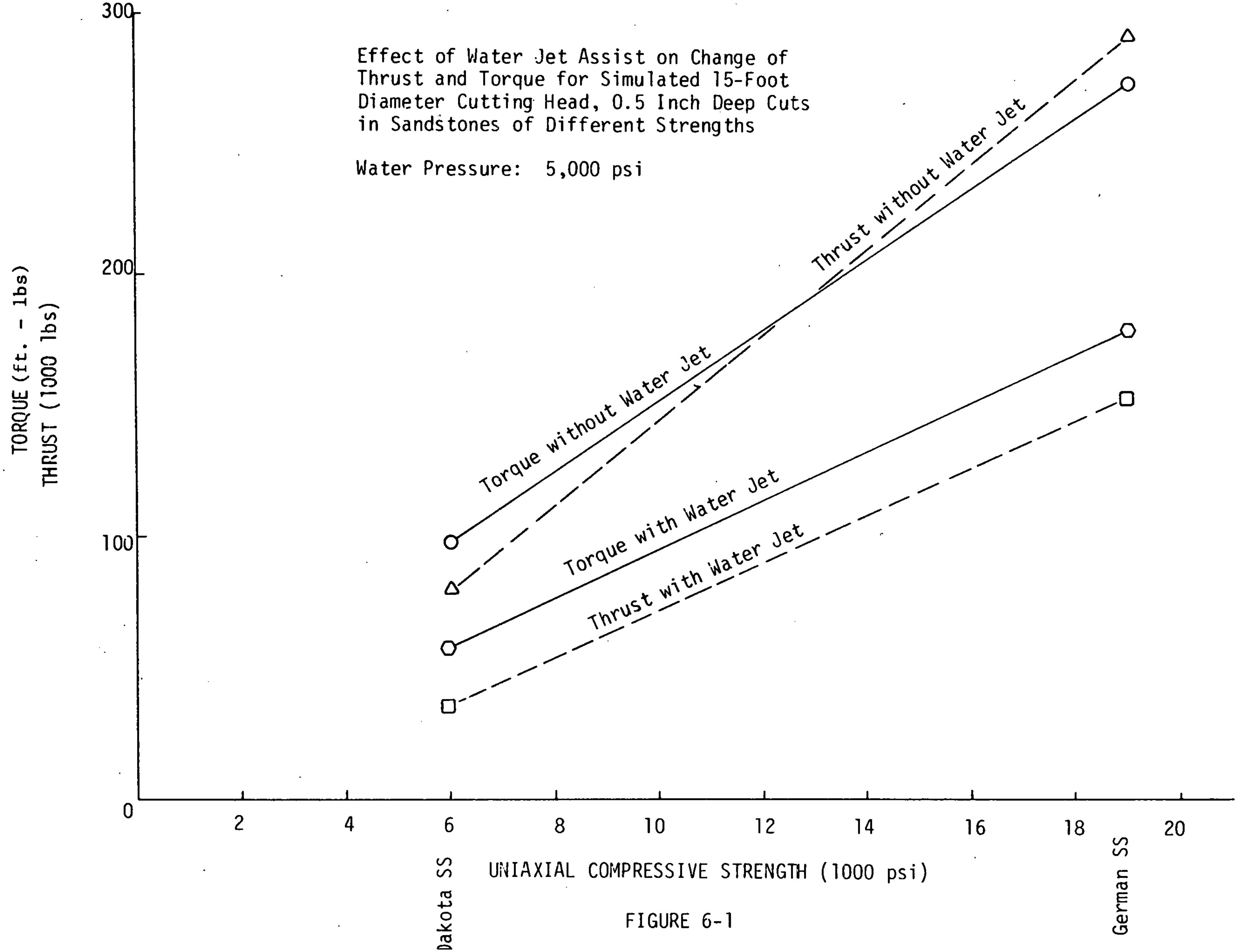

Effect of Water Jet Assist on Change of
Thrust and Torque for Simulated 15-Foot
Diameter Cutting Head, 0.5 Inch Deep Cuts
in Sandstones of Different Strengths
Water Pressure: 5,000 psi
TORQUE (ft. - lbs)
THRUST (1000 lbs)
300
200
100
0
Thrust without Water Jet
Torque without Water Jet
Torque with Water Jet
Thrust with Water Jet
2
4
6
8
10
12
14
16
18
20
Dakota SS
German SS
UNIAXIAL COMPRESSIVE STRENGTH (1000 psi)

FIGURE 6-1

Effect of Water Jet Assist on Change of Thrust and Torque for Simulated 15-Foot Diameter Cutting Head for 0.3 and 0.7 Inch Bit Penetration in German (Hard) Sandstone

Jet Pressure: 5,000 psi

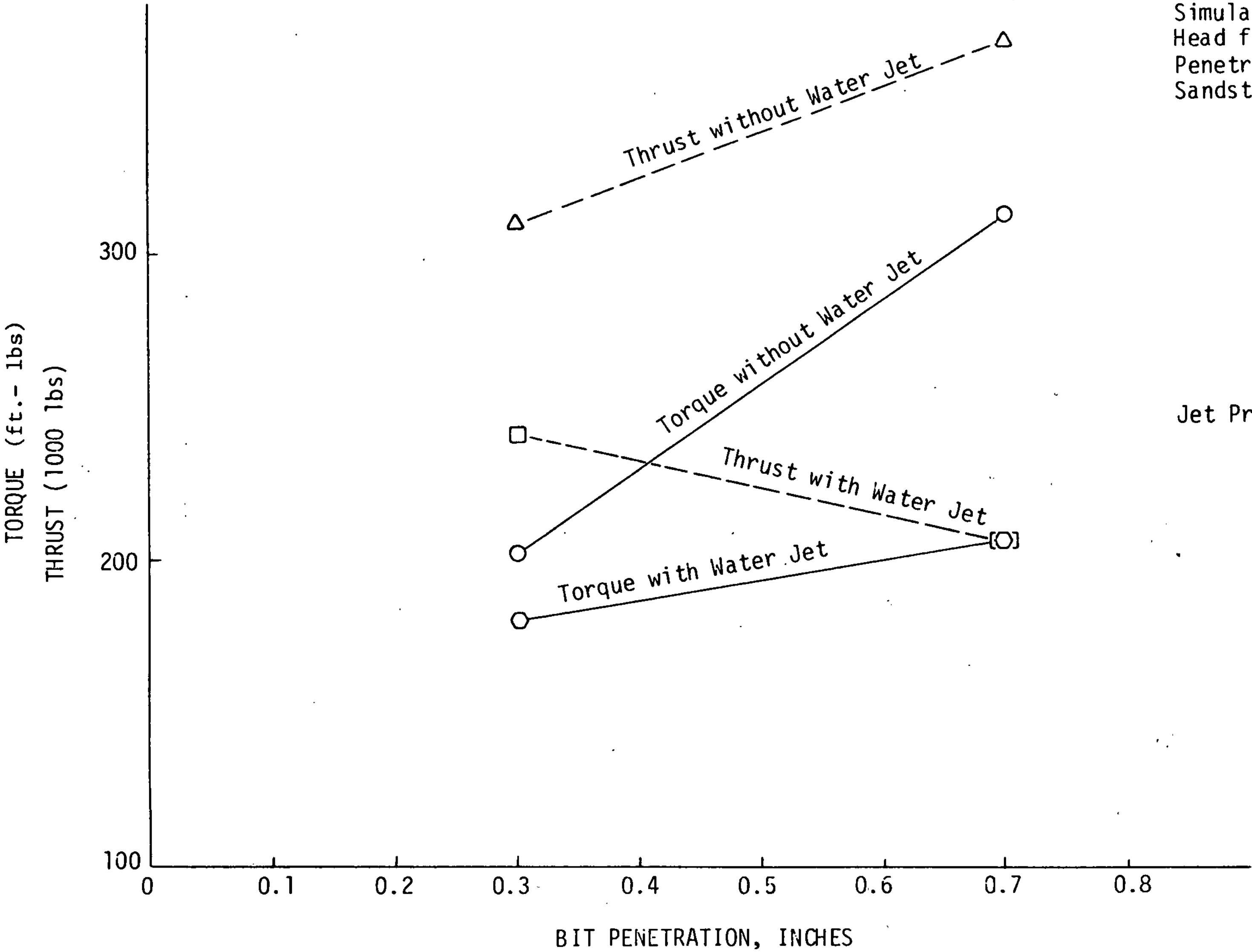


FIGURE 6-2

at 0.3 and 0.7-inch bit penetration for the German sandstone. The significant point is that the torque is roughly the same at 0.7-inch penetration with the water jet as 0.3-inch penetration without the jets. This indicates that with the water jets, the penetration rate could be at least doubled with no increase in torque. The reduction in thrust is also considerable with the water jet, but the thrust component consumes only a minor amount of the machine horsepower. Although not shown on the graph, comparable reductions occur in the Dakota sandstone with 0.5 and 1.0-inch deep cuts.

TABLE 5

Estimated Capital Cost for Water Jet System Added to 15-Foot Diameter TBM

Item	Est. Cost @	Number Needed	Total
Nozzles	$35	75	$2,625
Plumbing	$50	75	3,750
Attachments to Cutting Head	$25	75	1,875
Water Swivel	$2,000	1	2,000
Water Pump 40 gpm @5,000 psi w/150 hp explosion proof motor (Kobe size 4)	$42,000	2	84,000
Controls	$2,000	1	2,000
Labor for Installation (400 man hours at $15/hr)			6,000
		TOTAL	$100,000

The estimated cost per operating hour for a TBM, both with and without the water jet assist, is shown in Table 6. The costs are approximate and the analysis is only intended to illustrate the cost difference between the two methods. The TBM would be amortized over 10 years at 10 percent interest. The machine would be 15 feet in diameter and have a 300-horsepower boring head.

The calculations show that the addition of the water jet system would add between 9 and 10 percent to the operating cost of the TBM, but that in the sandstones tested, the water jet assist would increase the footage per hour, an amount that would result in over a 40 percent decrease in the cost per foot of tunnel advance. The interesting aspect of this analysis is that the capital cost and operating labor for the TBM overshadow the cost of installing and operating the water jet so greatly, that on the basis of this anlayiss, the water jet would only have to increase the cutting rate 10 percent to be economically beneficial.

TABLE 6

Cost Per Operating Hour and Per Foot for a 15-Foot Diameter TBM With and Without Water Jet Assist on Drag Bits (Based on 5,000 Hours Operating Life)

Item	Without Water Jet Cost/Hr	Without Water Jet Cost/Ft	With Water Jet Cost/Hr	With Water Jet Cost/Ft
Capital Cost* (ammortized)	$240	$ 20.00	$260	$ 9.30
Operating Costs				
Electric Power @8¢/kwh	24	2.00	38	1.35
Maintenance & Repair	400	33.50	550	1.95
Operating Labor 13 men @ $15/hr	195	16.30	195	7.00
Cutters $24/ft of advance	312	26.00	**546	19.50
TOTAL	$1,171	$97.80	$1,589	$56.70

Rate of Advance at same TBM torque

Without jet $0.3 \text{ in./rev} \times 8 \text{ rpm} \times \frac{60}{12} = 12 \frac{\text{ft}}{\text{hr}}$

With jet $0.7 \text{ in./rev} \times 8 \text{ rpm} \times \frac{60}{12} = 28 \frac{\text{ft}}{\text{hr}}$

---

*Capital cost calculated over 10 years at 10% cost of money

**Assumes 25% reduction in bit wear from use of water jets

Use of water jets reduces per foot cost by $\frac{97.8 - 56.7}{97.8} = 40\%$

7. SUMMARY AND CONCLUSIONS

The use of the high pressure water jet reduced the cutting forces on drag type bits in hard and soft sandstones, shale, and limestone. The technique was more effective with sandstones than with shale or limestone, the reduction in drag cutting forces in the sandstones being about 30 percent for a specific bit penetration. The jet was effective in shale but only at high (10,000 psi) pressures. The jet was not as effective in limestone. The most effective location for the jet was behind the bit, and the jet assist produced, percentage-wise, a greater reduction in cutting forces at deeper bit penetrations.

Most of the tests were made using a conical bit, but one series of tests made with a plow-type bit demonstrated that the water jet was effective in lowering cutting forces as the plow bit became worn. In addition to the reduction in cutting forces, the use of the water jets resulted in a great reduction in airborne dust from the cutting.

The economic analysis indicated, that for the sandstones, the use of the water jets could reduce the cost per foot of advance up to 40 percent over the costs of unassisted drag bit cutting.

The investigation demonstrated that the water jet can make a substantial contribution to reducing cutting forces on drag bit cutters in sedimentary rocks. Because the samples tested did not have joints or fractures (which would commonly be associated with in situ boring conditions), water jets might show even greater reductions in cutting forces on an actual TBM. The next logical step would be to fabricate a rotating boring head with drag bits and water jets and make full scale tests to evaluate bit spacing and penetration in different rocks in curved cutting paths.

The tests done in this project demonstrate that the water jet is of practical use and has economic potential in reducing time and costs on a tunnel boring machine. Development and implementation of the technique could be of benefit in coal mine development work.

8. REFERENCES

1. Roxborough, R., "Cutting Rock with Picks," The Mining Engineer, June 1973.

2. Hood, M., "Cutting Strong Rock with a Drag Bit Assisted by High Pressure Water Jets," Journal of the South African Institute of Mining and Metallurgy, Nov. 1976.

3. Barker, J.S., "A Laboratory Investigation at Rock Cutting Using Large Picks," Int. Journ. Rock Mech. and Mining Sci., Vol. 1, 1964.

4. Evans, I. and Pomeroy, C.D., "The Strength, Fracture and Workability of Coal," National Coal Board, Mining Research and Development Establishment, Burton on Trent, England, 1973.

5. Nishmatsu, Y., "The Mechanics of Rock Cutting," Int. Journal of Rock Mechanics and Mining Science, 1972, Vol. 9, pp 261-270.

6. Miller, R.J., "Laboratory Analysis of Small and Large Scale Linear Cutting of Rock for Improvement of Tunnel Boreability Prediction and Machine Design," Ph.D. Thesis, Colorado School of Mines, 1974.

7. Ozdemir, L., Miller, R.J., and Wang, F.D., "Mechanical Tunnel Boring - Prediction and Machine Design", Annual Report to National Science Foundation, APR 73-07776-A03, 1977.

8. Labus, T.J., "Energy Requirements for Rock Penetration by Water Jets," Third International Symposium on Jet Cutting Technology, Chicago, Ill., 1976, Paper E3.

9. Ross, N.A. and W.A. Hustrulid, "Some Comments on the Design of Medium to Hard Rock Tunnel Boring Machines," Dynamic Rock Mechanics, Ch. 46.

APPENDIX A

Description of Rock Samples Used in Tests:

1. Dakota Sandstone - Buff gray to mottled tan, fine-grained, well sorted quartz sandstone. Individual grains are subrounded to well rounded, composed of 98 percent quartz, 1 to 2 percent argillized fieldspars, less than 1 percent biotite. Hard specimens showed distinct lamination, but no other sedimentary or biorganic structures. The rock was moderately well cemented with silica and minor amounts of limonite. Specimens exhibited good permeability. Test specimens were acquired from the lower Cretaceous, South Platte formation (upper part of the Dakota group) about 3 miles south of Golden, Colorado.

2. German Sandstone - Light gray, fine-to-medium-grained, quartz sandstone. Quartz grains are well rounded and cemented with silica. Indistinct laminating and some broad band staining with limonite. Specimens exhibited good permeability. This sandstone was considerably harder than the Dakota and was used so that the results could be compared between soft and hard sandstones. The samples were obtained from a stone quarry near Dortmund, West Germany.

3. Lyons Limestone - Medium gray, weakly laminated lime mudstone, with segregations of sand-size lime fragments in thin, discontinuous laminations and as burrow fillings. Original depositional structure was almost completely destroyed by bioturbation. Hand specimen contains numerous large (3/8-inch-diameter) lime-filled burrow structures. Samples were obtained from a quarry about 2 miles east of Lyons, Colorado.

4. Lyons Shale - Dark gray, nonlaminated, carbonaceous mudstones, with numerous calcite-filled joints. Joint fillings are 0.2 to 0.5-inch thick.

Some joints contain pyrite in addition to the calcite. Samples obtained from the same quarry as the limestone.

Physical Properties of Samples:

Core samples were taken from all the rock types used in the testing program. The physical properties are as shown in the table.

Rock Type	Uniaxial Compressive Strength, psi	Porosity %
Dakota Sandstone	6,000	18.2
German Sandstone	19,000	4.9
Lyons Shale	14,000	5.0
Lyons Limestone	21,000	4.0

APPENDIX B

Calculation of Jet Horsepower

Orifice (in.)	Pressure (psi)	Velocity (ft/sec)	Q (ft^3/sec)	P_{hp}
0.012	1,000	308	2.43×10^{-4}	0.06
0.012	3,000	534	4.17×10^{-4}	0.33
0.012	9,000	925	7.29×10^{-4}	1.72
0.025	5,000	690	2.35×10^{-3}	3.08
0.025	10,000	975	3.32×10^{-3}	8.71
0.035	10,000	975	6.52×10^{-3}	17.10

Definitions

$$V = C_v \frac{2gP \times 144}{w} \qquad Q = AV$$

$$V = 0.8 \times 12.1\ P^{1/2} \qquad P_{HP} = \frac{Q \times P \times 144}{550}$$

where

V = velocity of jet (ft/sec)

P = water pressure behind nozzle (psi)

g = acceleration due to gravity (32.2 ft/sec^2)

w = volumetric weight of water (62.4 lb/ft^3)

Q = flow rate through nozzle (ft^3/sec^2)

P_{HP} = power of the jet in horsepower

C_v = velocity coefficient of nozzle (0.80)

APPENDIX C - TEST DATA

Plow Bit - In Dakota Sandstone - Summary
(Independent Cuts)

Bit Penetration (in.)	Water Jet Press. (psi)	Water Jet Diam. (in.)	Number of Cuts	Side (lb)	Normal (lb)	Forces Drag (lb)	Angle (Deg)	Total (lb)	Remarks
0.1	-0-		12	8	272	562	22	677	worn, 1000′
0.2	-0-		9	30	644	786	38	1119	worn, 1000′
0.2	3500	.025	5	35	683	637	37	935	jet in front
0.4	-0-		7	13	415	553	36	696	sharp, 100′
0.4	-0-		3	28	1691	1033	59	1996	worn, 1000′
0.4	-0-		19	363	2441	2000	50	3156	worn, 3000′
0.4	-0-		2	511	3657	2900	51	4667	dull, 5000′
0.4	3500	.025	6	48	367	627	39	732	jet in front
0.6	-0-		4	35	732	1535	24	1818	worn, 1000′
0.6	3500	.025	3	49	839	1173	32	1485	jet in front
0.8	3500	.025	1	180	1155	1583	36	1960	jet in front

APPENDIX C (cont'd.)
Conical Bit - in Dakota Sandstone - Summary
(Independent Cuts)

Bit Penetration (in.)	Water Jet Press. (psi).	Water Jet Diam. (in.)	Number of Cuts	Forces Side (lb)	Forces Normal (lb)	Forces Drag (lb)	Forces Angle (deg)	Forces Total (lb)	Remarks
0.1	-0-		13	1	1348	819	55	1602	
0.2	-0-		45	17	1215	1130	46	1678	
	2500	.025	2	60	979	1213	38	1559	jet .4 in front
	5000	.025	2	45	1005	1248	38	1603	
		.025	2	169	462	844	28	962	
	2500	.025	4	14	504	864	30	1002	jet behind
	5000	.025	5	11	307	640	26	712	
	10000	.025	7	6	272	561	26	628	
	2500	.025	5	32	628	781	37	1004	jet .1 ahead
	5000	.025	4	94	640	955	33	1154	
	8300	.025	1	86	525	773	34	935	
	10000	.025	2	6	287	665	23	725	
	1000	.048	1	1	649	900	35	1110	
	2500	.048	1	1	480	838	29	966	
	5000	.048	2	1	203	574	19	609	
	10000	.048	1	1	57	501	6	504	
0.4	-0-		20	63	1527	1672	34	2290	
	2500	.025	2	74	1245	1630	37	2051	jet .1 ahead
	5000	.025	2	30	953	1406	34	1699	
	8300	.025	2	30	745	1272	30	1474	
	2500	.025	3	17	716	973	36	1208	jet behind
	5000	.025	3	11	381	896	23	974	
	10000	.025	2	11	174	700	13	721	
	-0-		8	29	1650	1635	40	2460	new pick, 100'
	-0-		2	44	2543	2171	49	3344	worn, 1000'
	-0-		2	236	1366	1520	41	2044	worn, 2000'
	-0-		4	46	957	1668	29	1924	worn, 3000'
	-0-		4	71	1274	1410	42	1900	machined, 5000'

Conical Bit - in Dakota Sandstone - Summary (cont'd.)

Bit Penetration (in.)	Water Jet Press. (psi)	Water Jet Diam. (in.)	Number of Cuts	Forces Side (lb)	Forces Normal (lb)	Forces Drag (in.)	Forces Angle (deg)	Forces Total (lb)	Remarks
0.6	-0-		7	81	1580	1961	36	2421	
	2500	.025	3	19	1537	2561	30	2987	jet 0.1 ahead
	5000	.025	2	75	1295	2593	26	2899	
	8300	.025	2	72	997	2402	22	2600	
	2500	.025	2	52	821	1227	33	1477	jet from behind
	5000	.025	3	103	736	1616	24	1716	
	10000	.025	4	88	722	1089	33	1306	
0.8	5000	.025	2	99	1682	3003	29	3443	jet ahead 0.1"
	8300	.025	3	145	1134	2822	21	3041	

Conical Pick in German Sandstone - Summary

Cut Spacing (in.)	Bit Penetration (in.)	Water Jet Press. (psi)	Water Jet Diam. (in.)	Number of Cuts	Forces Side (lb)	Forces Normal (lb)	Forces Drag (lb)	Forces Angle (deg)	Forces Total (lb)	Remarks
1.0	0.3	-0-		37	609	2642	1945	50	3422	
		10000	.025	44	378	1308	1538	48	2246	jet behind
1.5	0.2	-0-		12	630	3933	2530	56	4681	
		5000	.025	12	521	2824	2044	54	3492	
1.5	0.3	-0-		15	1114	4134	2598	58	4886	
		5000	.025	23	828	3202	2299	54	3943	
1.5	0.5	-0-		78	1131	3862	3505	48	5217	
		1000	.012	21	685	2263	2147	42	3121	0.06 hp
		3000	.012	33	739	2440	2588	43	3561	0.33 hp
		9000	.012	28	718	2291	2570	41	3445	1.72 hp
		5000	.025	32	720	2042	2340	40	3121	3.08 hp
		10000	.025	26	649	1383	2417	29	2788	8.71 hp
1.5	0.7	-0-		6	2665	4938	3997	51	6353	
		5000	.025	12	1331	2735	2645	45	3821	

Conical Pick in Lyons Limestone - Summary

Cut Spacing (in.)	Bit Penetration (in.)	Water Jet Press. (psi)	Water Jet Diam. (in.)	Number of Cuts	Forces Side (lb)	Forces Normal (lb)	Forces Drag (lb)	Angle (deg)	Total (lb)	Remarks
1.5	0.5	-0-		97	890	3409	2146	57	4039	
		5000	.025	30	739	2885	1784	57	3393	jet behind (3.08 hp)
		10000	.025	38	1068	3510	2228	57	4158	jet behind (8.71 hp)
		10000	.035	7	1231	3691	2939	51	4719	(17.10 hp)
		10000-2x	.025	11	676	2400	1690	54	2935	(17.42 hp)
		5000	.025	4	766	2859	2277	51	3655	jet from side
		10000	.025	5	1084	3036	2583	49	3986	jet from side

Conical Pick in Lyons Shale - Summary

Cut Spacing (in.)	Bit Penetration (in.)	Water Jet Press. (psi)	Water Jet Diam. (in.)	Number of Cuts	Forces Side (lb)	Forces Normal (lb)	Forces Drag (lb)	Forces Angle (deg)	Forces Total (lb)	Remarks
1.0	0.2	-0-		40	138	508	344	55	615	
1.5	0.5	-0-		33	414	969	600	56	1147	
		5000	.025	14	185	1117	849	51	1410	
2.5	0.8	-0-		11	912	2818	2520	48	3783	
		10000	.025	14	211	946	1052	42	1442	

Conical Pick in Dakota Sandstone - Summary

Cut Spacing (in.)	Bit Penetration (in.)	Water Jet Press. (psi)	Water Jet Diam. (in.)	Number of Cuts	Forces Side (lb)	Forces Normal (lb)	Forces Drag (lb)	Angle (deg)	Total (lb)	Remarks
1.5	0.3	-0-		15	157	819	918	41	1231	
		5000	.025	20	138	550	672	39	857	jet behind
1.5	0.5	-0-		46	265	1069	1269	39	1663	
		5000	.025	40	188	450	707	32	844	jet behind
1.5	0.7	-0-		5	276	885	1050	40	1373	
		5000	.025	10	340	579	944	31	1107	jet behind
1.5	1.0	-0-		6	747	1184	1646	35	2028	
		5000	.025	13	659	614	1203	27	1352	jet behind
2.5	0.8	-0-		18	348	1216	1398	40	1853	
		5000	.025	23	477	830	1258	32	1540	jet behind
		10000	.025	12	309	641	1228	28	1389	jet behind