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DEVELOPMENT OF A WATER JET ASSISTED CUTTERHEAD FOR COAL MEASURE ROCKS

Contract J0233900
Excavation Engineering and Earth Mechanics Institute
Colorado School of Mines

BUREAU OF MINES
UNITED STATES DEPARTMENT OF THE INTERIOR

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NOTICE

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16. Abstract (Limit: 200 words)

The results of a laboratory research program aimed at the development of a water jet assisted drag bit cutting system for coal mine applications are presented. Two types of drag bits, a conical and a plow bit, were tested in a hard sandstone rock with jet pressures of up to 20,000 psi. Jet locations investigated were in-front and behind the bit. For each jet mounting location, three jet impingement distances with respect to bit tip were tested. The closest jet impingement location to bit tip was found most effective, providing the greatest force reductions on the bit. Overall, significant bit force reductions up to 50 percent were obtained with jet assist. Also observed was a drastic reduction in airborne dust when jets were employed.

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FOREWORD

This report was prepared by the Excavation Engineering and Earth Mechanics Institute of the Colorado School of Mines, Golden, Colorado under USBM Contract number J0233900. The contract was initiated under the Mining Research Program. It was administered under the technical direction of the Denver Research Center with Mr. Bob Evans acting as Technical Project Officer. Mr. Larry Rock was the contract administrator for the Bureau of Mines. This report is a summary of the work recently completed as a part of this contract during the period of September 22, 1979 to September 30, 1985. This report was submitted by the author on October 1985.

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1.0. INTRODUCTION

This report presents the results of a research investigation carried out at the Colorado School of Mines (CSM) toward the development of a water jet assisted drag bit cutting system for coal mining application. The basic concept involves the use of low to moderate pressure (less than 20,000 psi) water jets to assist the drag bit in terms of reduced cutting forces, prolonged bit life and lesser amount of dust generated from the cutting process. The ultimate goal is to develop a jet assisted cutting system that can be incorporated on present-day coal mine machinery to extend their application to abrasive coal measure rocks at greater rates and reduced costs than currently feasible. The intent is to improve the cutting performance of existing equipment to expedite coal mine development work, thus reducing the time required to bring new coal mines into production.

The test plan for this research investigation called for a three phase effort. The first phase involved an extensive series of tests on CSM linear cutter using a plow and a conical bit. These tests were designed to provide data related to jet location and orientation with respect to bit on the degree of performance improvement to be gained by jet assist. Also investigated under this phase were jet pressure effects on the rock cutting performance of both bits. The tests were run in a hard, abrasive sandstone formation.

During second phase of the research program, a three-foot diameter rotary cutterhead was designed, fabricated and assembled in the laboratory. The purpose of constructing such a test facility was to provide the capability to carry out laboratory tests to investigate multiple tool interaction and to determine speed effects on jet assisted drag bit cutting of coal measure rocks.

The Phase III of the research program called for a series of tests on the rotary cutterhead designed and fabricated under Phase II. However, due to budget cuts in the sponsoring agency, the funding for this Phase was not received, resulting in the termination of the research effort following the completion of the first two phases of work. Nevertheless, since its construction, the rotary cutterhead has been used extensively by the Bureau of Mines in support of their in-house research programs in the development of jet assisted cutting technology for coal mining applications. The scope of this test program had objectives similar to those originally proposed to be carried out in this study. Thus, where applicable, the findings of these tests are referred to in this report.

2.0. LABORATORY TEST EQUIPMENT

The Phase I test program for this study was conducted on a linear cutting machine available at the Colorado School of Mines. During Phase II, a laboratory rotary cutterhead test facility was designed and fabricated. This section presents a description of the test equipment and the test procedures used during testing.

2.1. Linear Cutting Machine

All Phase I experiments discussed in this report were performed using a linear cutting machine available from previous rock cutting research programs completed at CSM (Figure 2.1.). Basically, the machine incorporated a large, stiff steel frame onto which the cutter bit is mounted. The rock sample is contained within a steel box which is traversed under the bit with a servo-controlled hydraulic actuator. The rock box can also be translated sideways to permit setting of any desired indexing of cutter paths.

The linear cutter which has been in operation over the last several years, is designed to simulate field cutting conditions by providing the following capabilities:

1) capability of installing various sizes and types of actual field cutters;
2) can handle manufacturers suggested allowable cutter loads;
3) maximum deflection of .01 inch at a load of 25,000 pounds, allowing simulation of the stiffness of field cutters;
4) capable of much higher loads safely but with a corresponding increase in deflection, meaning reduced stiffness with increasing cutter load;
5) capable of being operated both in constant penetration and constant thrust modes;
6) full range of cutter speeds similar to those found on most field boring machines;

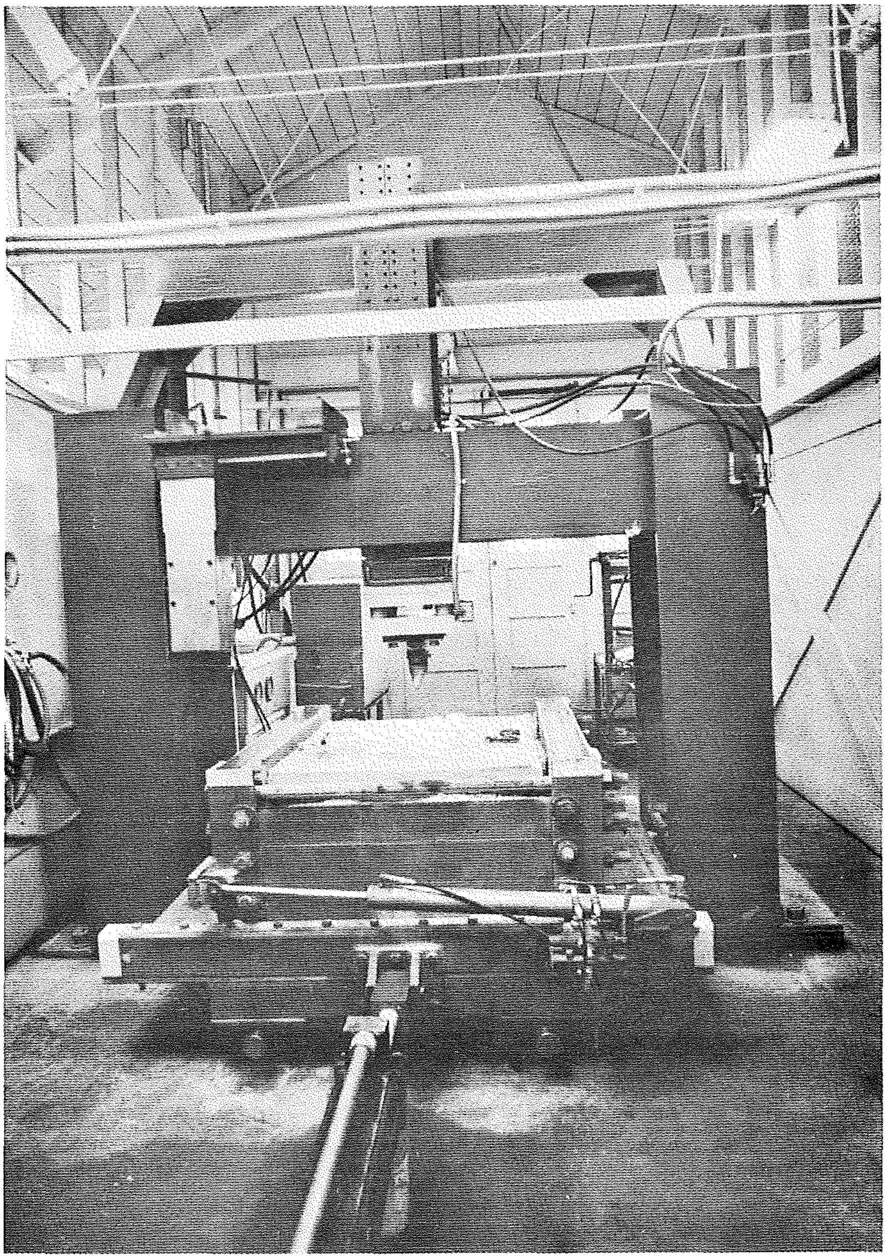


Figure 2.1. Linear rock cutting machine used for jet assisted drag bit cutting tests.

7) can be set to cut any desired depth, thus permitting the testing of a full range of cutter penetration depths;

8) capable of providing high cutter rolling forces to allow testing of high penetration depths.

9) permits testing of angled or skewed cutters;

10) lateral confining pressures can be applied to the specimen; simulating underground loading and confinement;

11) any required spacing of cuts is easily set by lateral translation of the specimen;

12) water jet assisted cutting with up to 70,000 psi operating pressure.

2.1.1. Hydraulic Components

The desired penetration of the cutter bit into the rock was set by hydraulically lowering the cutter holder frame and inserting precision metal spacers between this frame and the main supporting frame of the machine. After each cut, the box holding the specimen was translated sideways by the two hydraulic rams with the amount of translation corresponding to desired spacing of cuts. After these adjustments, the system was ready for another cut.

The horizontal movement of the specimen under the cutter was accomplished with a servo-controlled horizontal actuator. A linear variable differential transformer (LVDT) attached to the ram of this horizontal actuator was used to monitor the movement, thus allowing the electronic controller to maintain a constant speed of the specimen by comparing the output of this LVDT to that of the function generator. Due to servo-control capability, the cutting speed was infinitely variable up to a maximum of about 250 ft/min.

2.1.2. Instrumentation and Data Acquisition

The system employed for data acquisition and control on the linear cutter included a triaxial load cell, signal conditioners and high speed digital integrators.

The triaxial load cell, designed and fabricated at CSM was capable of resolving the load on the bit into its three mutually perpendicular components, vertical, drag and side forces.

The load cell consists of four hollow aluminum cylinders sandwiched between two aluminum plates which are in turn held together by four bolts (Figure 2.2.). Each aluminum cylinder contains three sets of diametrically applied axial and tangential strain gages (SR-4 type, 120 ohm), which are connected to construct three separate full bridge circuits to monitor the three force components. The four bolts passing through the hollow aluminum cylinders are pretensioned, thus maintaining an initial compression on the cylinders. Since the cylinders are not attached to the aluminum plates, they can not carry any tensile load; and the cutter loads are monitored by an increase or decrease in the initial compression. By careful arrangement of the strain gages on each bridge circuit, the effect of the two other force components is cancelled and only the desired one is indicated as the output for each channel.

Power to the bridge circuits was supplied by three self-balancing, isolated power units with built-in amplifier circuits. This system provided a full range of bridge sensitivities and allowed measuring various cutting loads with a nearly perfect balance between the bridge sensitivity and the inherent noise levels.

A digital integrator incorporating three separate channels was utilized for data acquisition. In this arrangement, the output from each load cell bridge was connected to a three channel time-base digital integrator for recording of cutting forces. A switching system mounted on the machine started and stopped

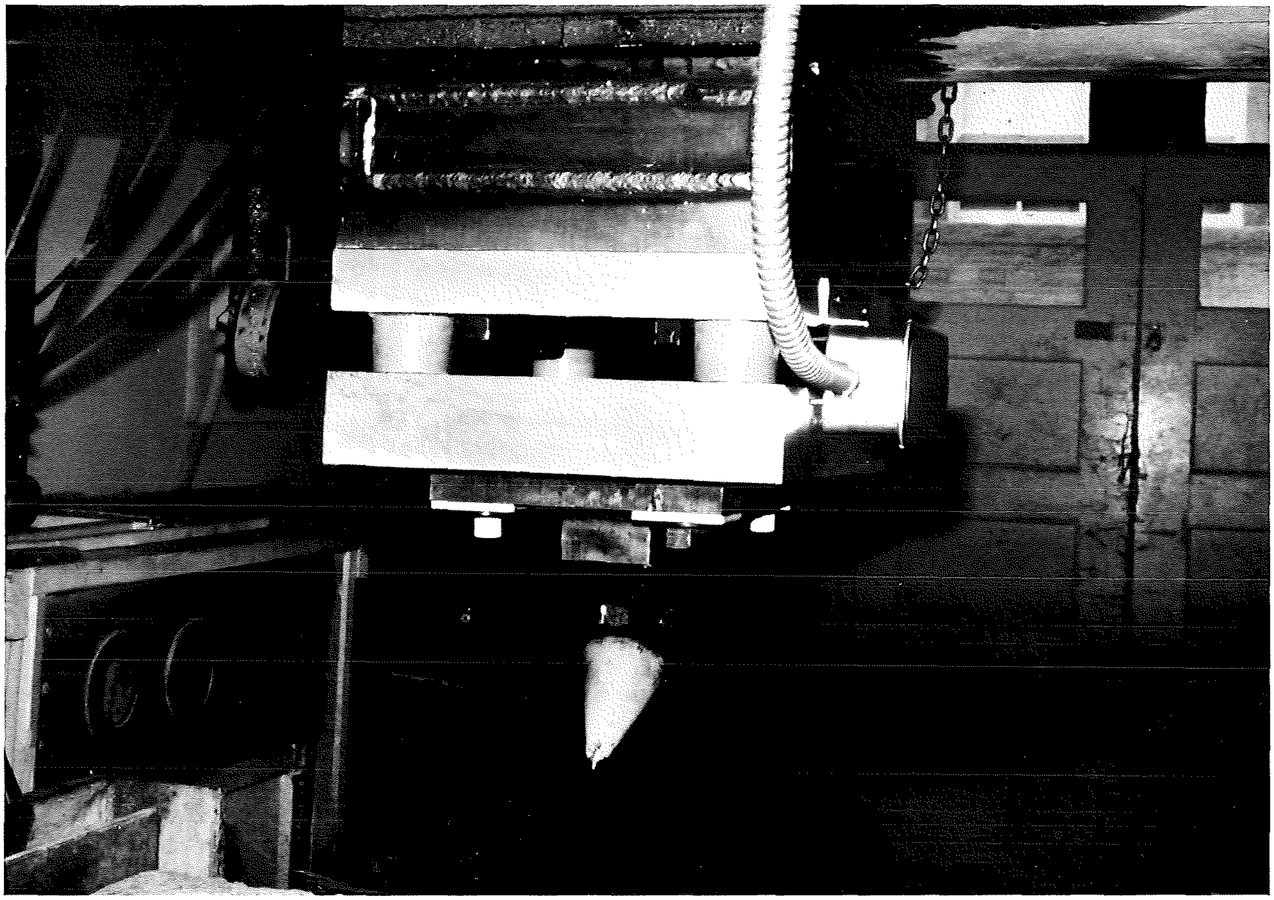


Figure 2.2. Triaxial load cell mounted on the linear cutter.

the integrator at the end lines marked on the sample. By dividing the integrator readings by the time it takes the cutter to travel between the two end lines and applying the necessary correction, forces on the cutter could be obtained. In addition to the average force values, a two channel digitizer was also incorporated into the circuit to serve as a peak detection unit. This unit recorded the peaks of the vertical and side forces since they are believed to be most relevant to machine and cutter saddle design. A view of the data acquisition system together with the machine power control units is shown in Figure 2.3.

2.1.3. Water Jet Equipment

Two pumping systems, one low and one high pressure, were used to supply the required water pressure to the jet nozzle. The low pressure unit was a trailer mounted triplex pump with a 60 kw diesel engine capable of generating up to 10,000 psi pressure. This pump was used for the low pressure testing up to its maximum pressure generating capacity. For the higher pressure range, the pump used was a double-acting intensifier incorporating a 100 kw electric motor driving a variable volume hydraulic pump. The duplex intensifier system included a logic control circuitry to govern the pumping cycle of the plungers in order to provide a relatively smooth pressure output. This unit was capable of generating 60,000 psi pressure at a maximum flow rate of 1.25 gal./min. Both pumping systems were fitted with pressure regulators to produce the desired jet pressure at the nozzle.

The jet nozzle assembly used for linear cutting tests consisted of a stainless steel tube with dimensions of 3/8 in. ID and 1/2 in. OD. A brass insert, containing a commercial sapphire orifice was held in the end of the tube with a set screw containing an axial hole for the jet to pass through (Figures 2.4. and 2.5.). The sapphire orifice was fitted into a recess in the insert and

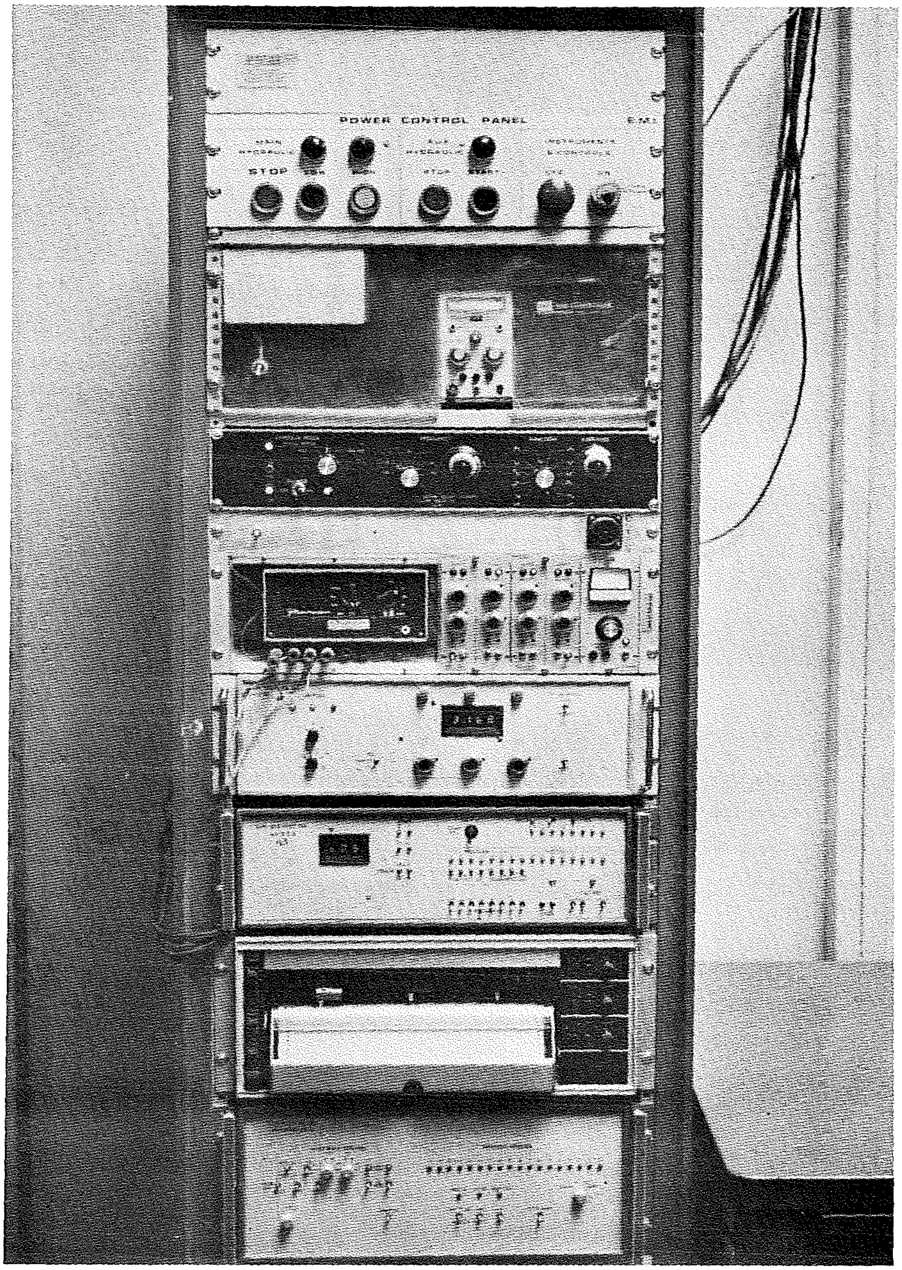


Figure 2.3. Control and data acquisition system for the linear cutter.

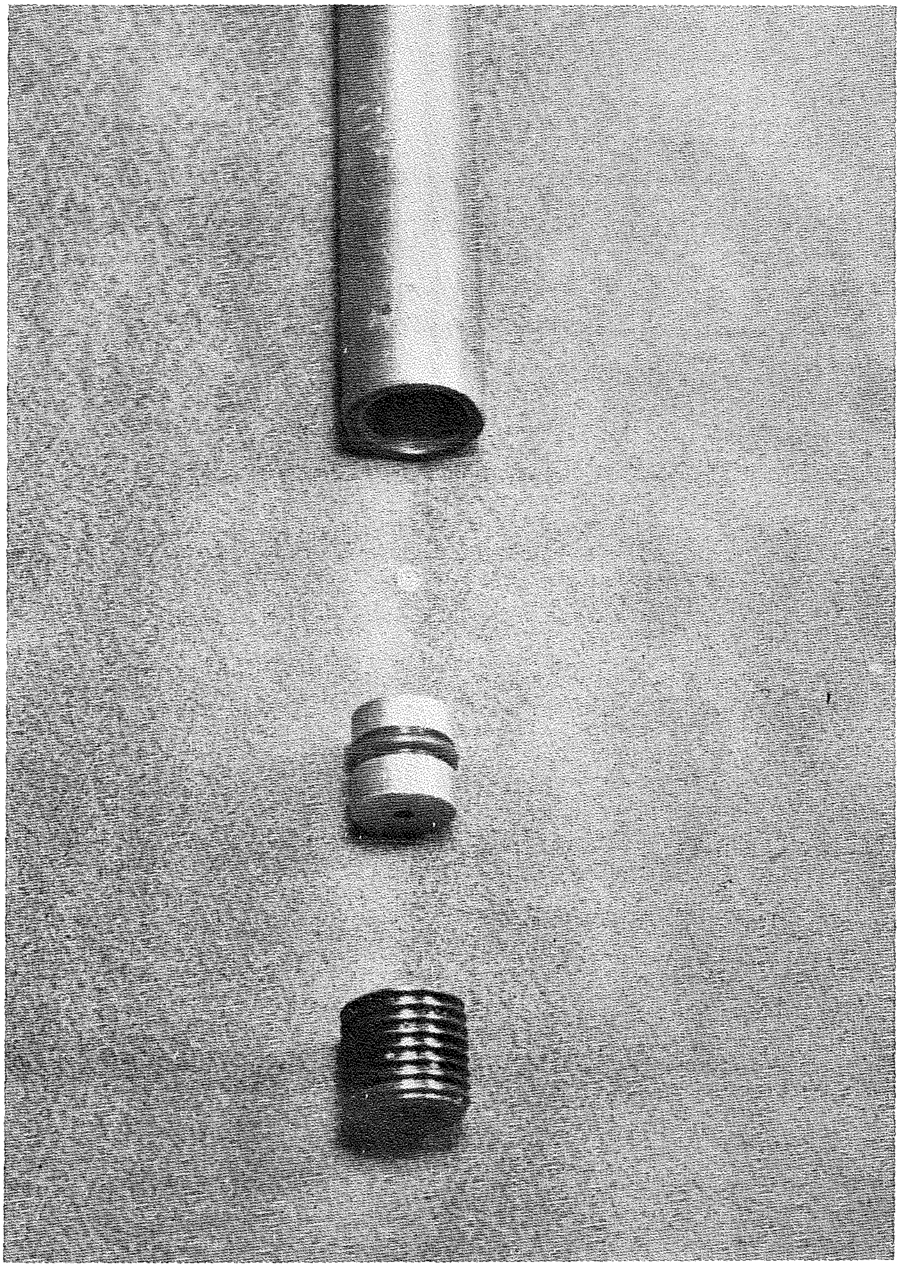


Figure 2.4. Water jet nozzle parts.

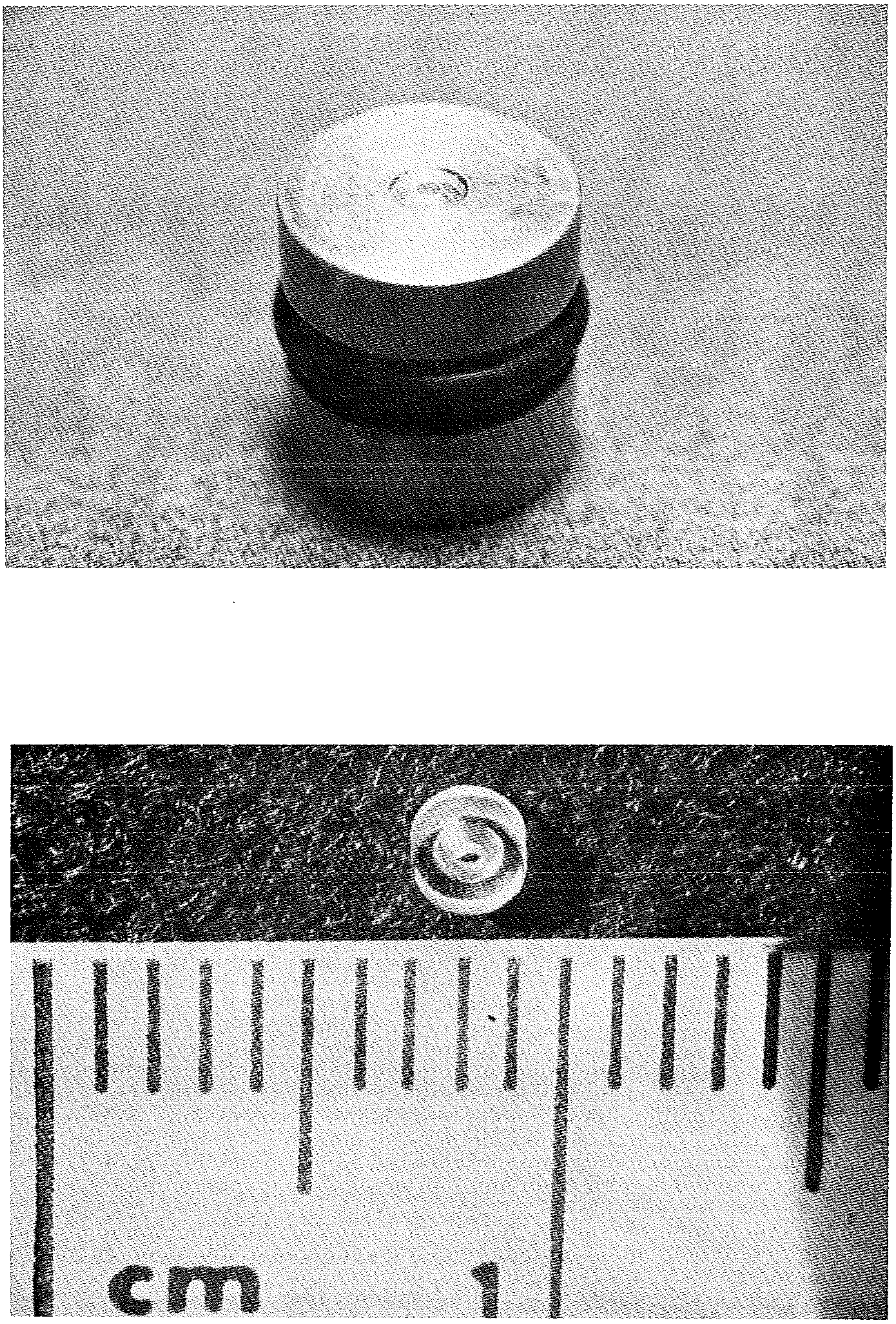


Figure 2.5. Water jet orifice and holder.

sealed by high pressure water acting against it. The insert in turn was sealed in the tube with an O-ring arrangement. This nozzle configuration worked very successfully during the entire testing program with pressures up to 20,000 psi.

Because of the successful operation of O-ring seals, no attempt was made to develop and use other sealing configurations, such as metal to metal seals.

The sapphire orifices used in the jet nozzles also performed well without any wear or degradation of jet integrity. Because of careful filtering of water, no nozzle plugging was encountered during the entire test program.

The water jet nozzle was attached to the bit mounting plate in a manner to allow changes in the orientation of the jet relative to the bit. The jet mounting fixture was fitted with swivel joints so that jet could be precisely positioned to strike the rock surface either in front, from behind, or from one side of the cutter bit.

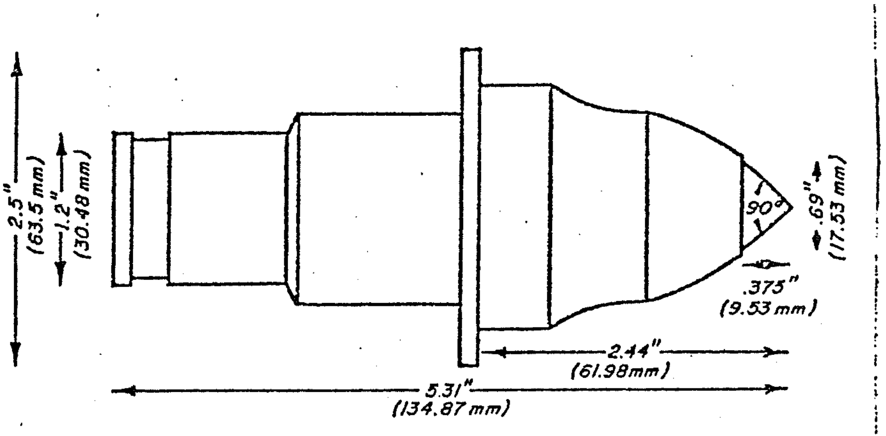
2.1.4. Cutter Bits

The cutter bits used in conjunction with jet assisted linear cutting tests included two commercial type of bits, a plow and a conical bit, shown in Figure 2.6. Both of these bits are commonly utilized on roadheader type coal mine development machines for excavating hard and abrasive coal measure strata.

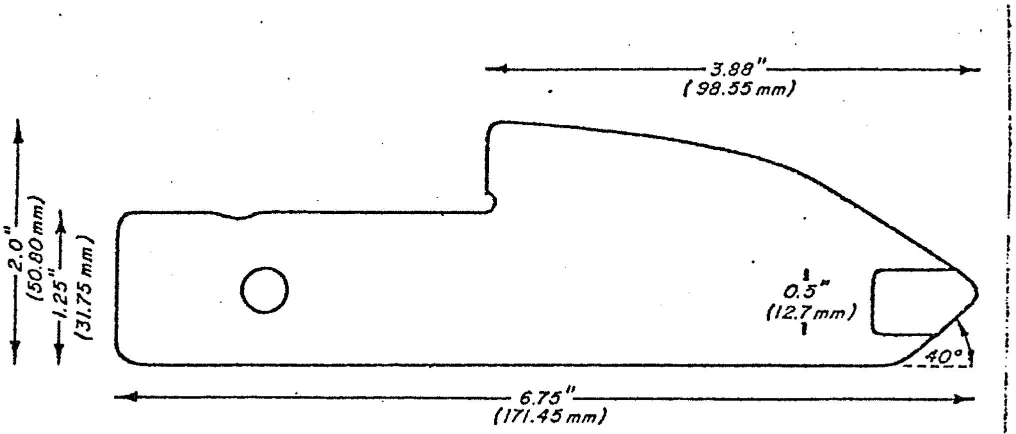
In laboratory testing, the bits were mounted in their respective holder box and then attached to the bottom plate of the load cell. Periodically during testing, the load cell was calibrated by loading the bit with a precision hydraulic cylinder and recording the data channel outputs at known increments of load exerted on the bit.

2.1.5. Rock Types

Since the prime goal of this research effort was to extend the current



CONICAL BIT USED FOR WATER JET DRAG BIT CUTTING TESTS



PLOW BIT USED FOR WATER JET DRAG BIT CUTTING TESTS

Figure 2.6. Type II drag bits used for water jet-assisted cutting tests

capabilities of excavation machinery to cutting of harder coal measure rocks, it was decided to carry out the laboratory test program in a rock formation representative of harder strata likely to be encountered in coal mine development. The requirements were that the rock type should be relatively hard and abrasive, and that present mechanical miners would experience difficulty in excavating such material from an economics viewpoint. Based on these considerations, it was then decided to use samples of a hard, abrasive sandstone formation with an average compressive strength of 19,000 psi. The required samples of this rock type for linear cutter tests were obtained from a quarry near Dortmund, West Germany. Actually, samples of this rock were already available from a previous research study and they were adopted for use in this test program as their properties closely met the requirements for the type of rock to be used. This sandstone, which in this report is referred to as the "German Sandstone," is a light gray, fine to medium grained, quartz sandstone. A more detailed description of the German Sandstone is given in Appendix A.

2.1.6. Test Procedures

The testing program with the linear cutter was performed using a constant penetration mode of testing. The penetration depth of the bit into the rock was held constant during testing and the bit forces required to maintain this penetration were measured. The desired bit penetration was set by placing metal spacers between the bit holder assembly and the machine cross-beam.

The rock samples were cast in concrete in the steel rock holder boxes and allowed to cure for a few days. The sample was then mounted on the machine test bed and a series of cuts were made across the rock surface prior to recording of data (Figure 2.7.). The purpose was to condition the rock surface

Figure 2.7. Conditioning of the rock surface prior to recording of test data.

and to eliminate any errors which would be introduced by cutting on a fresh, smooth rock face.

Before commencing with jet assisted cuts, a series of "dry" tests were carried out with each bit to develop baseline cutting data upon which to compare the effectiveness of jet assisted cutting toward enhancing drag bit performance. Each test consisted of several cuts (15 to 25) to obtain data at steady-state cutting conditions in order to reduce variability between cuts. In cases where data exhibited unacceptable variability, tests were repeated in new rock samples. For each cut, all three force components acting on the bit were measured and recorded. These readings were then input into the computer to calculate force averages, specific energy, cutting coefficient and other relevant test summaries. For jet assisted tests, the same test procedure was employed, except in general a larger number of cuts were taken to improve the statistical confidence in data.

2.2. Rotary Cutterhead

Under Phase II of this research program, a three-foot diameter rotary cutterhead was designed and fabricated in the laboratory. The purpose of constructing such an equipment was to provide the capability to test jet assisted drag bits at higher traverse speeds than what is feasible with the linear cutter apparatus. A second objective was to investigate multiple tool operation and resultant interaction from a standpoint of the effectiveness of jet assisted cutting.

2.2.1. Machine Description

Overall views of the laboratory rotary cutterhead are shown in Figures 2.8. and 2.9. The basic machine frame consists of a heavy I-beam weldment

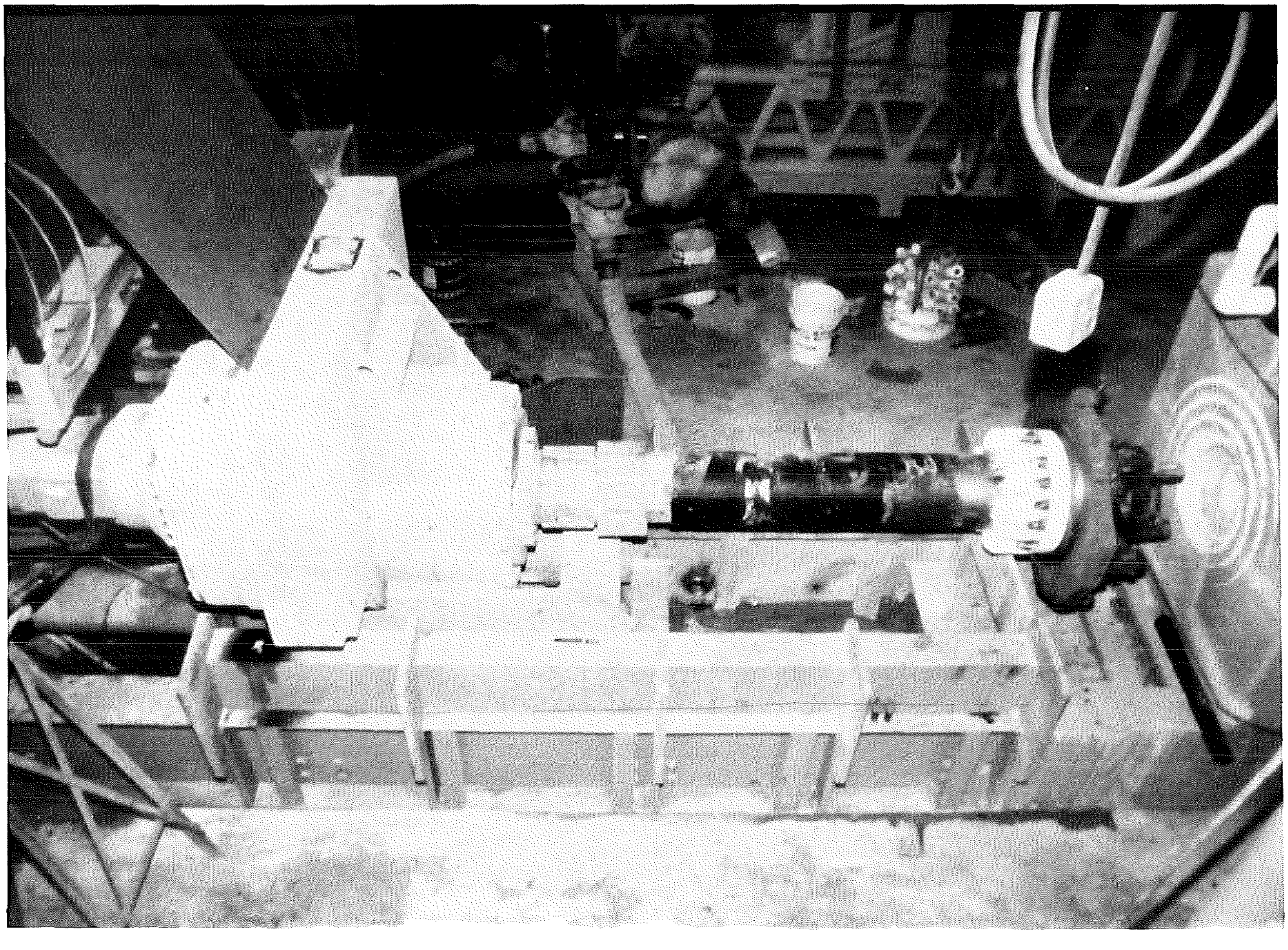


Figure 2.8. An overall view of the rotary cutterhead.

which serves to maintain all thrust and torque reactions within the system. The frame is bolted to the concrete foundation to provide stability during drilling.

The machine drive system consists of a Dresser Model-800 raise bore drive unit which features two pinions driving into a common gear (Appendix B). The drive unit includes four guide shoes which slide on structural guide columns. The columns are bolted to the base frame and further secured with a series of L-shaped steel plates.

The cutterhead rotation is provided by a variable volume hydraulic motor. A 150 hp AC motor driving a variable volume hydrostatic pump delivers the necessary oil to the drive motor (Figure 2.10.). Due to the hydraulic drive feature, the rotational speed of the drill bit is infinitely variable from 0 to 50 rpm. The torque generating capability is 25,000 ft-lbs. at 20 rpm. Beyond this speed, torque decreases with constant horespower input.

A double-acting hydraulic actuator is used to provide forward thrust to the bit. The maximum thrust capability currently available is 100,000 lbs. The machine is designed to withstand higher thrust loads which can be generated by adding a second actuator to the hydraulic thrusting mechanism. Power to the thrust actuator is supplied by a 20 hp AC motor driving a 10.0 gpm variable volume pump. The maximum stroke of the cutterhead is 54 inches.

The rotary cutterhead is designed to permit testing of bits of up to 3 feet in diameter. The drill pipe is filled with an adapter plate onto which various types of drill bits can be mounted. The rotary cutterhead is currently operated with manual hydraulic controls. A control panel located behind the machine in an elevated position contains all necessary controls and meters for the manual operation of the equipment.

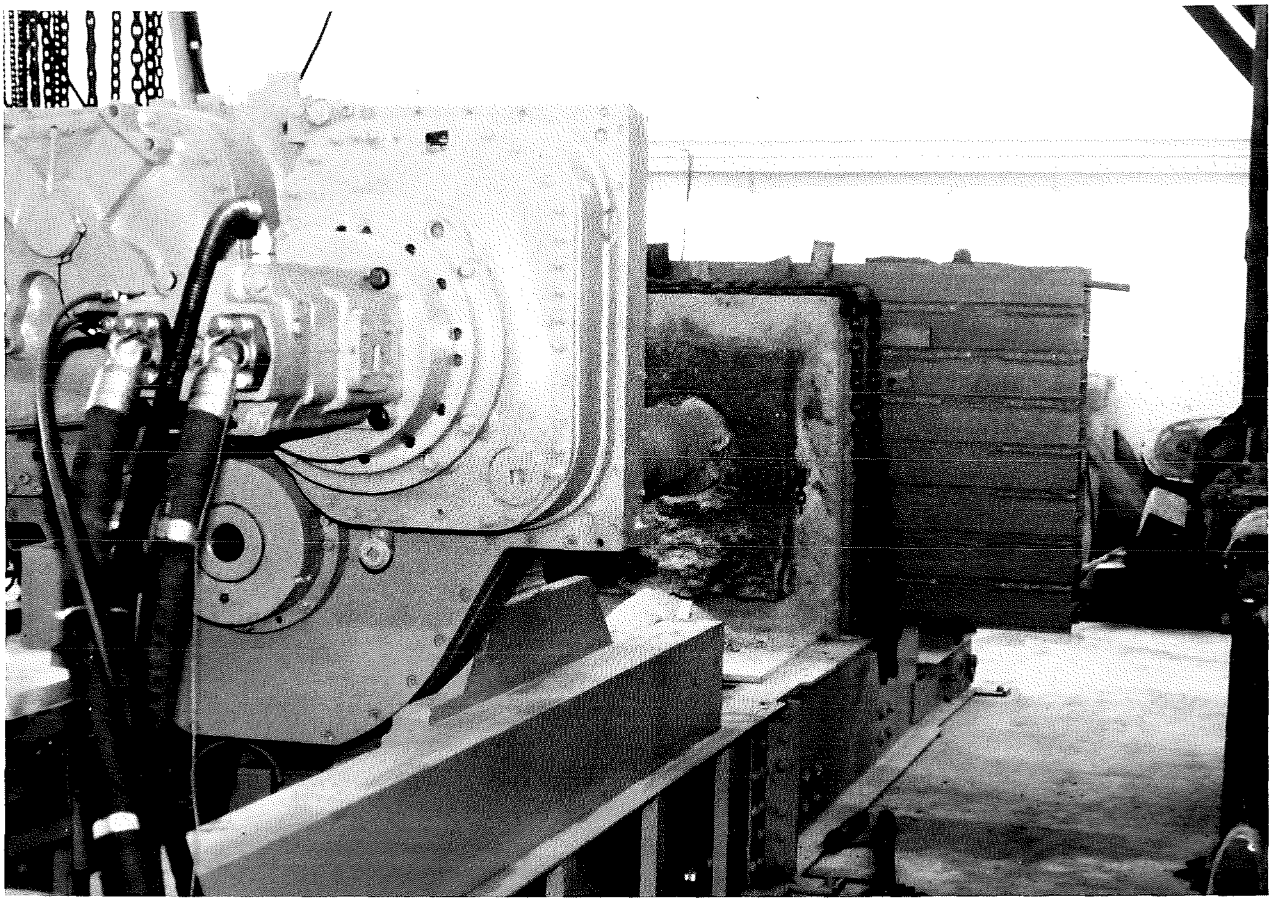


Figure 2.10. The hydraulic rotary drive system on the rotary cutterhead.

2.2.2. Instrumentation

The laboratory rotary cutterhead is equipped with a series of transducers to monitor and measure various operative parameters. Presently, instrumentation is available for measuring thrust, torque, rpm, penetration rate, water-jet pressure and flow. Provisions have been made for expanding the number of data channels that can be measured as need arises.

Machine thrust is measured with a pressure transducer installed on the thrust actuator hydraulic line. A similar type pressure transducer is also used for measuring the torque pressure supplied to the drive motor. Penetration rate measurement is accomplished with a 10-turn potentiometer mounted on one of the guide shoes. This potentiometer is calibrated to produce a certain voltage output for a given linear movement of the drive assembly with respect to the fixed base frame. A DC-generator type transducer is used to measure the rotational speed of the cutterhead.

2.2.3. Data Acquisition

A computer based data acquisition system is used for recording and analysis of data from the transducers installed on the rotary cutterhead. The main component of the system is a MicroVax II computer with 7 MB memory, a dual 400 KB floppy, a 71 MB Winchester disk and a 95 MB cartridge tape. Interfaced to the MicroVax II is a Raster Technology model 380 graphics computer used for graphical display of test data. Also available as additional data storage is a Fujitsu 336 MB SMD Winchester drive plus a 1/2 inch Fujitsu 625/1600 BPI tape drive. Data and test graphs can be printed out on a high speed, Hewlett-Packard plotter. Also available is a twelve-channel light beam recorder featuring high frequency response and a wide selection of chart speeds.

Data treatment and analysis is performed using various statistical software packages. The user has the option to plot any data channel, to perform various regression analyses on the data or any other desired statistical analysis. The data acquisition system also has the capability to store all raw data on 8-inch floppy discs or 1/2 inch 6250 BPI tapes. The purpose of storing data is to allow future analysis to return to the original data files.

A picture of the data acquisition and analysis system used for rotary cutterhead tests is shown in Figure 2.11.

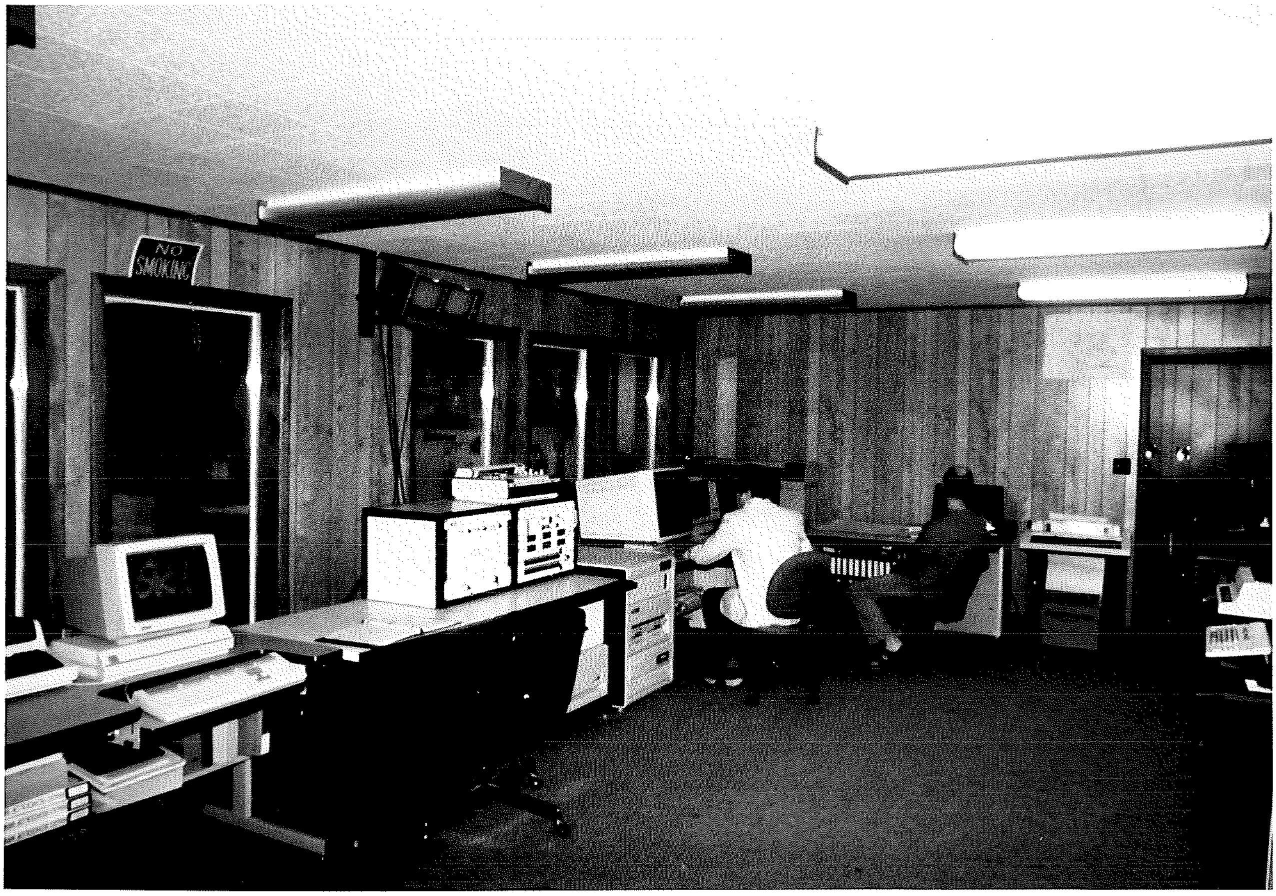


Figure 2.11. The data acquisition and analysis center for the rotary cutterhead.

3.0. LABORATORY TEST RESULTS

As previously noted, the laboratory test program for this research effort was divided into three major phases. Phase I involved our extensive series of cutting tests on CSM linear cutter. In this phase, two commercially available drag type bits were tested in a hard, abrasive sandstone formation. The prime objective of these tests was to evaluate the parameters influencing jet assisted cutting and to provide an initial assessment of the degree of benefits that can be accrued in terms of improving the drag bit cutting performance. The linear cutter tests were performed with one bit at a time, thus the operation and the interaction of multiple bits characteristic of a mechanical mining machine was not simulated. To develop the capability of investigating jet cutting effects with multiple tool operation, a rotary cutterhead was designed and constructed in the second phase of the research program. In addition to allowing for testing of several, interacting bits at a time, this test facility also provided the capability for testing at higher bit cutting speeds than those feasible with the linear cutter. The Phase III test program was structured to address these issues, but, as stated earlier, it was cancelled due to lack of funding. However, the rotary cutterhead was utilized by the Bureau of Mines for conducting a series of jet assisted cutting tests in support of their inhouse research efforts. These tests examined most of the parameters originally intended for investigation under Phase III of that research effort. The results of tests run by the Bureau of Mines are published elsewhere (1), and a brief summary of the major findings relevant to this study is presented later in this report.

3.1. Results of Linear Cutting Tests

Both the conical and the plow bits were tested in German sandstone with and without jet assist. The unassisted or "dry" cuts were designed to develop baseline data for comparing the effectiveness of jet assisted cutting. Tests were carried out at two depths of penetration, 0.10 and 0.20 inches. These values were determined based on an evaluation of penetration depths commonly achieved in field excavation with these types of bits. The cutting speed during testing was held constant at about 50 ft/min. For each test, several passes were taken across the rock surface with each pass containing a number of cuts at a fixed depth of penetration (Figure 3.1.). Monitored and recorded for each cut were the three force components acting on the bit, the side, vertical and the drag forces. As discussed earlier, a triplex pump was used for generating jet pressures below 10,000 psi. For higher pressures, the pumping system used was a duplex-intensifier system. The jet nozzle was attached to the bit using a special holder mechanism designed and fabricated in the laboratory. This fixture incorporated swivel joints so that any desired jet angle and impingement orientation can be set and maintained easily.

For the jet assisted tests, two jet orientations relative to the bit were investigated. For the plow bit, the jet was mounted either in front of or behind the bit and was oriented to impinge the zone in the immediate vicinity of the cutter tip. Only one jet orientation, in front of the bit, could be tested with the conical bit. The particular geometry of the conical bit precluded jet mounting behind the bit as the jet stream could not clear the bit shoulder in order to effectively strike the crushed zone below the cutting tip.

Prior to actual test program, a series of preliminary tests were performed to gain some insight as to how sensitive the effect of jet assist was on jet location with respect to the bit. From these initial trials, it became evident that the exact location of jet impingement on rock surface relative to the bit

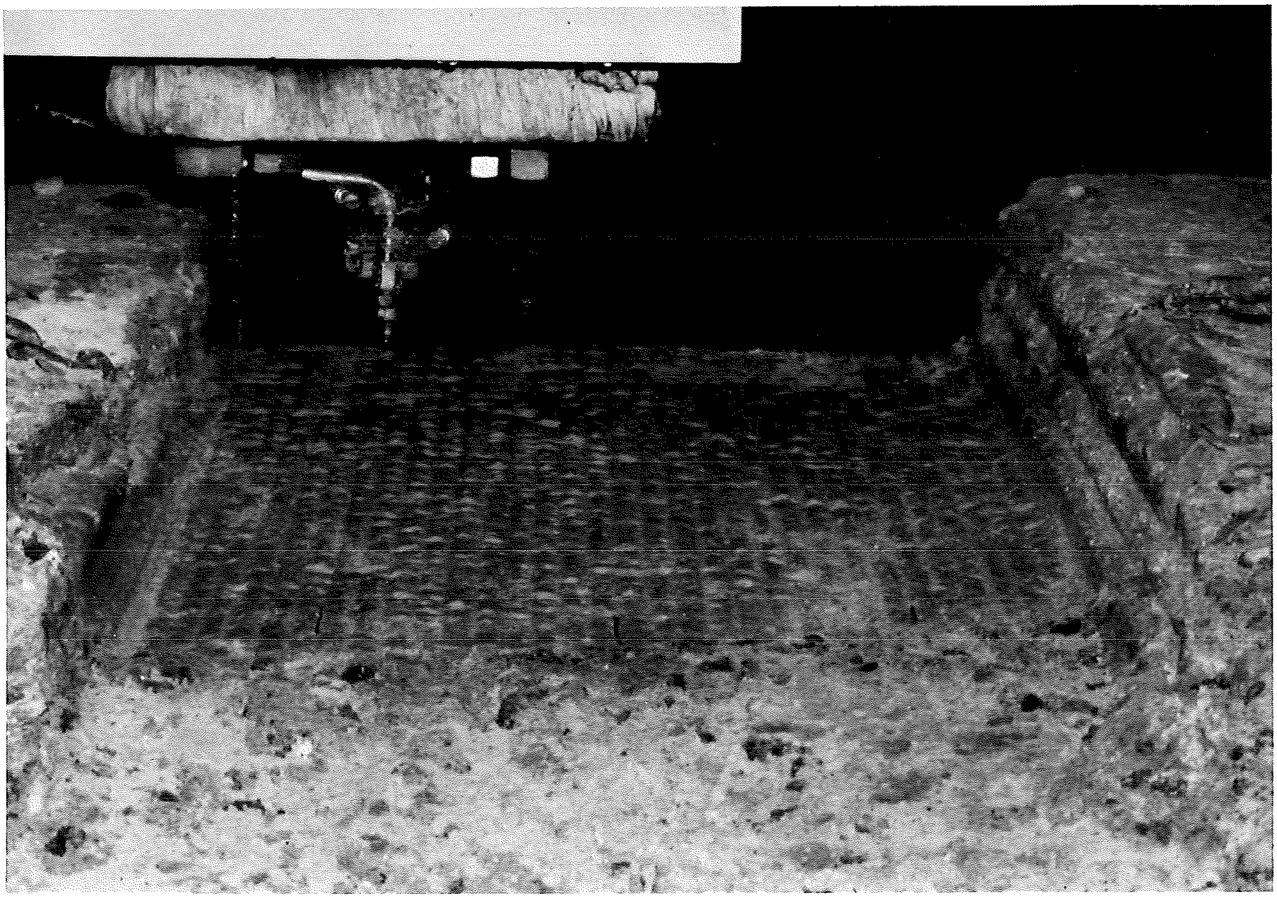


Figure 3.1. A representative picture of the rock surface during linear cutting tests.

had an influence on the degree of bit force reductions brought about by jet assist. To evaluate this effect in more detail, it was decided to perform the laboratory tests by including another variable into the test program corresponding to the exact distance of jet impingement from the penetrating edge of the bit. Hence, for the two jet mounting locations, three jet orientations were tested so that the jet would impinge the rock surface at distances of 1/8 inch, 1/4 inch, or 1/2 inch in front of or behind the cutter tip. In all tests, extreme care was exercised to assure proper jet orientation to obtain any one of these impingement locations.

The linear cutter test results are listed in Tables 3.1. through 3.3. Figures 3.2. and 3.3. show pictures of jet assisted cuttings with both bits used in the test program.

For testing with the plow bit at a 0.10 depth of penetration, the test results with different jet impingement locations in front of the bit are shown in Figures 3.4. and 3.5. for the vertical and drag forces, respectively . These plots show the effect of jet location on bit force reductions due to jet assist at various jet pressures. Two major observations can be made from the results shown in these graphs. First, as expected, the increased jet pressure contributes to a higher degree of bit force reductions, although a leveling-off trend is seen to occur at higher pressures. This indicates that no additional force reductions may be obtained for jet pressures above a certain value. The second conclusion that can be drawn from these plots relate to the jet impingement location. For this particular jet arrangement, the closest jet location to the bit tip gives the greatest reduction in bit forces. This result agrees with the findings of other investigators from previous jet assisted cutting studies in that jet impingement on the rock surface should be very close to the penetrating

TABLE 3.1 - Results of Laboratory Linear Cutting Tests with Jet-Assisted Plow Bit in German Sandstone (0.025 inch nozzle, jet in front)

Bit Pen. (in.)	Jet Pressure (psi)	Jet Location (in.)	Side Force (lbs.)	Vertical Force (lbs.)	Drag Force (lbs.)
.10	Dry Cut	Dry Cut	1,052	7,775	5,986
.10	5,000	1/8" in front	890	6,212	4,224
.10	5,000	1/4" in front	975	7,168	5,089
.10	5,000	1/2" in front	1,130	7,626	5,033
.10	Dry Cut	Dry Cut	1,052	7,775	5,986
.10	10,000	1/8" in front	990	5,673	4,481
.10	10,000	1/4" in front	905	5,780	4,335
.10	10,000	1/2" in front	790	5,929	4,291
.10	Dry Cut	Dry Cut	1,052	7,775	5,986
.10	15,000	1/8" in front	705	4,015	3,298
.10	15,000	1/4" in front	810	4,419	3,480
.10	15,000	1/2" in front	942	5,161	4,072
.10	Dry Cut	Dry Cut	1,052	7,775	5,986
.10	20,000	1/8" in front	806	4,002	3,010
.10	20,000	1/4" in front	692	4,608	3,594
.10	20,000	1/2" in front	725	5,003	3,892

TABLE 3.1, Continued.

Bit Pen. (in.)	Jet Pressure (psi)	Jet Location	Side Force (lbs.)	Vertical Force (lbs.)	Drag Force (lbs.)
.20	Dry Cut	Dry Cut	2,010	14,511	13,780
.20	5,000	1/8" in front	1,811	11,386	9,076
.20	5,000	1/4" in front	1,865	12,370	10,510
.20	5,000	1/2" in front	1,690	13,407	11,785
.20	Dry Cut	Dry Cut	2,010	14,511	13,780
.20	10,000	1/8" in front	1,906	9,688	8,981
.20	10,000	1/4" in front	1,458	10,780	9,737
.20	10,000	1/2" in front	1,676	10,949	9,478
.20	Dry Cut	Dry Cut	2,010	14,511	13,780
.20	15,000	1/8" in front	1,810	10,254	9,061
.20	15,000	1/4" in front	1,694	10,551	8,973
.20	15,000	1/2" in front	1,676	12,046	9,873
.20	Dry Cut	Dry Cut	2,010	14,511	13,780
.20	20,000	1/8" in front	1,705	9,432	7,892
.20	20,000	1/4" in front	2,016	11,144	9,056
.20	20,000	1/2" in front	1,853	11,197	8,978

TABLE 3.2 - Results of Laboratory Linear Cutting Tests with Jet-Assisted Plow Bit in German Sandstone (0.025 inch nozzle, jet from behind)

Bit Pen. (in.)	Jet Pressure (psi)	Jet Location	Side Force (lbs.)	Vertical Force (lbs.)	Drag Force (lbs.)
.10	Dry Cut	Dry Cut	1,052	7,775	5,986
.10	5,000	1/8" behind	906	5,443	4,154
.10	5,000	1/4" behind	895	5,794	4,069
.10	5,000	1/2" behind	970	5,753	4,375
.10	Dry Cut	Dry Cut	1,052	7,775	5,986
.10	10,000	1/8" behind	886	5,228	4,406
.10	10,000	1/4" behind	871	5,403	4,275
.10	10,000	1/2" behind	972	5,902	4,892
.10	Dry Cut	Dry Cut	1,052	7,775	5,986
.10	15,000	1/8" behind	992	5,713	4,315
.10	15,000	1/4" behind	851	5,659	4,406
.10	15,000	1/2" behind	869	5,807	4,671
.10	Dry Cut	Dry Cut	1,052	7,775	5,986
.10	20,000	1/8" behind	975	7,303	5,506
.10	20,000	1/4" behind	1,006	5,659	4,605
.10	20,000	1/2" behind	892	5,807	4,478

TABLE 3.2, Continued.

Bit Pen. (in.)	Jet Pressure (psi)	Jet Location	Side Force (lbs.)	Vertical Force (lbs.)	Drag Force (lbs.)
.20	Dry Cut	Dry Cut	2,010	14,511	13,780
.20	5,000	1/8" behind	1,806	10,605	9,965
.20	5,000	1/4" behind	1,700	10,146	9,363
.20	5,000	1/2" behind	1,905	8,866	9,052
.20	Dry Cut	Dry Cut	2,010	14,511	13,780
.20	10,000	1/8" behind	1,706	9,836	9,602
.20	10,000	1/4" behind	1,667	11,912	1,065
.20	10,000	1/2" behind	1,971	11,170	1,173
.20	Dry Cut	Dry Cut	2,010	14,511	13,780
.20	15,000	1/8" behind	1,905	10,227	1,061
.20	15,000	1/4" behind	1,866	12,720	1,132
.20	15,000	1/2" behind	1,805	12,181	1,073
.20	Dry Cut	Dry Cut	2,010	14,511	13,780
.20	20,000	1/8" behind	1,966	9,244	9,432
.20	20,000	1/4" behind	2,030	10,483	9,305
.20	20,000	1/2" behind	1,875	9,109	9,873

TABLE 3.3 - Results of Laboratory Linear Cutting Tests with Jet-Assisted Conical Bit in German Sandstone (0.025 inch nozzle, jet in front)

Bit Pen. (in.)	Jet Pressure (psi)	Jet Location	Side Force (lbs.)	Vertical Force (lbs.)	Drag Force (lbs.)
.10	Dry Cut	Dry Cut	433	6,317	4,065
.10	5,000	1/8" in front	181	5,402	3,463
.10	5,000	1/4" in front	247	5,583	3,862
.10	5,000	1/2" in front	181	6,270	3,676
.10	Dry Cut	Dry Cut	433	6,317	4,065
.10	10,000	1/8" in front	410	5,073	3,312
.10	10,000	1/4" in front	361	5,406	3,658
.10	10,000	1/2" in front	306	5,865	3,620
.10	Dry Cut	Dry Cut	433	6,317	4,065
.10	15,000	1/8" in front	387	4,943	3,064
.10	15,000	1/4" in front	567	5,522	3,639
.10	15,000	1/2" in front	331	6,128	3,709
.10	Dry Cut	Dry Cut	384	6,317	4,065
.10	20,000	1/8" in front	452	4,762	3,144
.10	20,000	1/4" in front	156	5,155	3,350
.10	20,000	1/2" in front	267	5,953	3,270

TABLE 3.3, Continued.

Bit Pen. (in.)	Jet Pressure (psi)	Jet Location	Side Force (lbs.)	Vertical Force (lbs.)	Drag Force (lbs.)
.20	Dry Cut	Dry Cut	918	10,210	6,126
.20	5,000	1/8" in front	692	8,906	5,505
.20	5,000	1/4" in front	781	8,160	5,132
.20	5,000	1/2" in front	705	8,315	5,490
.20	Dry Cut	Dry Cut	918	10,210	6,126
.20	10,000	1/8" in front	850	8,510	5,360
.20	10,000	1/4" in front	816	7,960	5,210
.20	10,000	1/2" in front	785	8,290	5,381
.20	Dry Cut	Dry Cut	918	10,210	6,126
.20	15,000	1/8" in front	784	8,189	5,143
.20	15,000	1/4" in front	812	7,637	5,501
.20	15,000	1/2" in front	858	8,055	5,453
.20	Dry Cut	Dry Cut	918	10,210	6,126
.20	20,000	1/8" in front	849	7,058	5,181
.20	20,000	1/4" in front	636	8,567	4,960
.20	20,000	1/2" in front	710	7,708	4,872

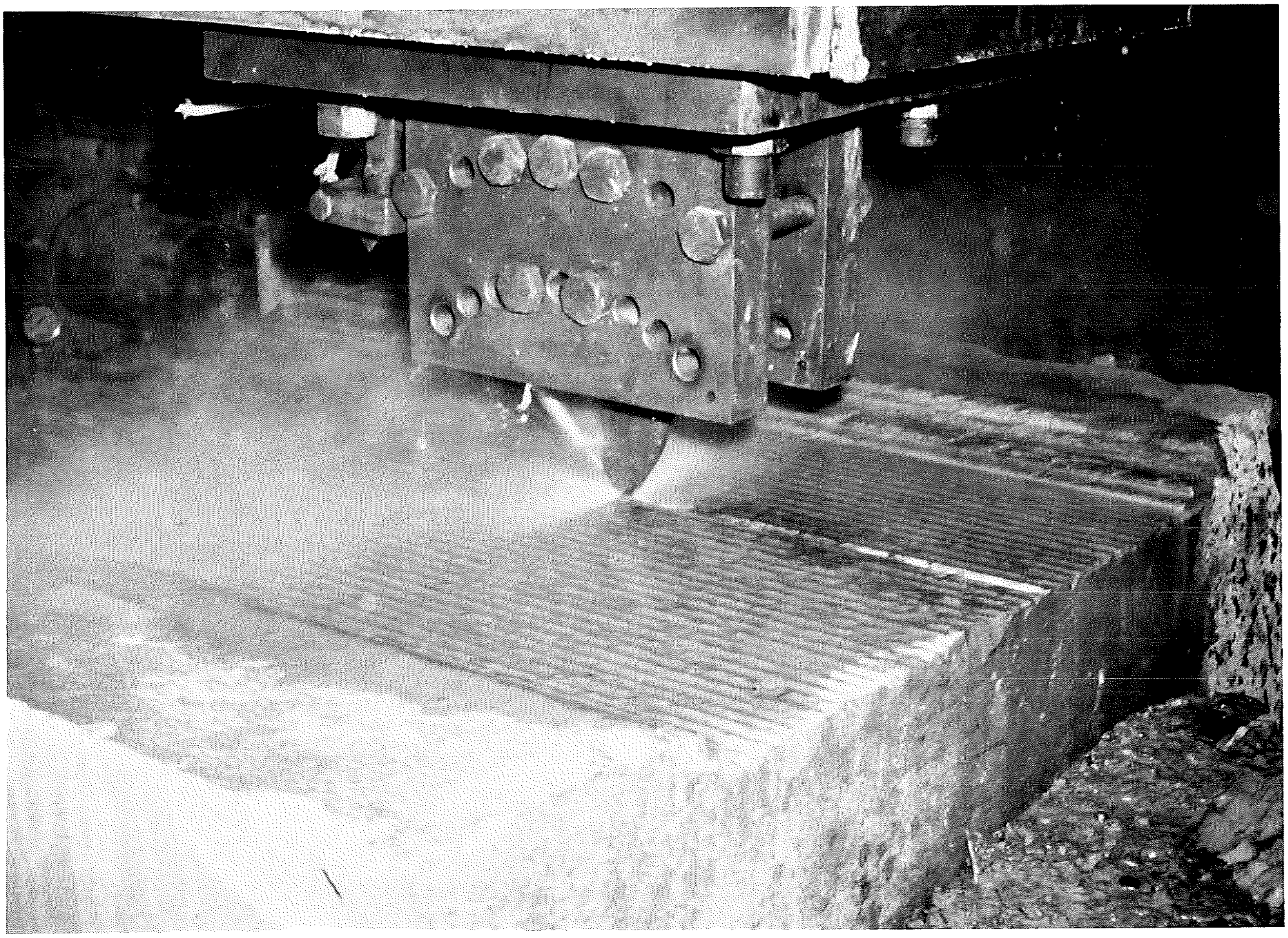


Figure 3.2. Testing of jet assisted plow bit on the linear cutter.

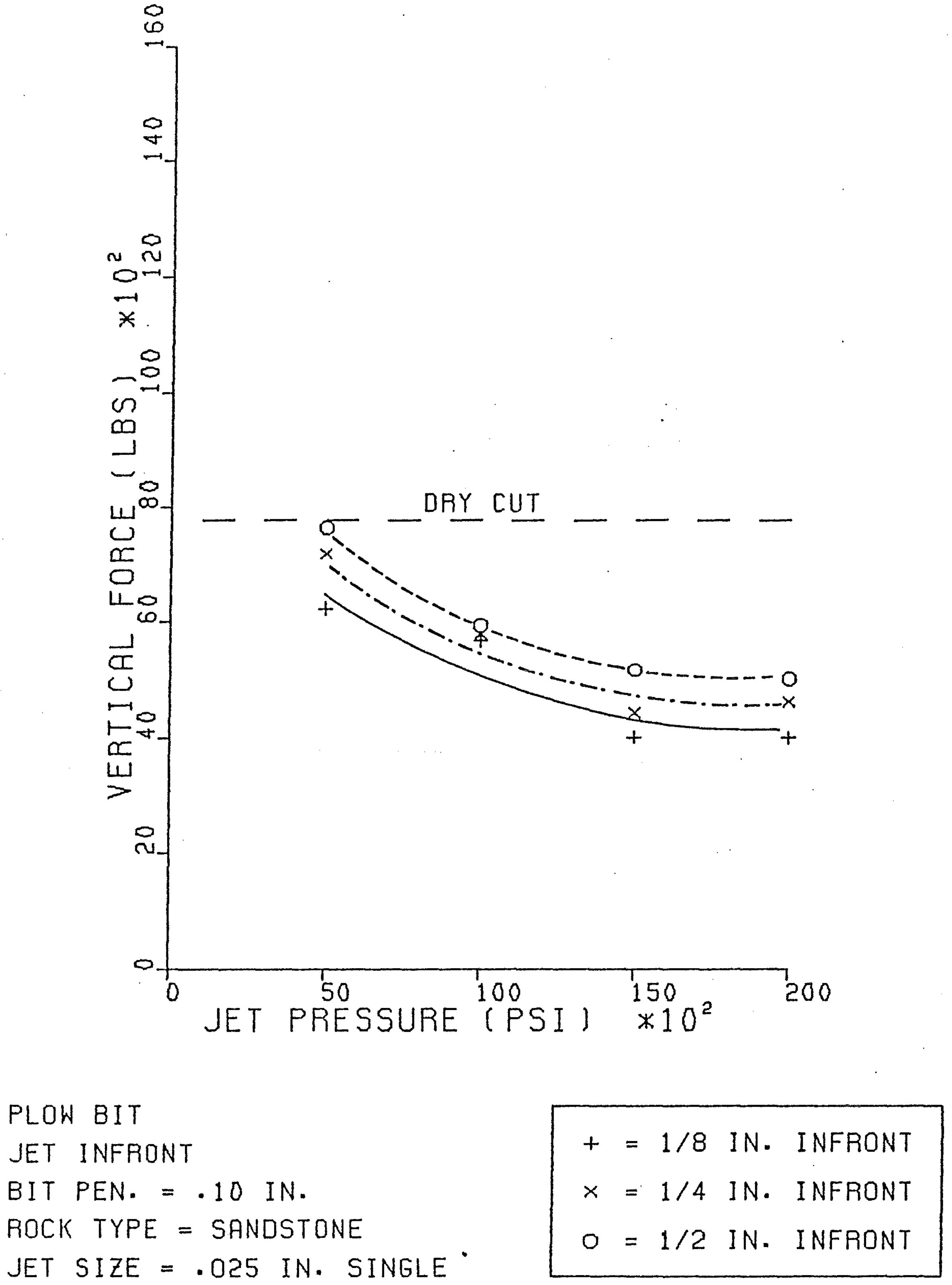
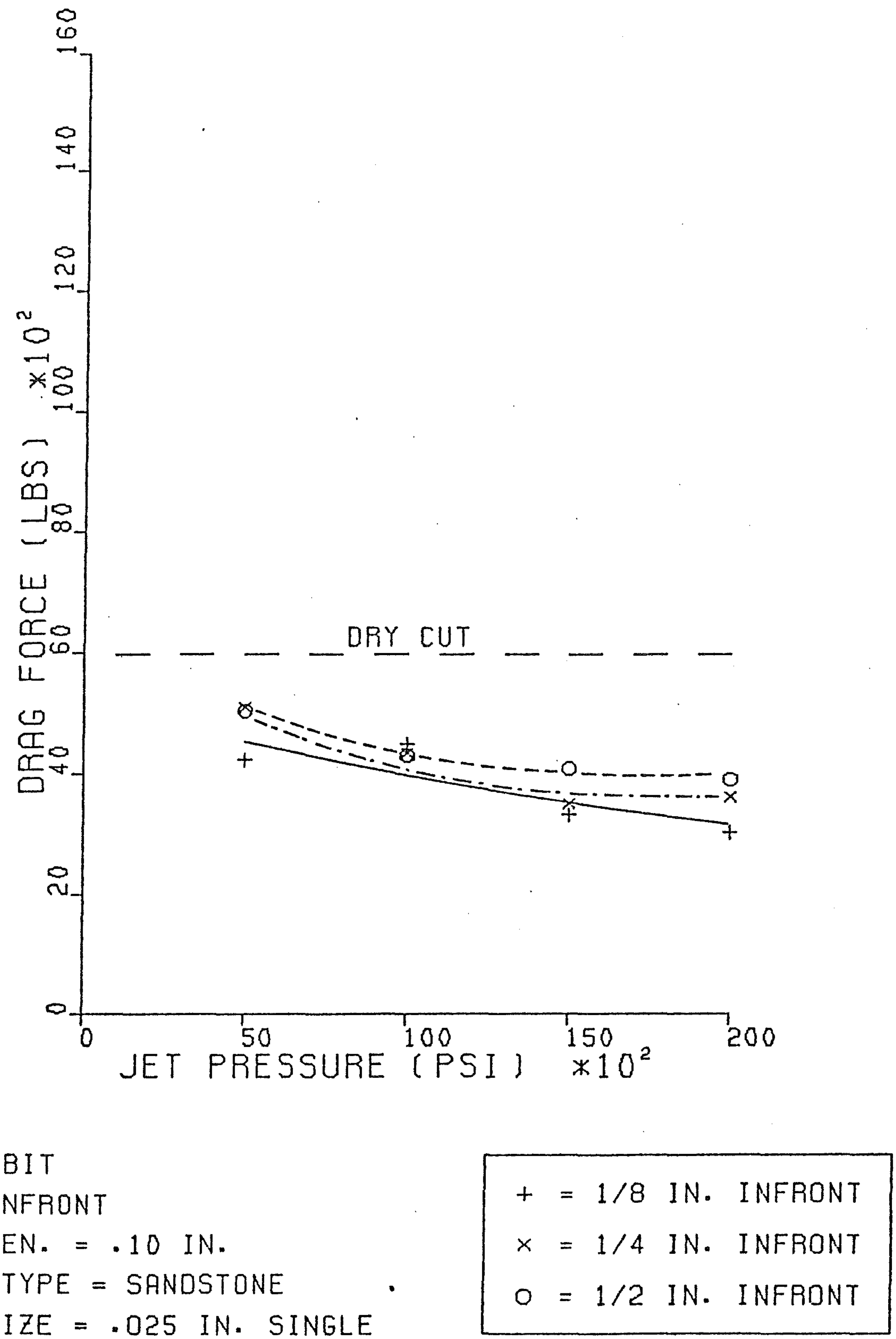

VERTICAL FORCE (LBS) *10²
0
20
40
60
80
100
120
140
160
DRY CUT
0
50
100
150
200
JET PRESSURE (PSI) *10²
PLOW BIT
JET INFRONT
BIT PEN. = .10 IN.
ROCK TYPE = SANDSTONE
JET SIZE = .025 IN. SINGLE
+ = 1/8 IN. INFRONT
× = 1/4 IN. INFRONT
o = 1/2 IN. INFRONT

Figure 3.4.



PLOW BIT
JET INFRONT
BIT PEN. = .10 IN.
ROCK TYPE = SANDSTONE
JET SIZE = .025 IN. SINGLE

Figure 3.5.

edge of the bit in order to produce the greatest degree of performance enhancement. In Figures 3.6. and 3.7., the same test results are displayed in terms of percent reduction in bit forces due to jet assist as compared to dry cutting only. As is evident from these graphs, bit force reductions approaching 50 percent were feasible at higher jet pressures and at the closest jet impingement location to the bit tip.

Figures 3.8. through 3.11. show the results of tests performed with the plow bit at a 0.20 inch penetration depth in German sandstone. As before, the jet for these tests was positioned in front of the bit and oriented to impinge the rock at a distance of 1/8 inch, 1/4 inch or 1/2 inch away from the bit tip. The trends depicted in these figures are very similar to those obtained with the same test parameters at a 0.10 depth of penetration. Again, the degree of bit force reductions with jet assist becomes greater with increasing pressure. Furthermore, as before, closest jet location to the bit provides the greatest reduction in bit forces. As previously noted, testing of the plow bit using jet assist included jet locations of both in front and behind the bit. The purpose of investigating both jet locations was to determine the best jet impingement location which would provide the greatest force reduction and the highest degree of enhancement in rock cutting performance. The test results for the case of jet behind the plow bit for two depths of penetration were presented earlier in Table 3.2. The graphical display of results at 0.10 inch penetration are given in Figures 3.12. and 3.13. The most important observation to be made from these plots concerns the jet pressure effects on bit force reductions. As indicated, contrary to what was obtained with jet positioning in front of the bit, increased pressure does not cause a further reduction in bit forces. In fact, the force trends plotted in Figures 3.12. through 3.15. point to the independence of bit performance enhancement from jet pressure.

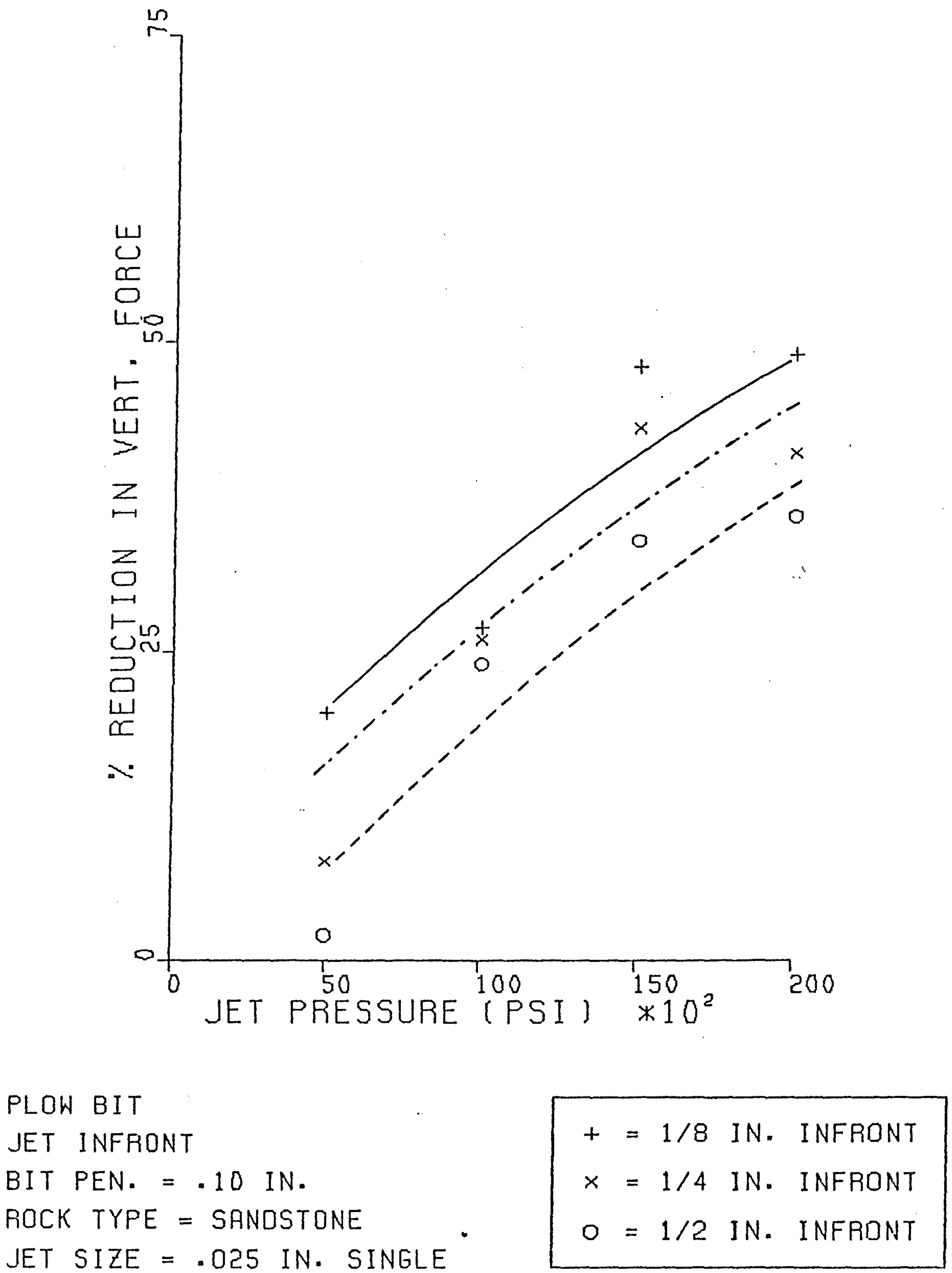
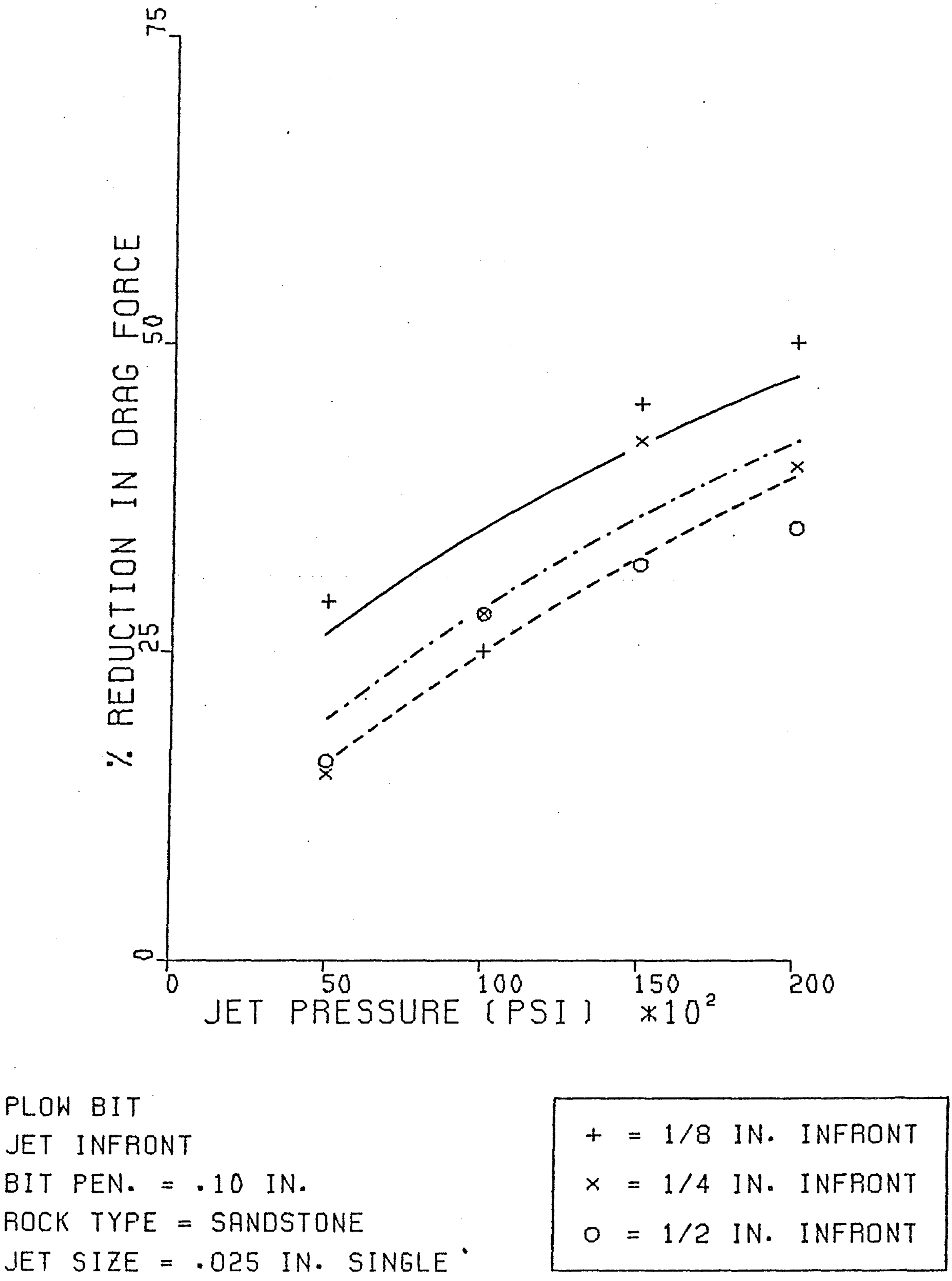

75
50
25
0
% REDUCTION IN VERT. FORCE
0
50
100
150
200
JET PRESSURE (PSI) *10²
PLOW BIT
JET INFRONT
BIT PEN. = .10 IN.
ROCK TYPE = SANDSTONE
JET SIZE = .025 IN. SINGLE
+ = 1/8 IN. INFRONT
× = 1/4 IN. INFRONT
o = 1/2 IN. INFRONT

Figure 3.6.



PLOW BIT
JET INFRONT
BIT PEN. = .10 IN.
ROCK TYPE = SANDSTONE
JET SIZE = .025 IN. SINGLE

Figure 3.7.

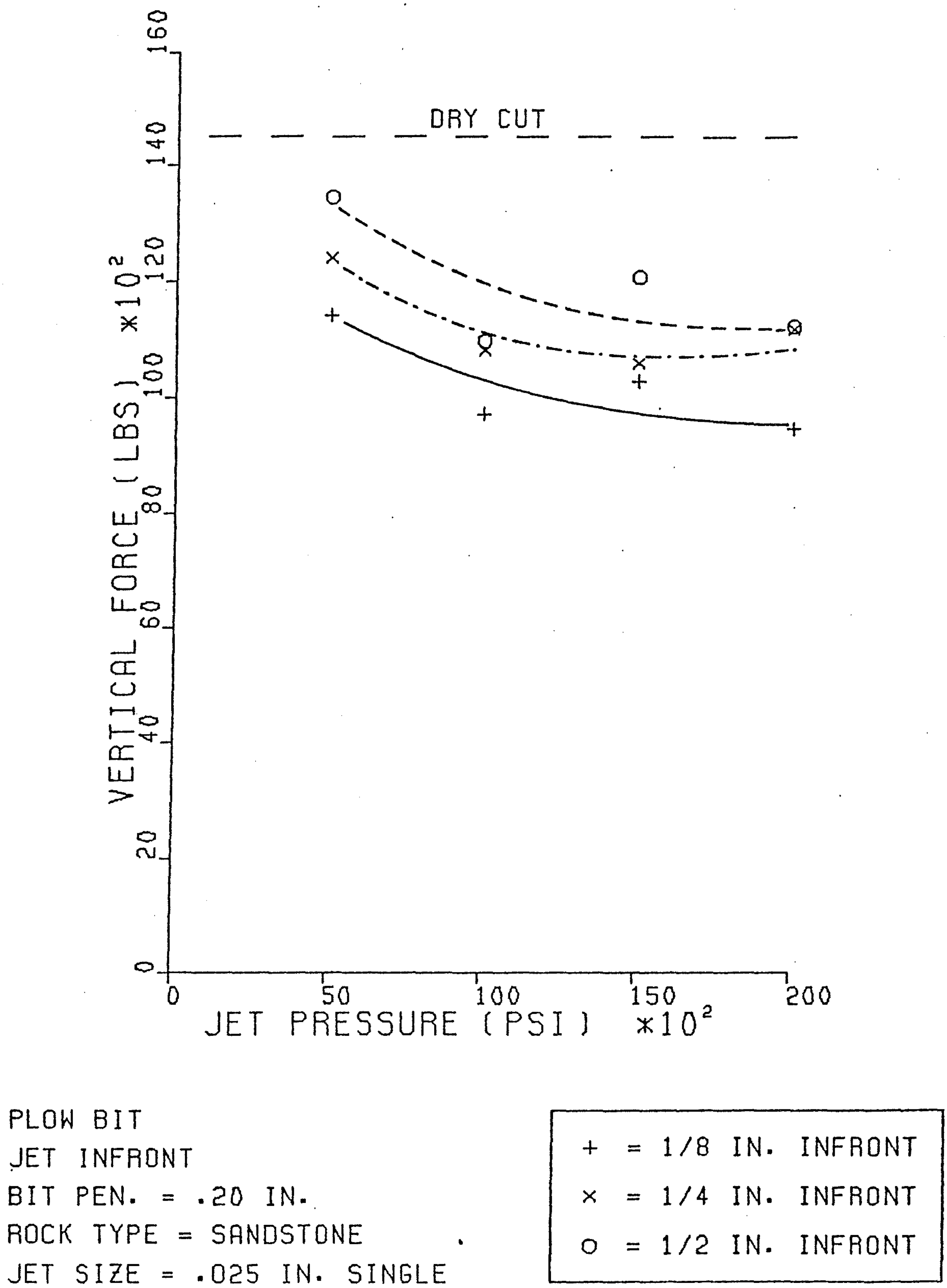

DRY CUT
VERTICAL FORCE (LBS) *10²
JET PRESSURE (PSI) *10²
0
20
40
60
80
100
120
140
160
0
50
100
150
200
PLOW BIT
JET INFRONT
BIT PEN. = .20 IN.
ROCK TYPE = SANDSTONE
JET SIZE = .025 IN. SINGLE
+ = 1/8 IN. INFRONT
× = 1/4 IN. INFRONT
○ = 1/2 IN. INFRONT

Figure 3.8.

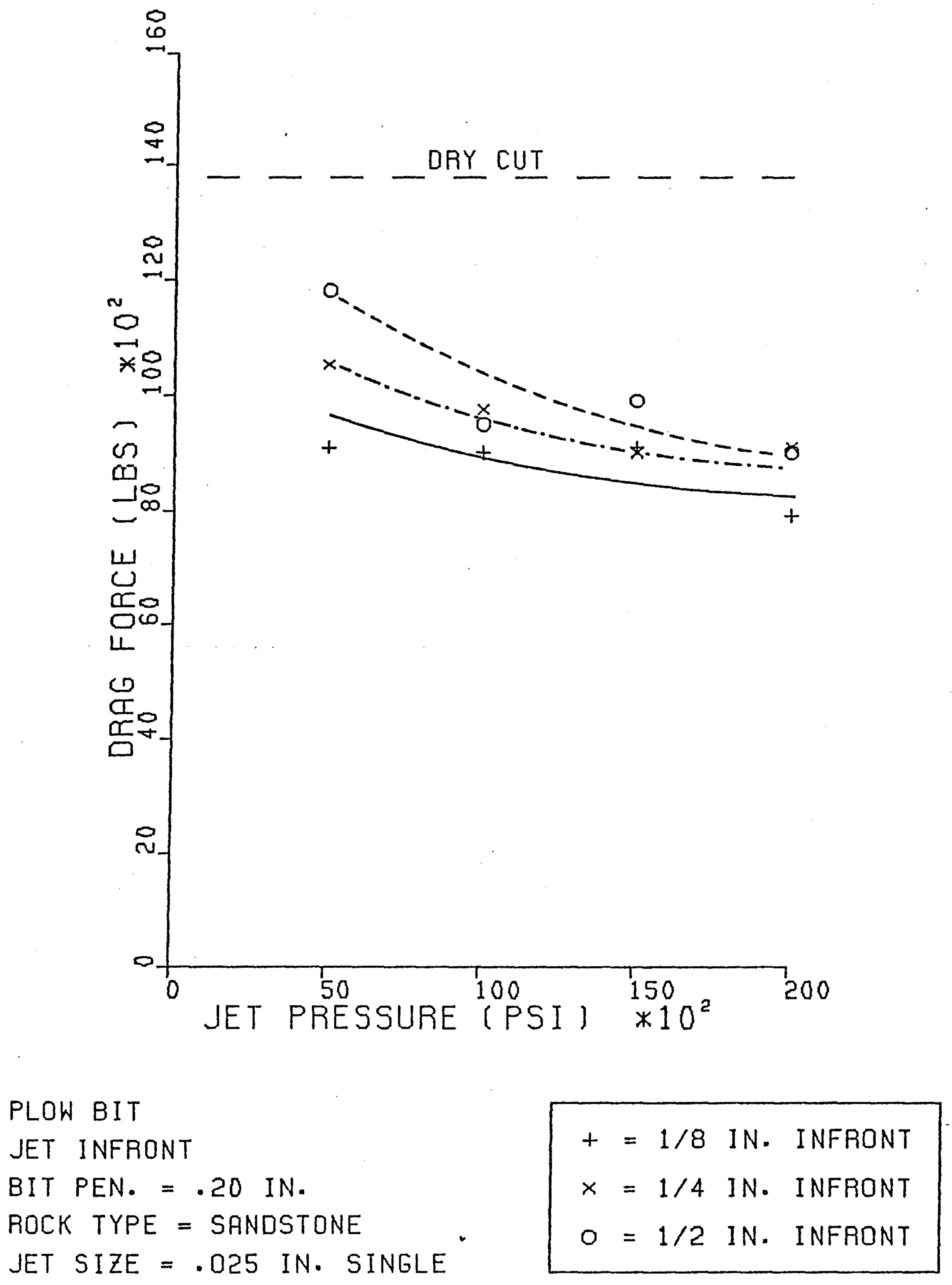

160
140
120
100
80
60
40
20
0
DRAG FORCE (LBS) *10²
DRY CUT
0
50
100
150
200
JET PRESSURE (PSI) *10²
PLOW BIT
JET INFRONT
BIT PEN. = .20 IN.
ROCK TYPE = SANDSTONE
JET SIZE = .025 IN. SINGLE
+ = 1/8 IN. INFRONT
× = 1/4 IN. INFRONT
o = 1/2 IN. INFRONT

Figure 3.9.

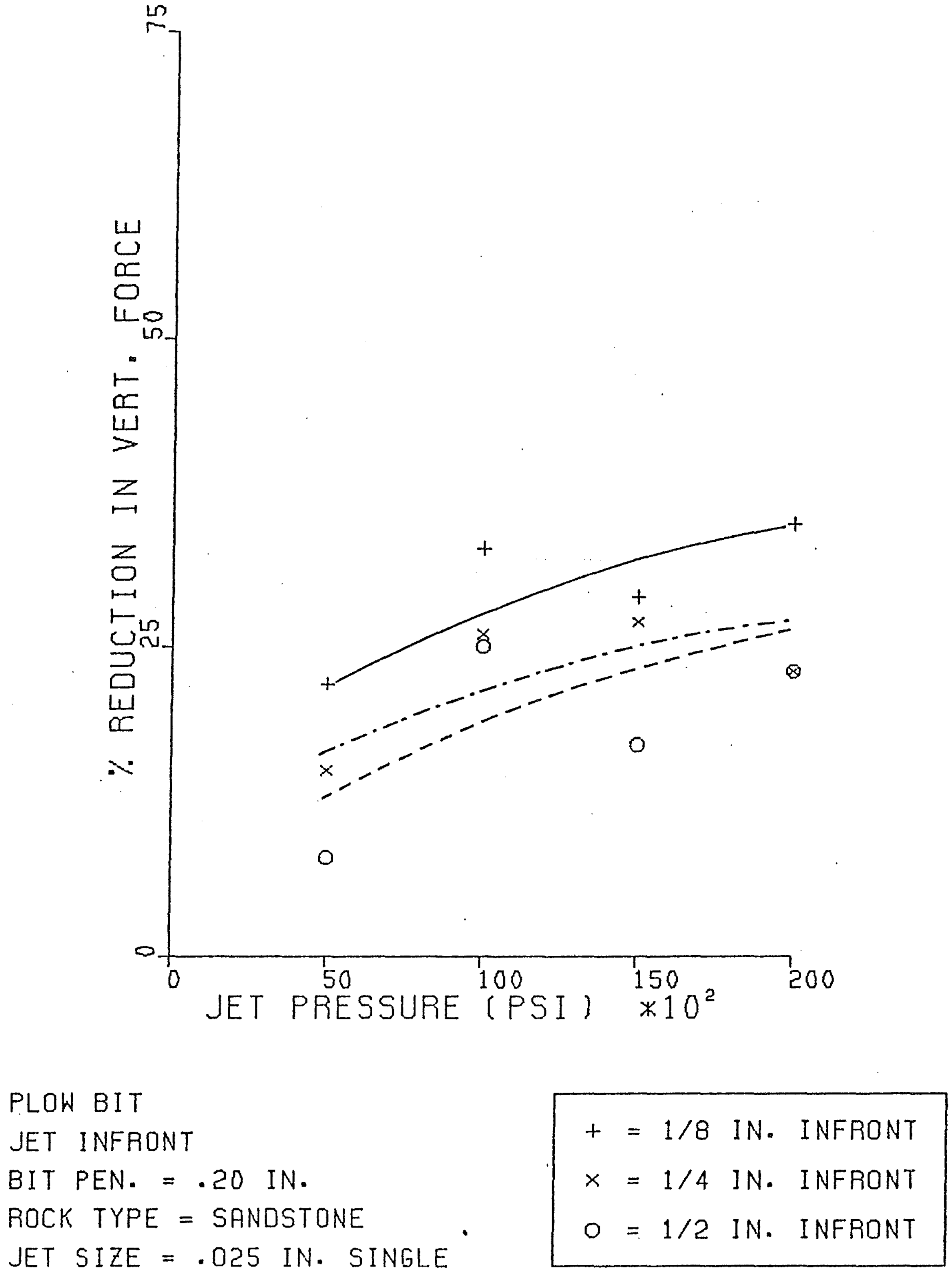

% REDUCTION IN VERT. FORCE
75
50
25
0
0
50
100
150
200
JET PRESSURE (PSI) *10²
PLOW BIT
JET INFRONT
BIT PEN. = .20 IN.
ROCK TYPE = SANDSTONE
JET SIZE = .025 IN. SINGLE
+ = 1/8 IN. INFRONT
× = 1/4 IN. INFRONT
o = 1/2 IN. INFRONT

Figure 3.10.

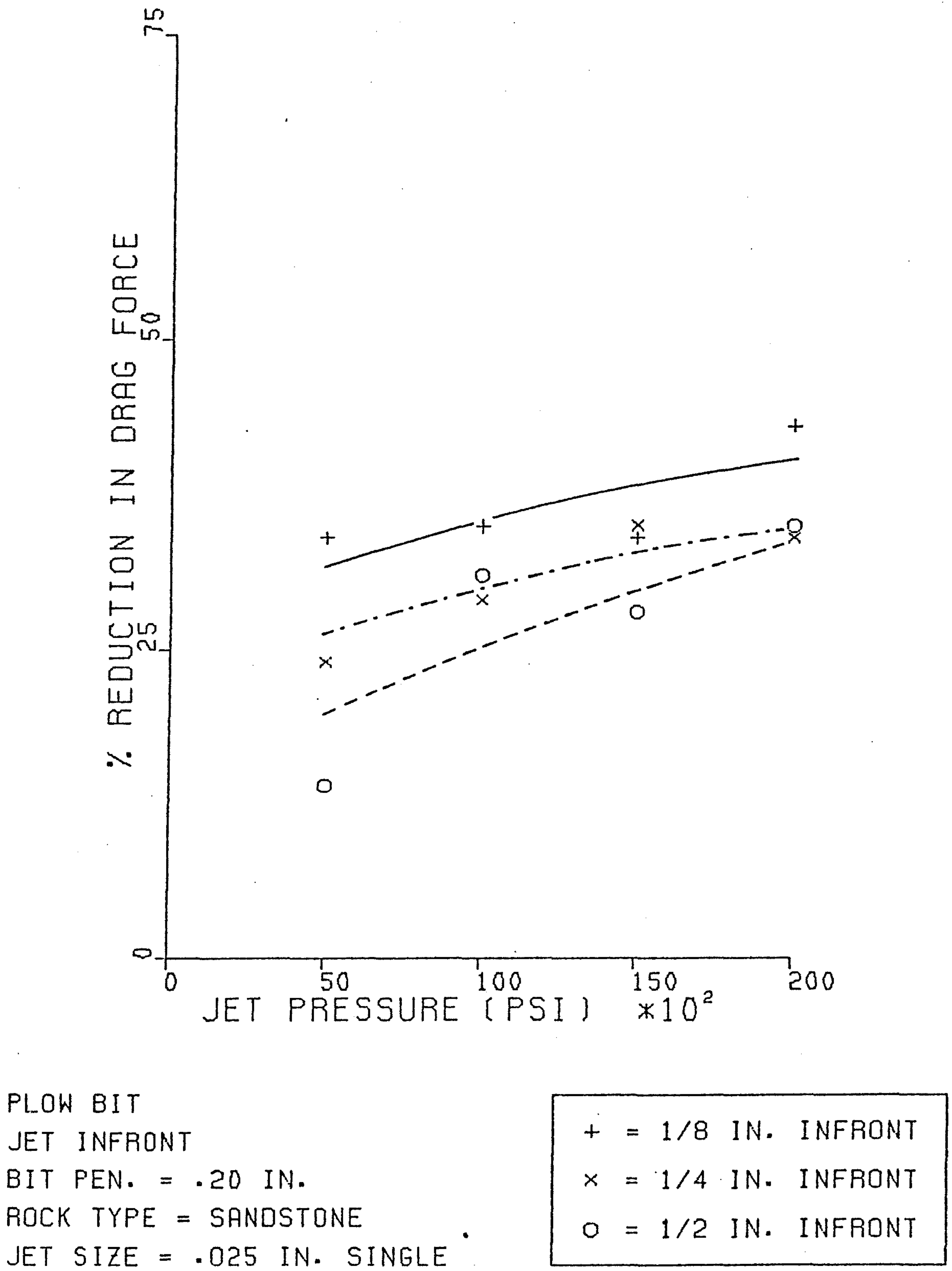
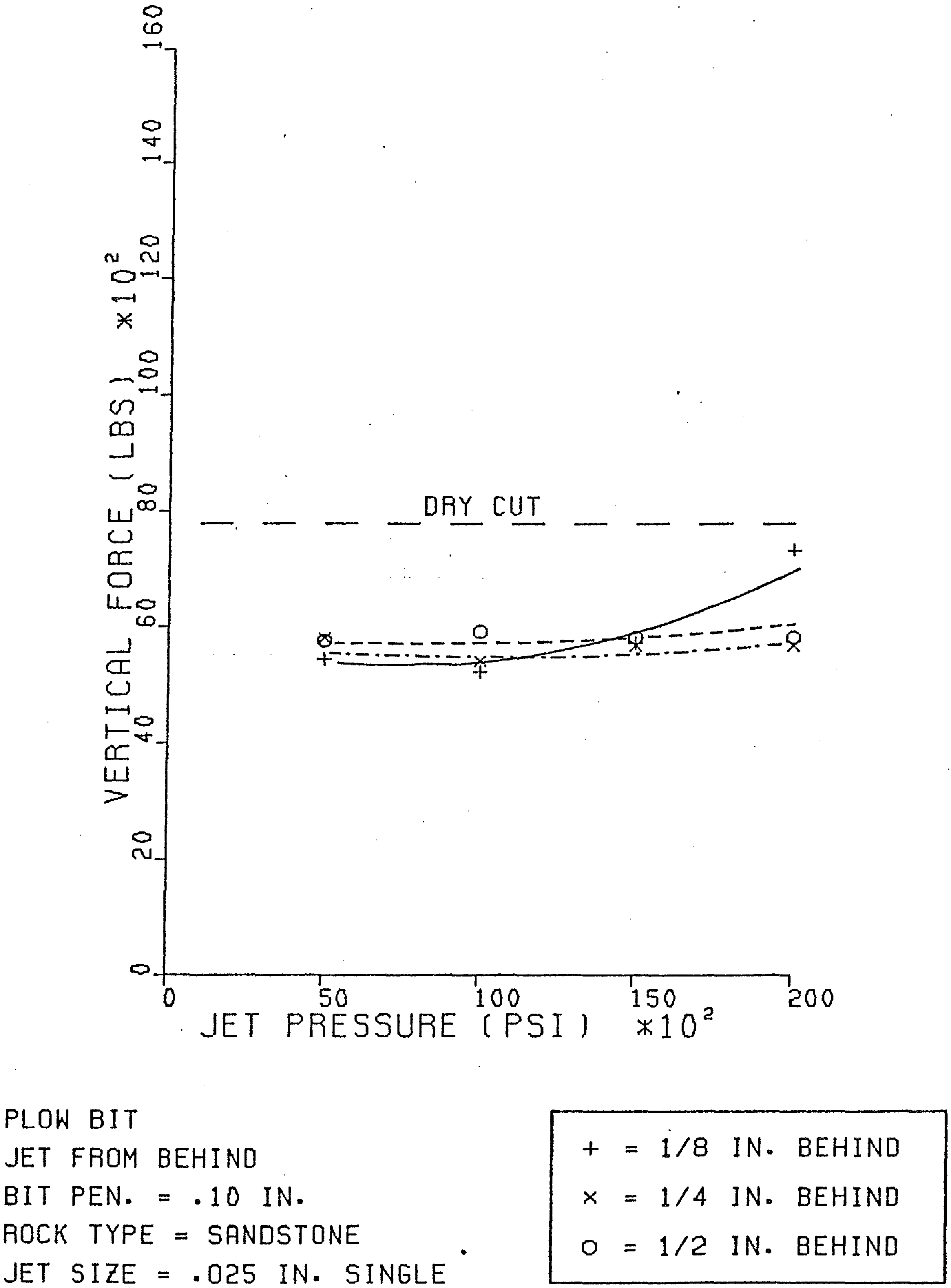
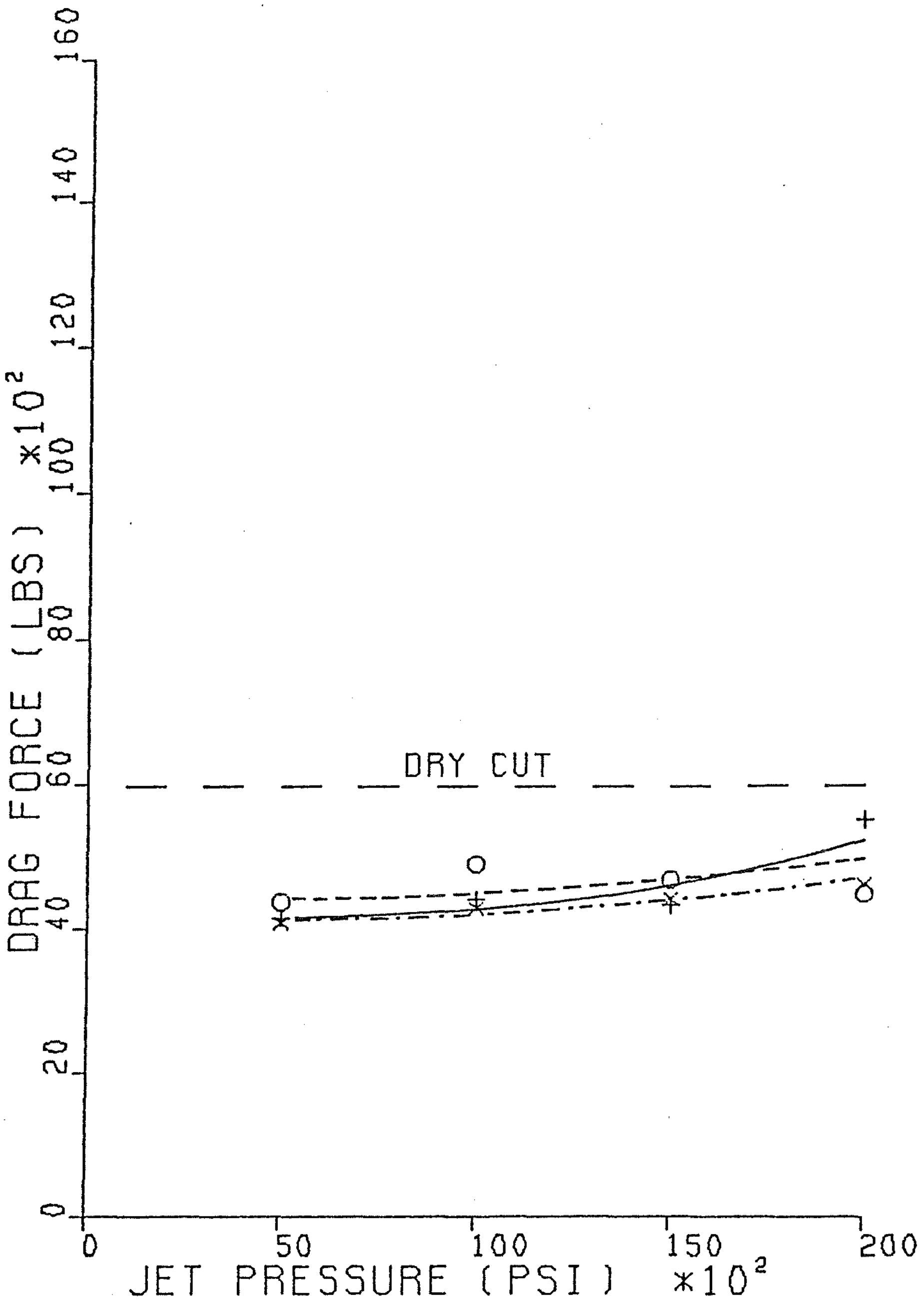

75
50
25
0
% REDUCTION IN DRAG FORCE
0
50
100
150
200
JET PRESSURE (PSI) *10²
PLOW BIT
JET INFRONT
BIT PEN. = .20 IN.
ROCK TYPE = SANDSTONE
JET SIZE = .025 IN. SINGLE
+ = 1/8 IN. INFRONT
× = 1/4 IN. INFRONT
o = 1/2 IN. INFRONT

Figure 3.11.



PLOW BIT
JET FROM BEHIND
BIT PEN. = .10 IN.
ROCK TYPE = SANDSTONE
JET SIZE = .025 IN. SINGLE

Figure 3.12.



PLOW BIT
JET FROM BEHIND
BIT PEN. = .10 IN.
ROCK TYPE = SANDSTONE
JET SIZE = .025 IN. SINGLE

+ = 1/8 IN. BEHIND
× = 1/4 IN. BEHIND
○ = 1/2 IN. BEHIND

Figure 3.13.

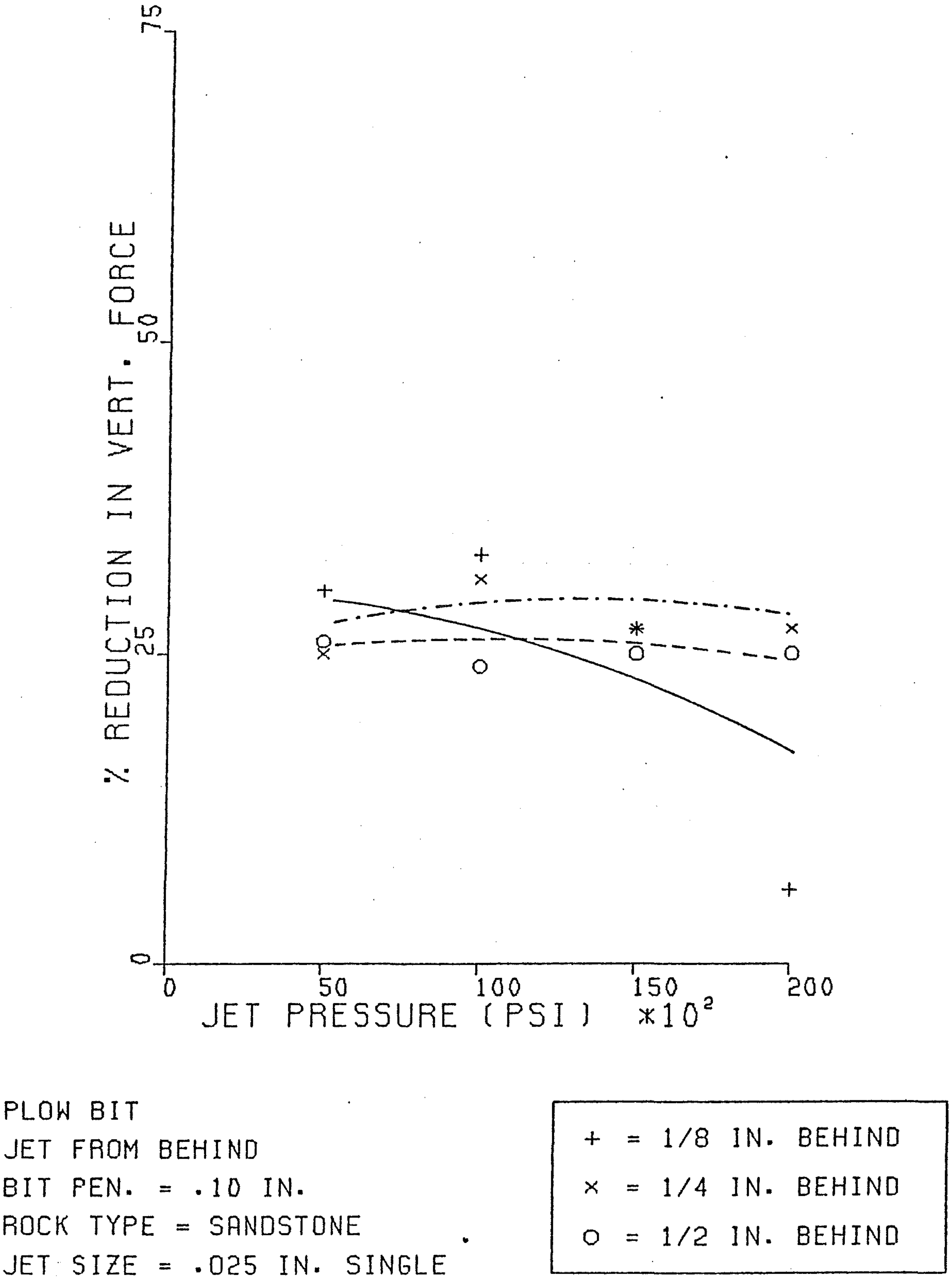
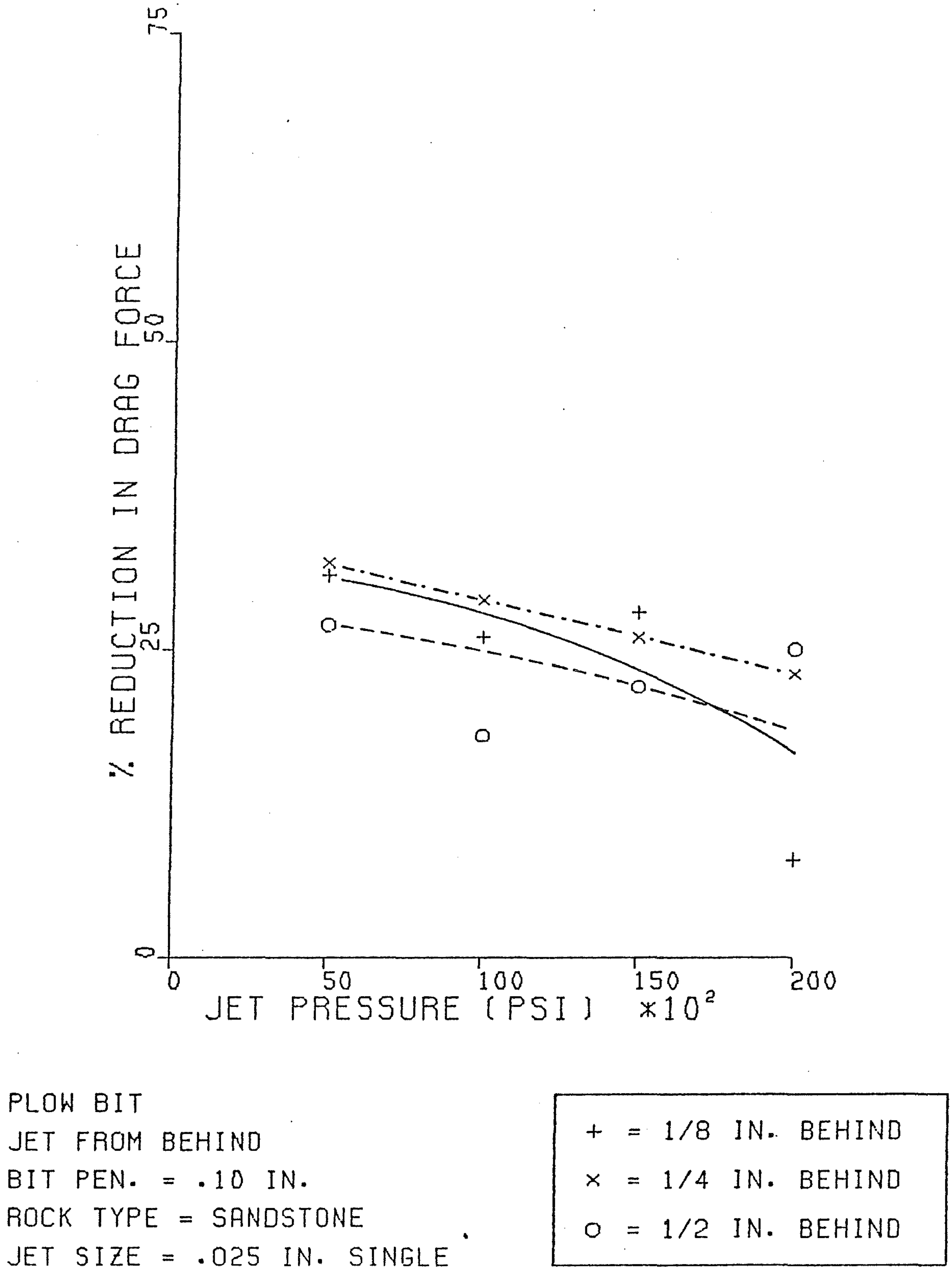

% REDUCTION IN VERT. FORCE
0
25
50
75
0
50
100
150
200
JET PRESSURE (PSI) *10²
PLOW BIT
JET FROM BEHIND
BIT PEN. = .10 IN.
ROCK TYPE = SANDSTONE
JET SIZE = .025 IN. SINGLE
+ = 1/8 IN. BEHIND
× = 1/4 IN. BEHIND
○ = 1/2 IN. BEHIND

Figure 3.14.



PLOW BIT
JET FROM BEHIND
BIT PEN. = .10 IN.
ROCK TYPE = SANDSTONE
JET SIZE = .025 IN. SINGLE

Figure 3.15.

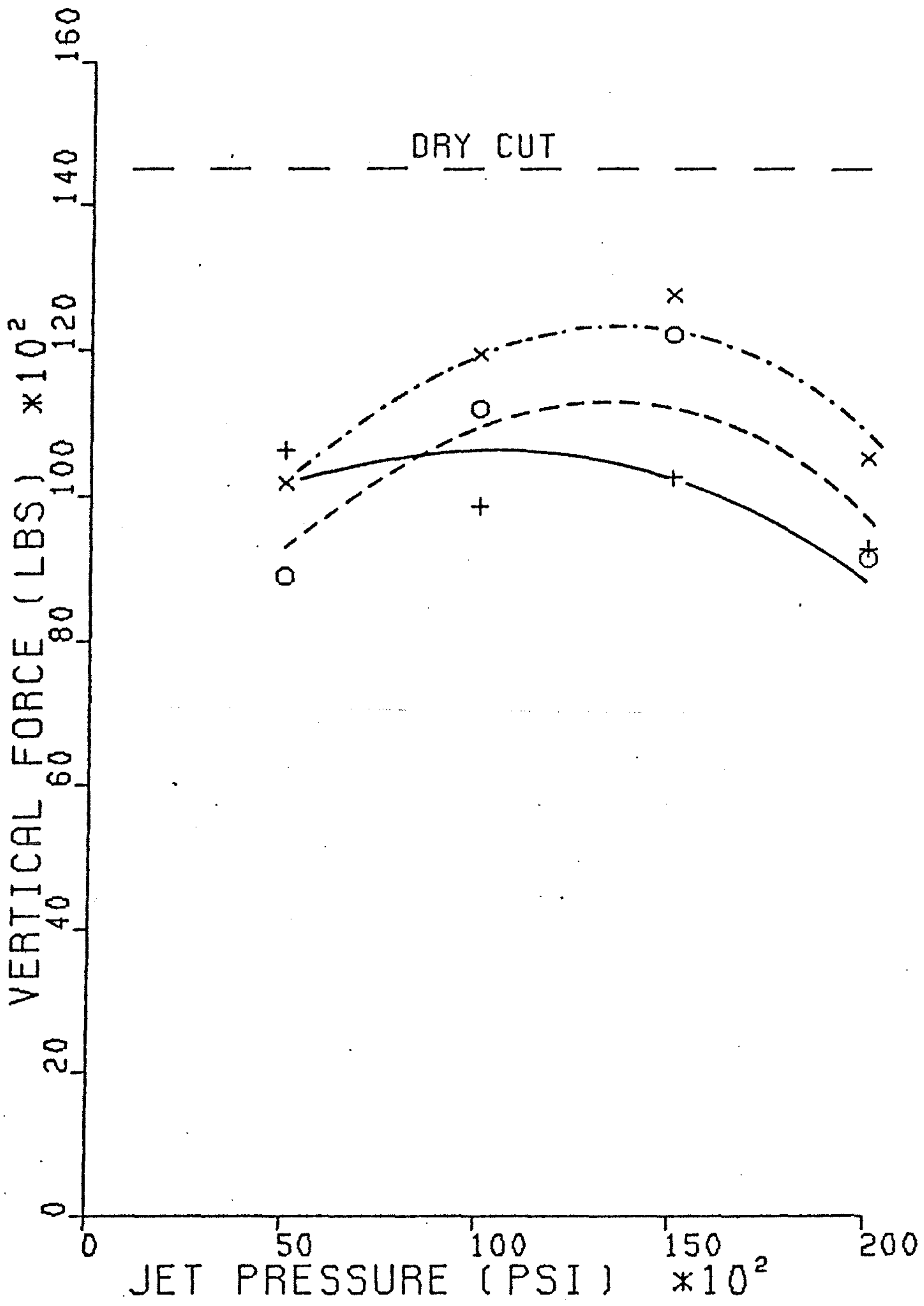
Moreover, especially for the drag force component, increased pressure appears to create a drop in the percent force reduction obtained compared to dry cutting, as shown in Figure 3.15.

For jet assisted cutting at 0.20 inch depth of penetration, with jet positioned to strike the rock from behind the plow bit, the test results are shown in Figures 3.16. through 3.19. Although data exhibits an appreciable amount of scatter, it is indicated that as with the shallow penetration, the reduction of bit forces due to jet assist appears essentially independent of jet pressure. Thus, based on overall test results for the arrangement where the jet is located behind the plow bit, the analysis of results indicate that the degree of force reductions brought about by jet assist remain fairly constant with respect to jet pressure.

The conical bit was also tested with jet assist at two different penetrations in German sandstone. As discussed earlier, only the position of jet in front could be investigated in testing of the conical bit. The jet location behind the bit could not be tested due to particular bit geometry such that jet would not clear the bit shank in order to impinge in the immediate vicinity of bit tip.

Figures 3.20. through 3.23. show the results of tests performed at 0.10 in. depth of penetration with jet positioned in front of the conical bit. Increased pressure is seen to cause a greater reduction in bit forces, although the effect is considerably less than that observed in tests with jet placed in front of the plow bit. Again, jet location closest to the bit tip results in greatest force reductions. Similar trends are also observed in results of tests carried out at 0.20 in. penetration, as shown in Figures 3.24. through 3.27.

Additional pictures of linear cutting tests are shown in Figures 3.28. through 3.31.



PLOW BIT
JET FROM BEHIND
BIT PEN. = .20 IN.
ROCK TYPE = SANDSTONE
JET SIZE = .025 IN. SINGLE

+ = 1/8 IN. BEHIND
× = 1/4 IN. BEHIND
o = 1/2 IN. BEHIND

Figure 3.16.

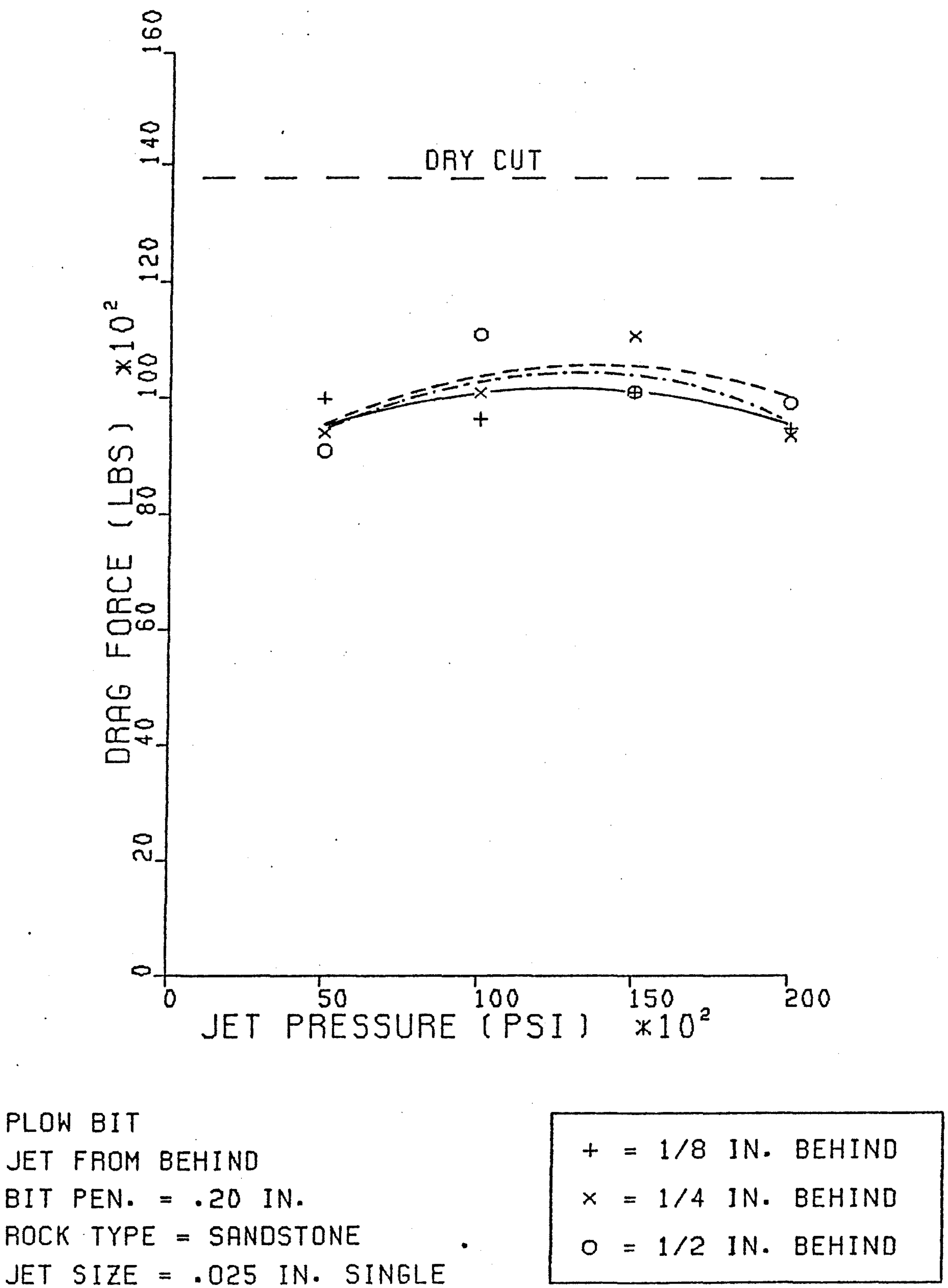

DRY CUT
DRAG FORCE (LBS) ×10²
0
20
40
60
80
100
120
140
160
JET PRESSURE (PSI) ×10²
0
50
100
150
200
PLOW BIT
JET FROM BEHIND
BIT PEN. = .20 IN.
ROCK TYPE = SANDSTONE
JET SIZE = .025 IN. SINGLE
+ = 1/8 IN. BEHIND
× = 1/4 IN. BEHIND
o = 1/2 IN. BEHIND

Figure 3.17.

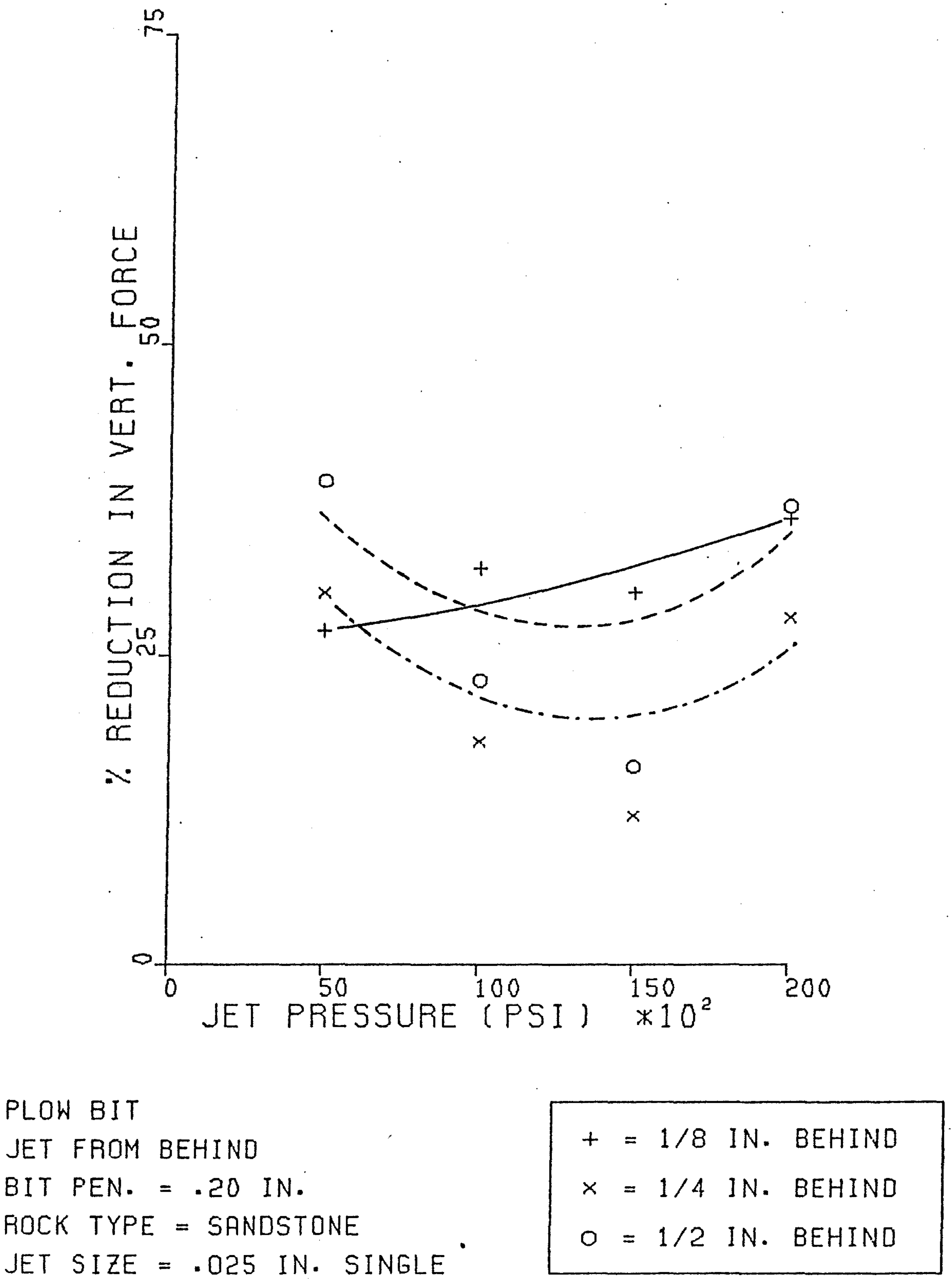
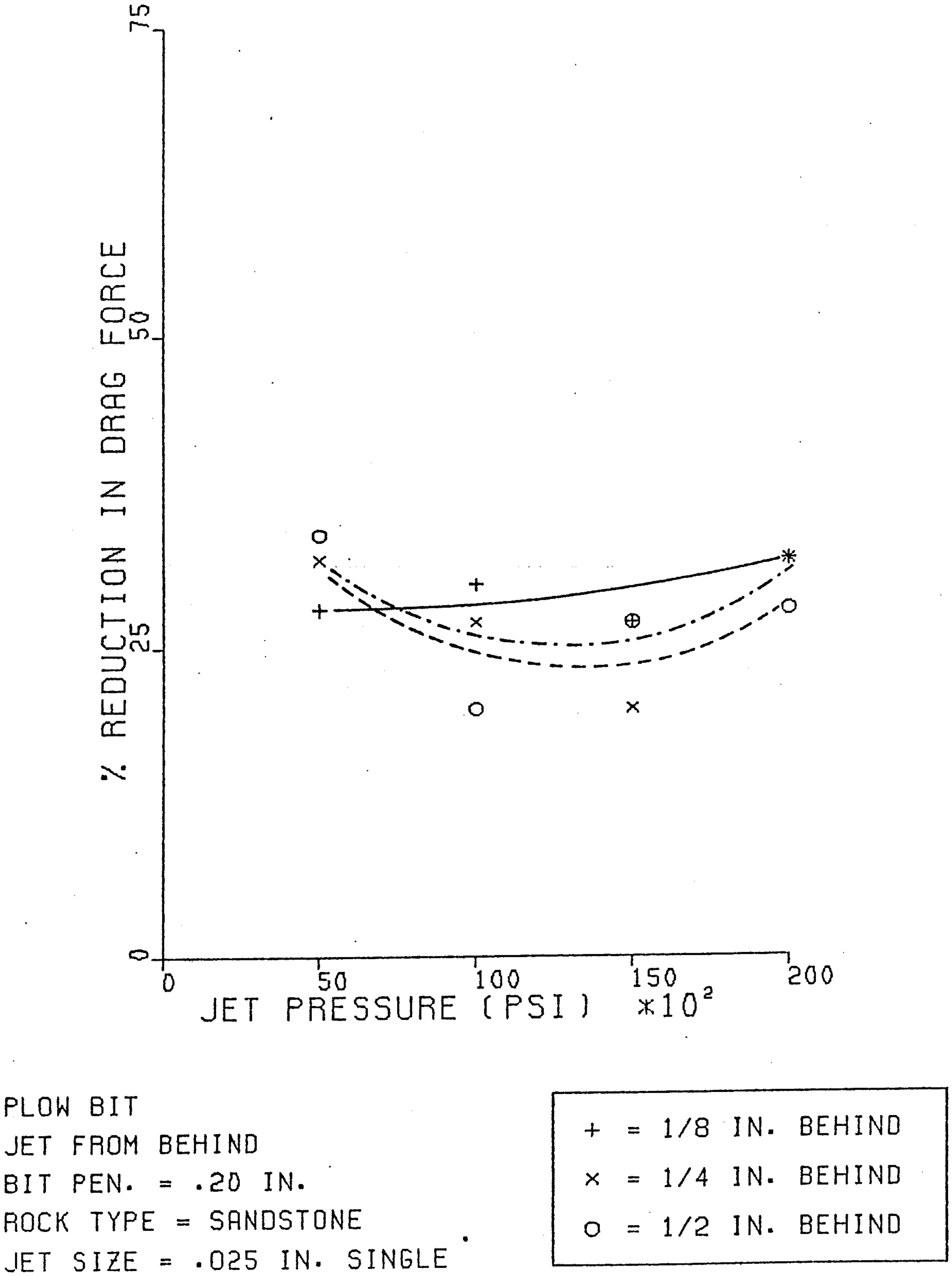
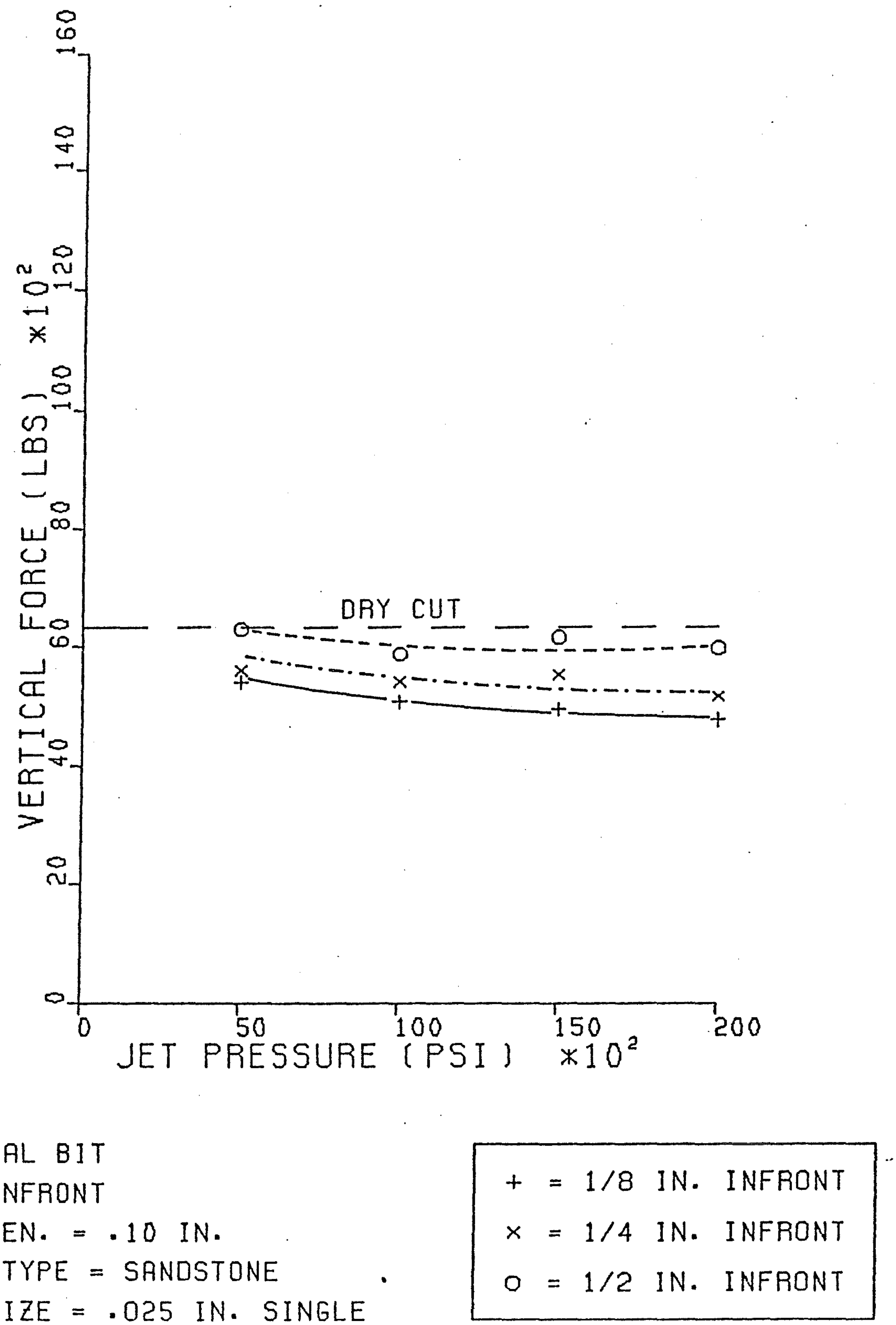

% REDUCTION IN VERT. FORCE
0
25
50
75
0
50
100
150
200
JET PRESSURE (PSI) *10²
PLOW BIT
JET FROM BEHIND
BIT PEN. = .20 IN.
ROCK TYPE = SANDSTONE
JET SIZE = .025 IN. SINGLE
+ = 1/8 IN. BEHIND
× = 1/4 IN. BEHIND
o = 1/2 IN. BEHIND

Figure 3.18.



PLOW BIT
JET FROM BEHIND
BIT PEN. = .20 IN.
ROCK TYPE = SANDSTONE
JET SIZE = .025 IN. SINGLE

Figure 3.19.



CONICAL BIT
JET INFRONT
BIT PEN. = .10 IN.
ROCK TYPE = SANDSTONE
JET SIZE = .025 IN. SINGLE

Figure 3.20.

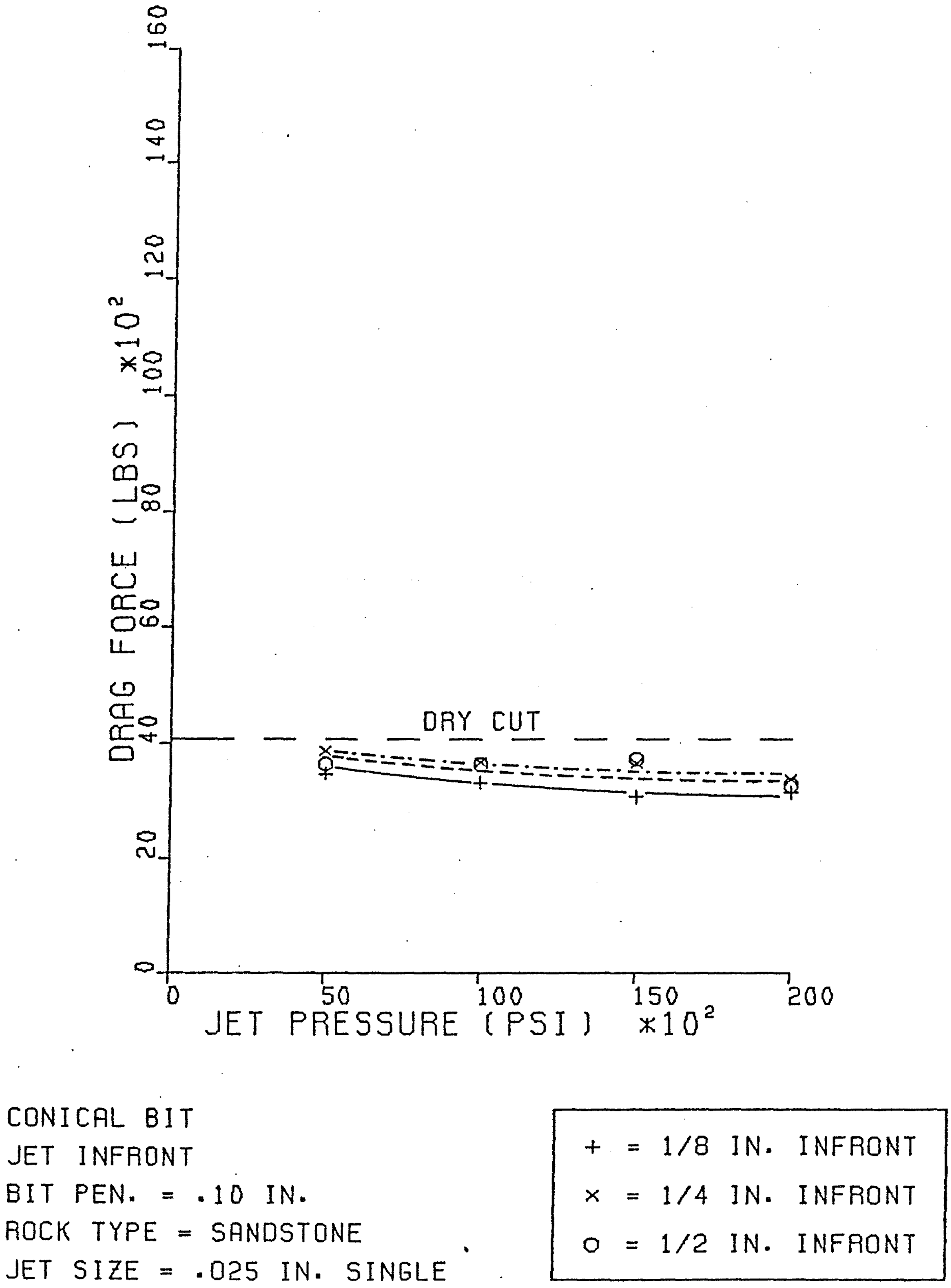

DRAG FORCE (LBS) $\times 10^2$
0
20
40
60
80
100
120
140
160
DRY CUT
0
50
100
150
200
JET PRESSURE (PSI) $\times 10^2$
CONICAL BIT
JET INFRONT
BIT PEN. = .10 IN.
ROCK TYPE = SANDSTONE
JET SIZE = .025 IN. SINGLE
+ = 1/8 IN. INFRONT
× = 1/4 IN. INFRONT
○ = 1/2 IN. INFRONT

Figure 3.21.

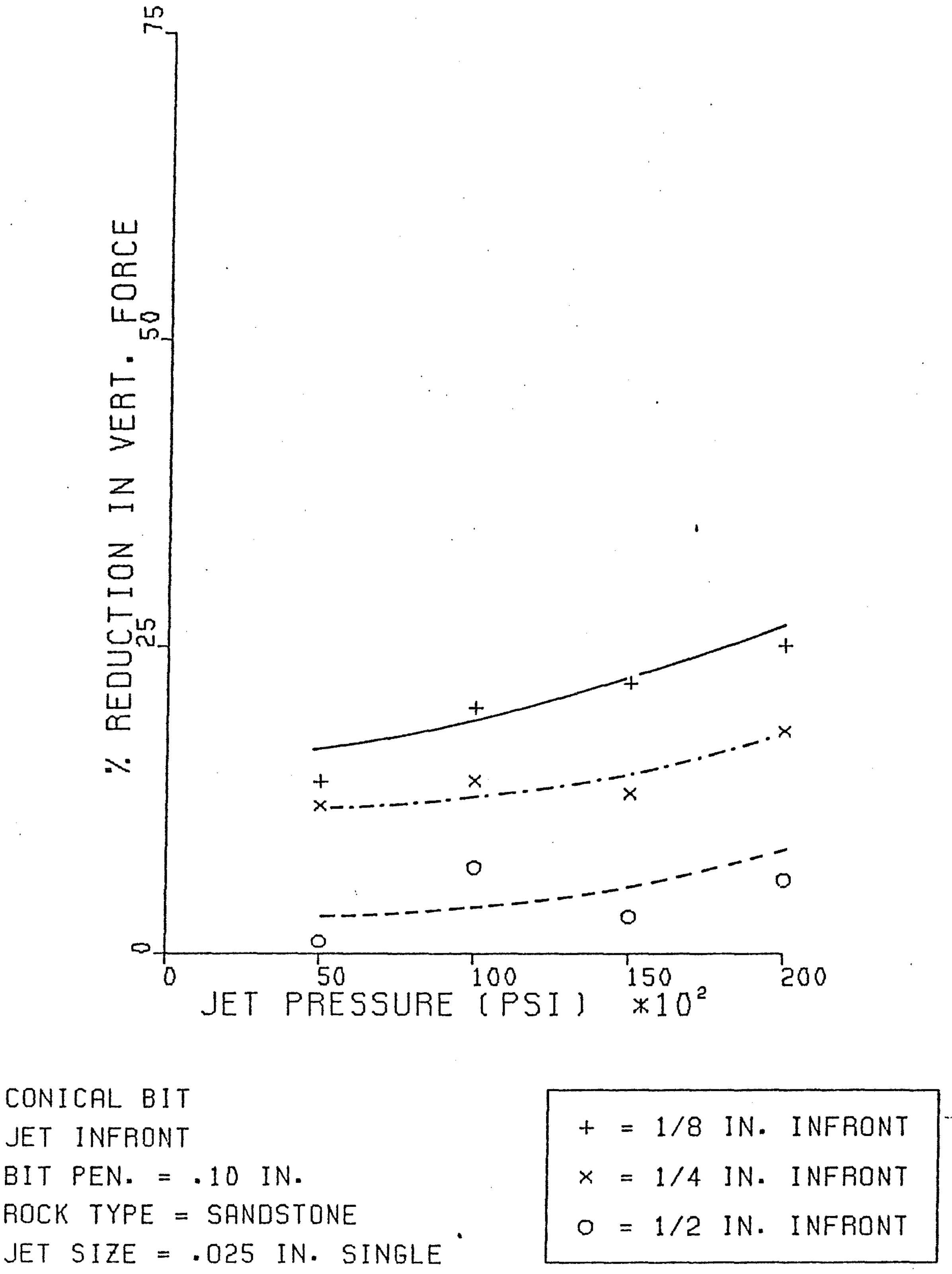
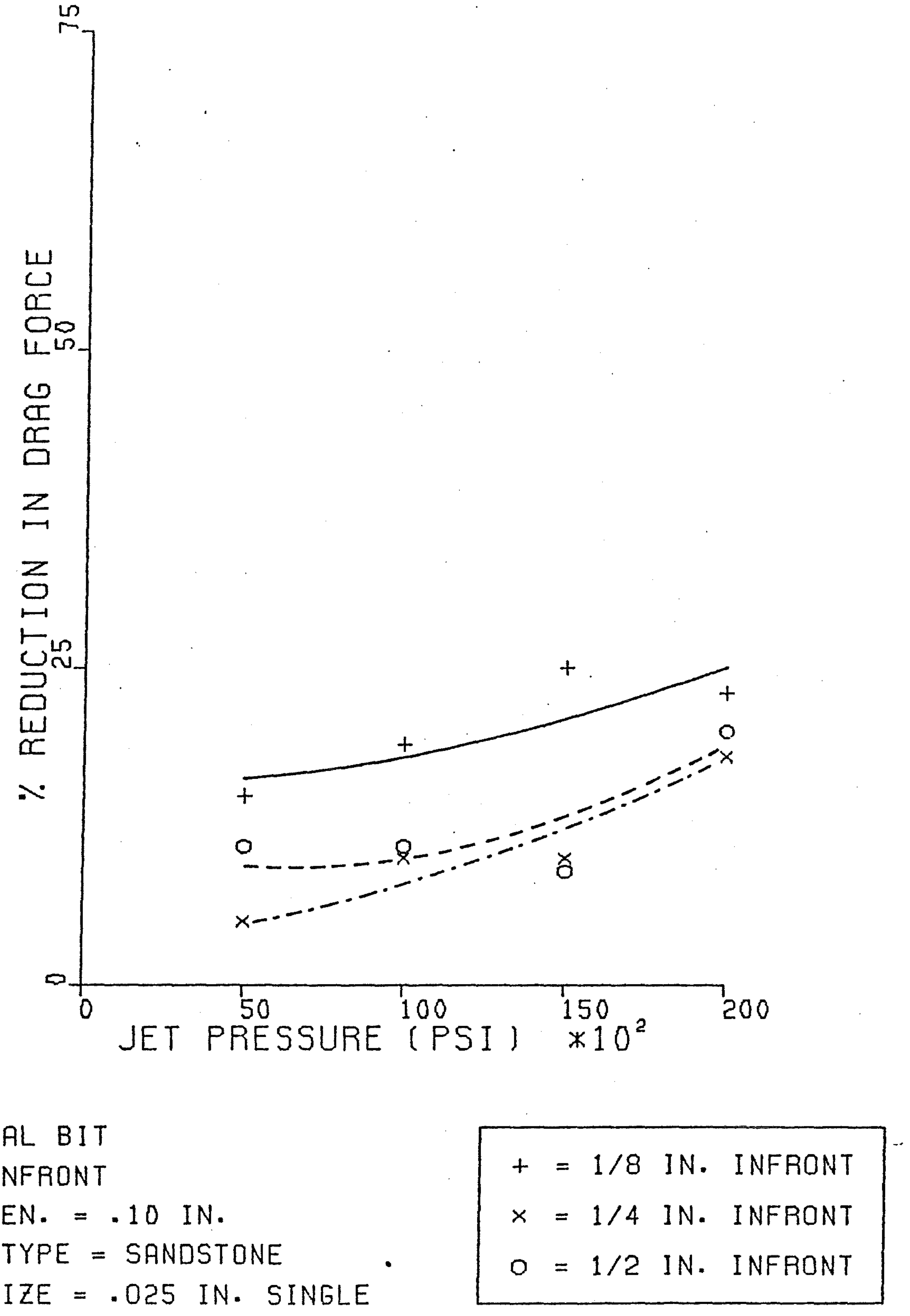

% REDUCTION IN VERT. FORCE
0
25
50
75
0
50
100
150
200
JET PRESSURE (PSI) *10²
CONICAL BIT
JET INFRONT
BIT PEN. = .10 IN.
ROCK TYPE = SANDSTONE
JET SIZE = .025 IN. SINGLE
+ = 1/8 IN. INFRONT
× = 1/4 IN. INFRONT
o = 1/2 IN. INFRONT

Figure 3.22.



CONICAL BIT
JET INFRONT
BIT PEN. = .10 IN.
ROCK TYPE = SANDSTONE
JET SIZE = .025 IN. SINGLE

Figure 3.23.

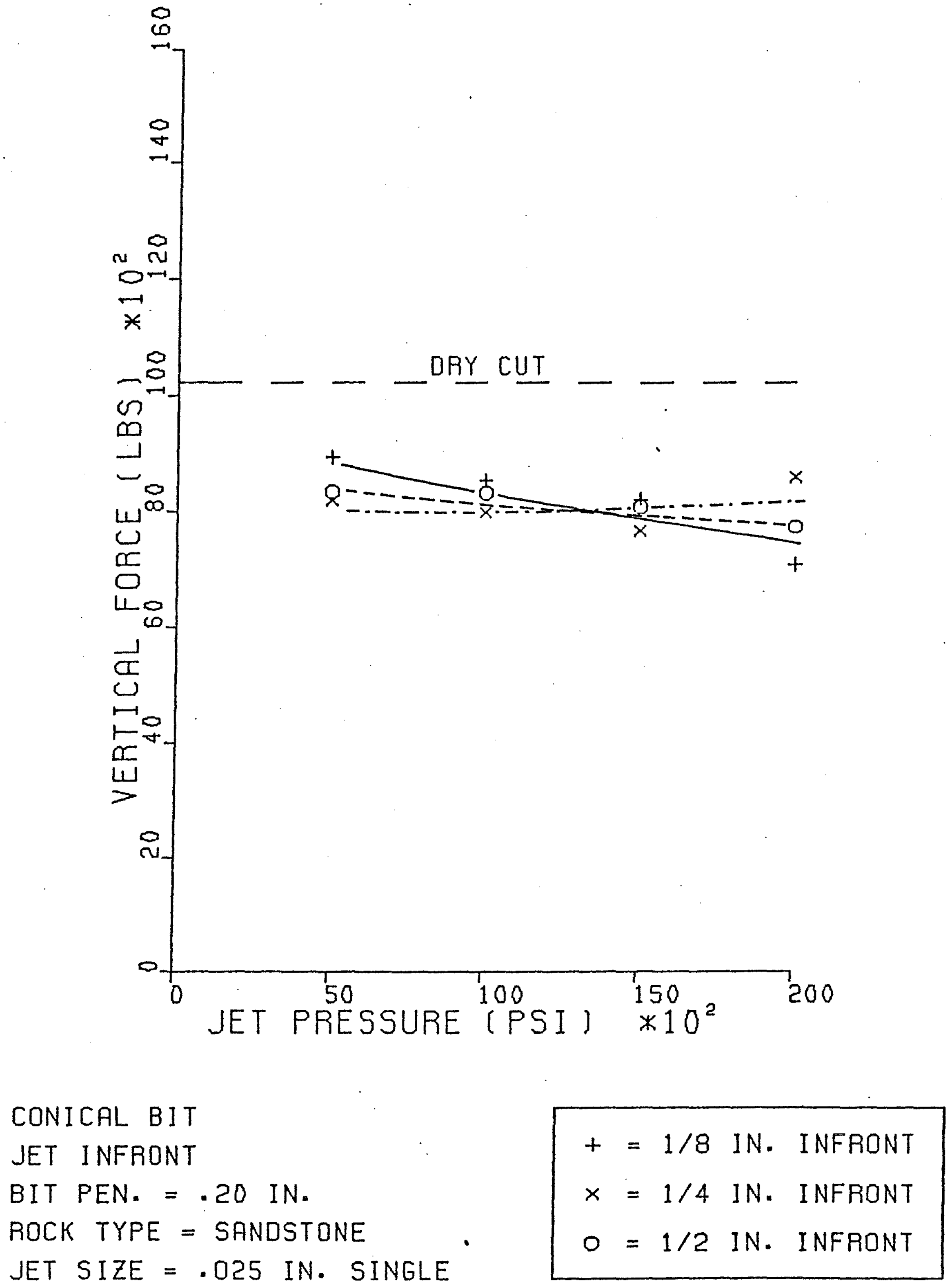

VERTICAL FORCE (LBS) *10²
0
20
40
60
80
100
120
140
160
DRY CUT
JET PRESSURE (PSI) *10²
0
50
100
150
200
CONICAL BIT
JET INFRONT
BIT PEN. = .20 IN.
ROCK TYPE = SANDSTONE
JET SIZE = .025 IN. SINGLE
+ = 1/8 IN. INFRONT
× = 1/4 IN. INFRONT
○ = 1/2 IN. INFRONT

Figure 3.24.

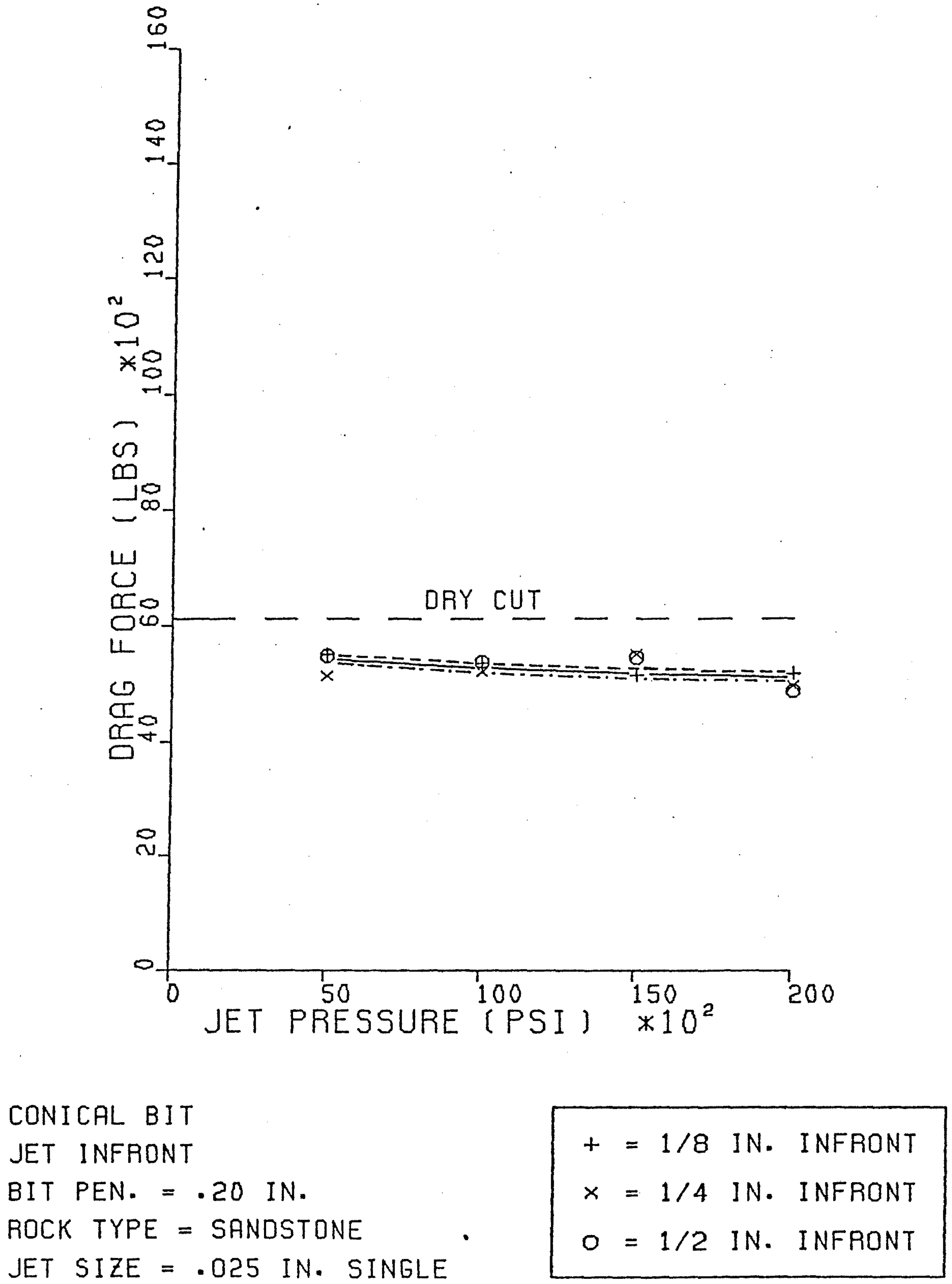
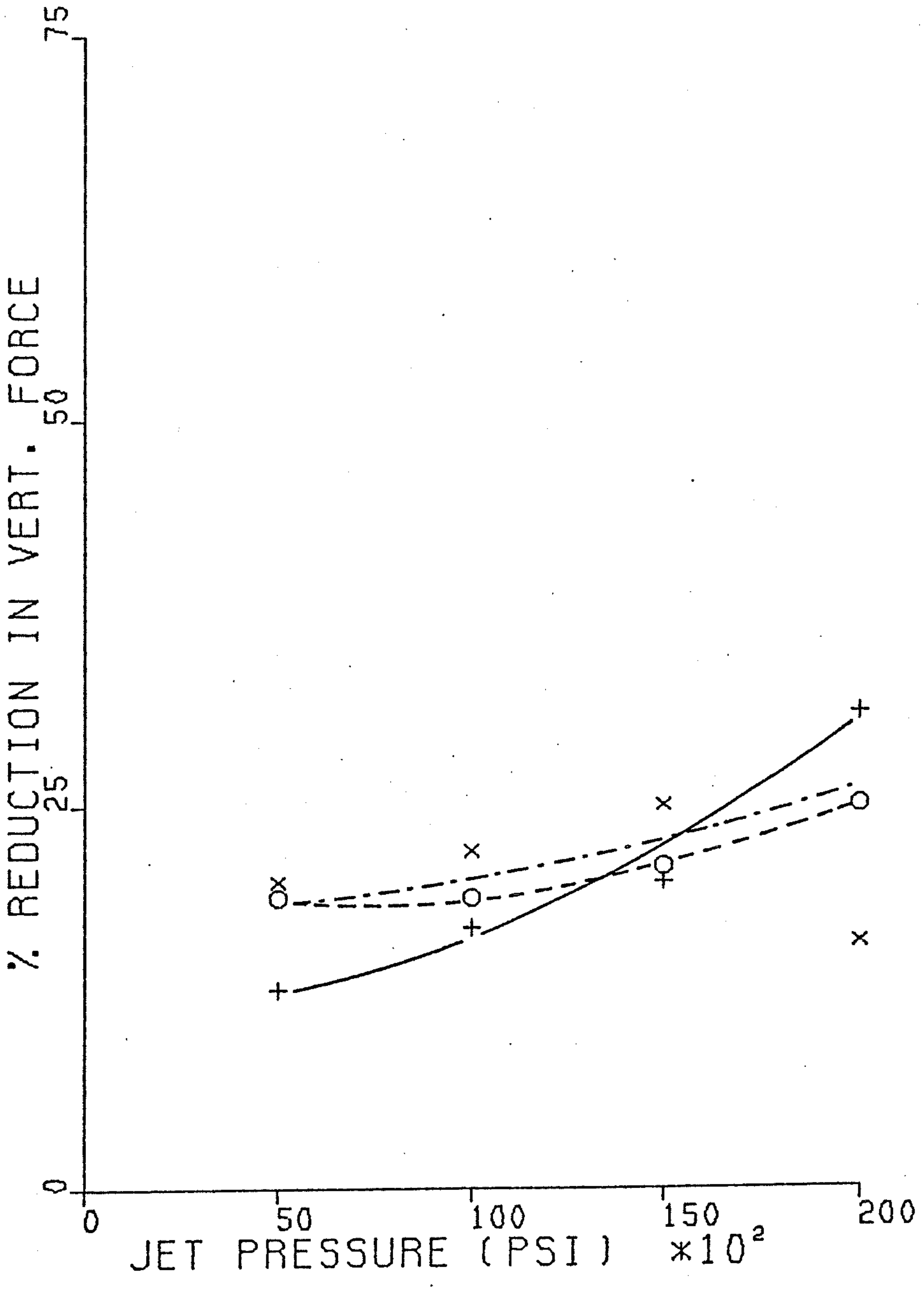

DRAG FORCE (LBS) *10²
0
20
40
60
80
100
120
140
160
DRY CUT
JET PRESSURE (PSI) *10²
0
50
100
150
200
CONICAL BIT
JET INFRONT
BIT PEN. = .20 IN.
ROCK TYPE = SANDSTONE
JET SIZE = .025 IN. SINGLE
+ = 1/8 IN. INFRONT
× = 1/4 IN. INFRONT
o = 1/2 IN. INFRONT

Figure 3.25.



CONICAL BIT
JET INFRONT
BIT PEN. = .20 IN.
ROCK TYPE = SANDSTONE
JET SIZE = .025 IN. SINGLE

+ = 1/8 IN. INFRONT
× = 1/4 IN. INFRONT
o = 1/2 IN. INFRONT

Figure 3.26.

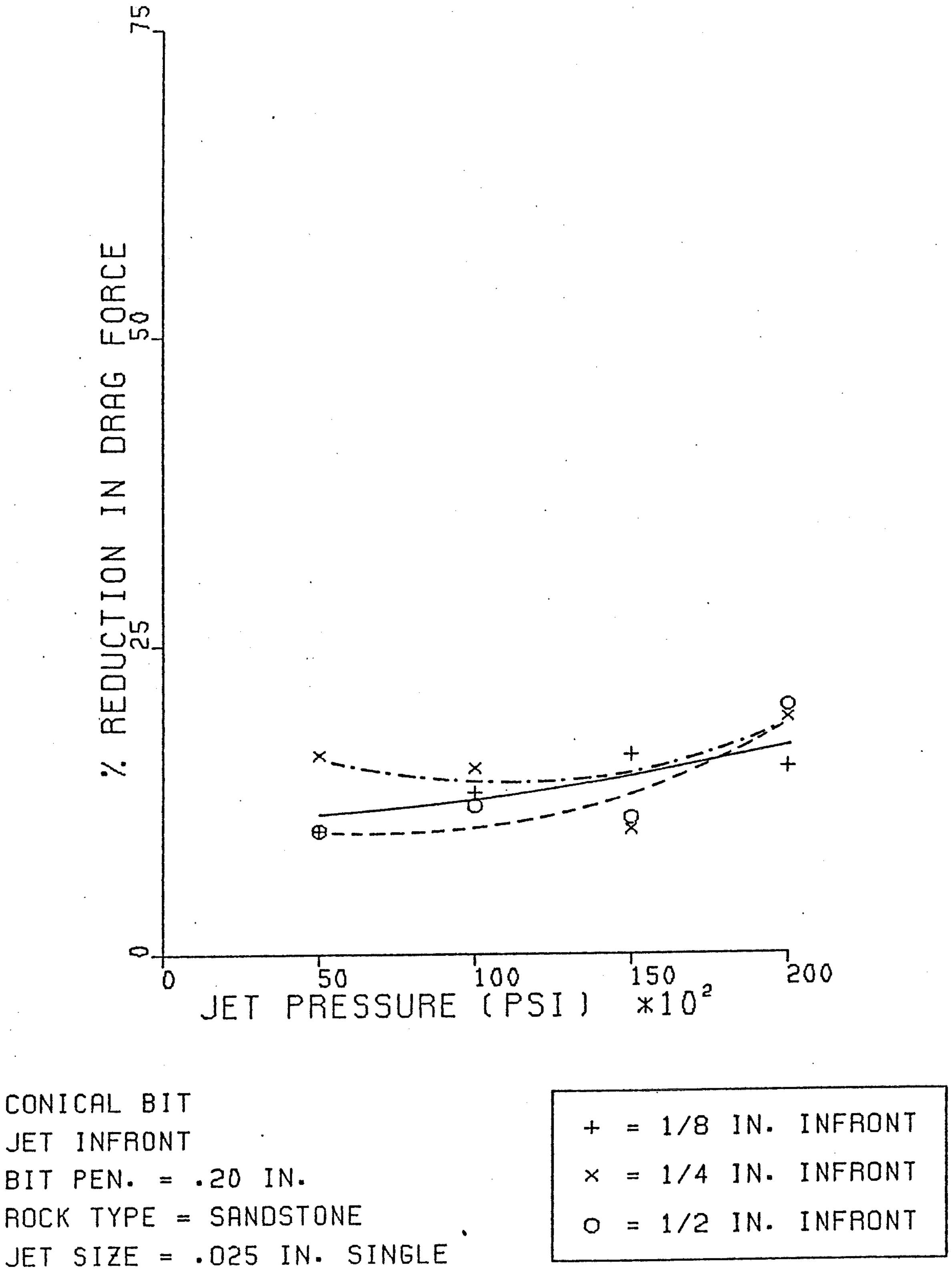

% REDUCTION IN DRAG FORCE
0
25
50
75
0
50
100
150
200
JET PRESSURE (PSI) *10²
CONICAL BIT
JET INFRONT
BIT PEN. = .20 IN.
ROCK TYPE = SANDSTONE
JET SIZE = .025 IN. SINGLE
+ = 1/8 IN. INFRONT
× = 1/4 IN. INFRONT
o = 1/2 IN. INFRONT

Figure 3.27.

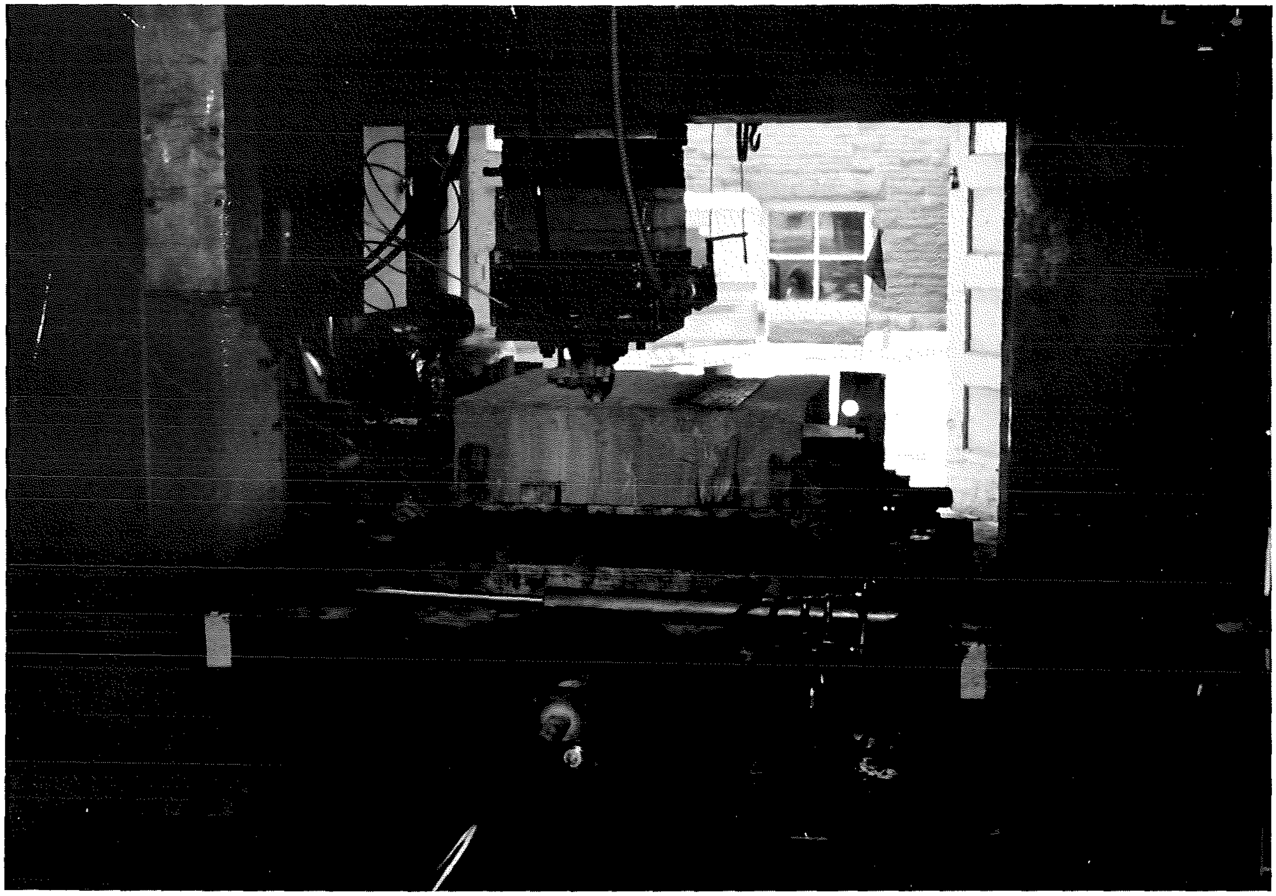


Figure 3.28. Overall view of jet assisted drag bit testing on the linear cutter.

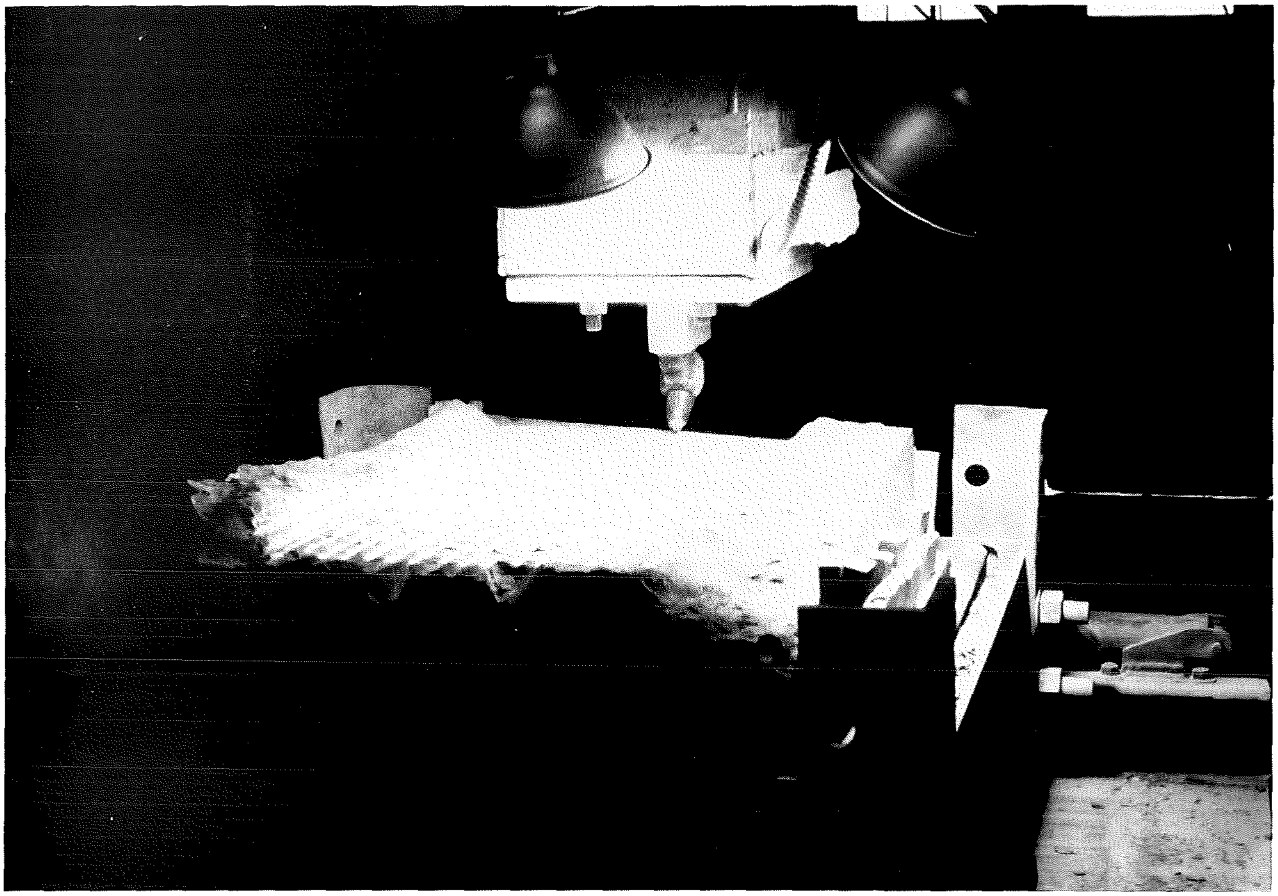


Figure 3.29. Rock surface conditioning.

Figure 3.30. Dry cutting tests with the conical bit.

Figure 3.31. The conical bit with jet assist.

3.2. Discussion of Linear Cutter Test Results

The test results obtained from linear cutting tests in German sandstone have demonstrated that significant bit force reductions are attainable by applying low to moderate pressure jets to drag bits. For both the plow and the conical bit, jet impingement location on rock surface with respect to bit was seen to have a significant effect on the amount of bit force reductions due to water jet assist. The closest jet location to the tip (1/8 inch in this case) provided the greatest bit force reductions. This beneficial effect of jet assist was found to decrease as the distance between the jet impingement location and the bit tip was increased.

When jet was oriented to impinge the rock in front of the bit, the jet pressure affected the degree of jet assist with higher pressure producing proportionately greater reductions in bit forces. However, the results indicate that this effect might be diminishing at higher pressures such that beyond a certain range of jet pressure, no additional force reductions may be gained with increased water pressure.

When jet impingement on the rock surface occurred from behind the bit, significant bit force reductions again were obtained, although the degree of jet assist was found to remain essentially the same regardless of jet pressure. That is, increased jet pressure did not produce a proportionately higher reduction in bit forces, as was observed for jet location in front of the bit.

For jet pressures less than about 10,000 psi, jet location behind the plow bit resulted in greater force reductions than jet in front of the bit. No such comparison was possible for the conical bit since, as stated earlier, jet location behind the bit could not be tested due to particular bit geometry.

Although no quantitative measurements were made, visual observations of bit wear patterns indicated that the use of water jets was also effective in reducing bit wear compared to dry cuts. Also observed visually was a significant reduction in airborne dust when jets were employed.

Several investigators working in the area of water jet assisted rock cutting have proposed theories intended to explain the mechanism by which a water jet augmented dray bit cutting system functions (2.3). Based on the findings of this study, it is believed that the explanation proposed by Dubugnon (3) provides a reasonably accurate understanding of the principles underlying the operation of a water jet assisted drag bit cutting system. Dubugnon suggests that water jet assist is affected by the occurrence of a three step process: (1) the erosion of the crushed zone underneath the bit, (2) hydraulic fracturing and, (3) pore pressurization.

The crushed zone erosion beneath the cutting tip due to water jet impingement can take place at relatively low or moderate jet pressures. Since the vertical force acting on the bit is largely influenced by the presence and extent of the crushed zone, elimination or reduction in size of this zone with jet assist might explain why the vertical force is reduced to a greater extent than the drag force with jet impingement even at low water pressures. Thus, it is suggested that the bit vertical force reduction due to jet assist results from the elimination or reduction in the size of this crushed zone that exists beneath the cutting tip of the bit. This phenomenon is also believed to account for the reduction in airborne dust and the lower rate of bit wear due to jet assist.

The second mechanism, hydraulic fracturing of the rock, is expected to require higher jet pressures in order to become effective. Hydraulic fracturing simply means that additional spalling or chipping of the rock occurs as jet penetrates and opens up the subsurface cracks produced by the bit. This hydraulic fracturing primarily affects the drag force, since additional chipping ahead of the bit reduces the effort to traverse the bit, resulting in lower drag force requirements. In this investigation, a simple test was carried out to confirm the occurrence of hydraulic fracturing with jet assist. Several cuts were first made over the rock surface with the drag bit alone under normal, dry cutting conditions. The rock surface was then cleaned to remove all the chips produced by the cutting action of the bit. The jet was then successively traversed across the rock surface directly in line with each cutting path. A surprisingly large amount of extra chips was created when jet traversed along each cutting path. As more material was removed with increasing jet pressure, this was a further confirmation of the fact that the amount of hydraulic fracturing is dependent on jet pressure with a greater degree of hydraulic fracturing taking place at higher jet pressures.

The third mechanism, pore pressurization, proposed by Dubugnon, can be adopted as an accurate explanation why different rocks behave differently under jet assisted cutting. This would explain why sandstones, which have a high porosity, are more amenable to jet assisted cutting than shales or limestones, which incorporate relatively low porosity.

As noted earlier, for jet pressures less than 10,000 psi, jet location behind the plow bit was found more effective, resulting in greater bit force reduction than jet in-front. At higher pressures, however, cutting with a frontal jet provided higher force reductions while the increased jet pressure did not contribute to additional force reductions when jet was placed behind the bit.

It would appear that from a machine design viewpoint, a frontal jet would be easier to install and operate than the one mounted to strike the rock surface from behind the bit. Moreover, it might prove more difficult to maintain a rear jet and to assure its survivability under severe field cutting conditions. Thus, the test results presented in this report together with machine design considerations tend to favor a frontal jet over a rear-mounted jet.

Another test observation that is of interest concerns the effect of bit penetration depth on the degree of bit force reductions obtained from jet assist. For the plow bit with jet in-front, no difference could be detected in percent force reductions for cutting at 0.10 and 0.20 inch penetrations at jet pressures below approximately 10,000 psi. For higher pressures, percent force reductions at the lower penetration were greater for all jet impingement locations relative to bit tip. When jet was mounted behind the plow bit, both depths of bit penetration were found to provide approximately the same degree of force reductions with jet assist. Thus, for this case, jet assist effects on bit performance appeared to be independent of bit penetration for the two depths of penetration tested. The same conclusion appeared to hold true for jet placed in-front of the conical bit. Again, the bit penetration did not seem to influence the degree of force reductions brought about by jet assist.

In dry cutting, past laboratory and field research has shown that the bit cutting performance becomes more efficient with increasing depth of penetration. This is because deeper bit penetrations create higher stress concentrations in the rock with the result being the development and release of larger chips and less fines, both contributing to lower specific energy of cutting. Although the results of this test program point to the independence of jet assist effects on bit penetration, it would be premature to draw a firm conclusion regarding bit penetration relationship with the degree of jet assist as only two depths of penetration were tested. One would expect jets to become more effective at deeper bit penetrations. Additional tests spanning a wide range of bit penetrations will have to be performed to develop more data to examine this relationship in more detail.

3.3. Rotary Cutterhead Tests

As stated earlier, a three-foot diameter rotary cutterhead was designed and fabricated under Phase II of the research program. This equipment provided the capability to carry out jet assisted drag bit tests at high traverse speeds and to evaluate multiple bit operation and interaction. With these capabilities, tests could be run using this facility under more closely simulated field cutting conditions where several bits attack the rock at any given time and the bit traverse speeds are much higher than most laboratory test equipment are capable of producing. Using the rotary cutterhead, it was then planned to run a test program to investigate these effects as part of Phase II research effort. As discussed previously, however, this phase was not pursued due to lack of funding.

A test program very similar in objectives to those proposed under Phase III was conducted by the Bureau of Mines using the rotary cutterhead. These tests were intended to develop data to support the Bureau of Mines in-house efforts in the area of jet assisted cutting for coal mine applications. Thus, the equipment was made available to the Bureau which in turn carried out a series of test programs using a specially built, high-speed cutterhead. The findings of these tests are published elsewhere (1). Figures 3.32. through 3.35. show pictures of the test setup, the cutterhead and the rock sample used for testing.

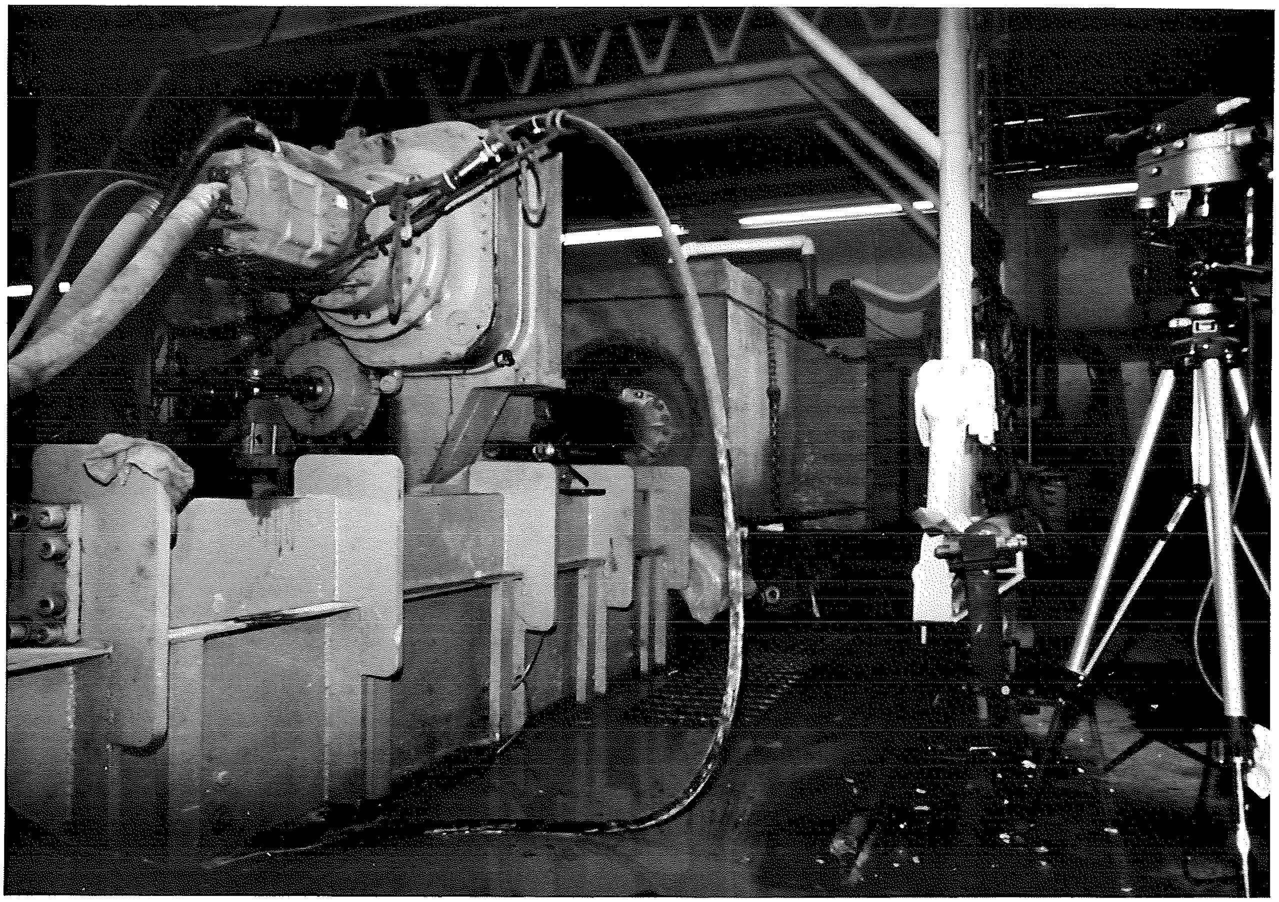


Figure 3.32. Overall view of the rotary cutterhead with the three-foot diameter jet assisted, drag bit cutterhead.

Figure 3.33. Collaring in with the rotary cutterhead.

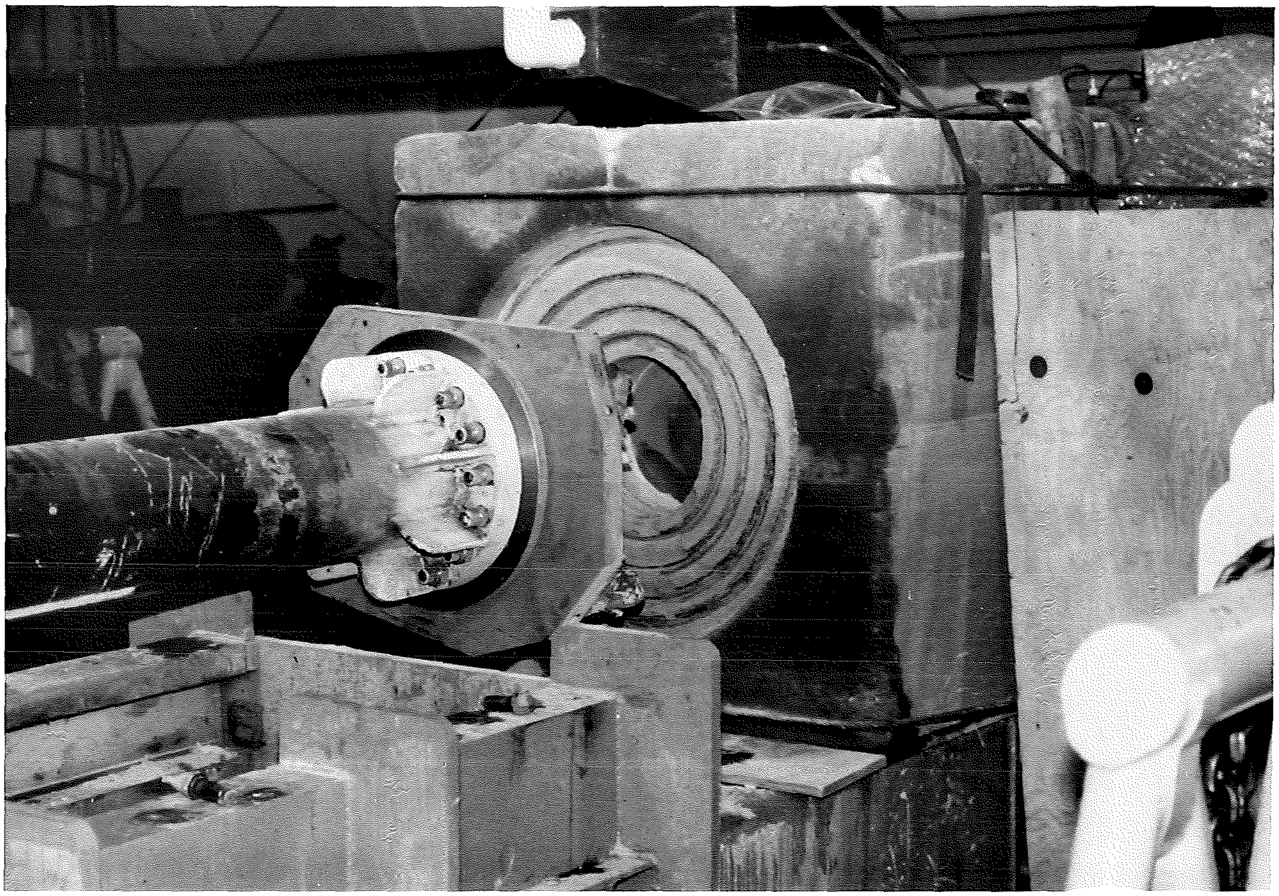


Figure 3.34. The cutting pattern created by the three foot cutterhead using drag bits with jet assist.

The rotary cutterhead tests were again carried out in a sample of the German sandstone having an average compressive strength of 19,000 psi. The most important conclusion reached from these tests was that the German sandstone could not be cut either with the conical or the plow bits without using water jets. Due to the hardness and abrasivity of this rock, attempts to cut it without jet assist caused excessive bit wear and in most cases resulted in complete destruction of the cutter bits. Thus, the only way to penetrate this rock with drag bits was through the application of water jets. Even at jet pressures as low as 2000 psi, a marked improvement was attained in tool life accompanied by a sharp reduction in cutting forces.

Another significant observation made from these tests was related to cutting speed effects on the performance of jet assisted drag bits. No measurable degradation of cutting performance was found to occur within the range of cutting speeds from about 35 to 290 ft/min. Overall, with jet assisted cutting, the three-foot diameter, drag bit equipped cutterhead was able to achieve a maximum penetration rate of 88 ft/hr.

As with linear cutting tests, the test program carried out on the rotary cutterhead has again demonstrated the benefits of applying water jets to assist the drag bits. In both cases, jet assisted cutting not only provided significant reductions in bit force requirements, but also resulted in a major improvement in bit life.

4.0. CONCLUSIONS

The results of this investigation have demonstrated that a water jet assisted drag bit cutting system can provide significant benefits in terms of reduced cutting forces and improved bit performance. The technique shows great potential as an effective means of improving the overall performance and economics of continuous miners and roadheaders, or any other type of coal mine machinery equipped with drag cutter bits. The water jet assist can extend the present capabilities of these machines to cut harder and more abrasive rocks at greater cutting rates with reduced bit wear, resulting in improved economics of the operation. The following conclusions can be drawn based on the results of this research effort:

1. The bit force reductions due to jet assist was found to be sensitive to the location where jet impinges the rock surface relative to bit penetrating edge. For both the plow and the conical bit tested in the laboratory, the greatest cutting force reductions were obtained when jet impingement point was closest to the bit tip, which was 1/8 inches in this case.
2. When jet was positioned in front of the plow bit, increasing water pressure produced proportionately greater reductions in bit forces required to maintain a given depth of cut with respect to cutting without jet assist. However, the results also indicated that this beneficial effect of jet assist may be diminishing at higher pressures such that no additional reduction in bit forces may be gained for jet pressures above a certain value. More testing and analysis is needed to develop a better understanding of this phenomenon, but it is believed that at higher pressures, jet tends to "undercut" the

rock, therefore not allowing the bit to create the crushed zone necessary to develop and propagate cracks through the rock mass.

3. For the conical bit, increased jet pressure also resulted in a higher degree of bit force reductions, but the overall influence of jet pressure was much smaller than that obtained with the plow bit.
4. When jet was oriented to strike the rock surface from behind the plow bit, significant bit force reductions were again observed, although the degree of jet assist was found to remain essentially independent of jet pressure within the range of pressures tested in the laboratory. This finding was unexpected and an explanation of this phenomenon needs to await further testing.
5. For jet pressures below 10,000 psi, jet location behind the plow bit was found more effective, providing greater reduction in bit forces than the jet location in front. No such comparison could be made for the conical bit as jet positioning behind the bit could not be tried due to particular bit geometry.
6. For the plow bit with jet in front, both the vertical and drag forces were reduced up to 50 percent at 20,000 psi pressure and 0.10 inch depth of cut with jet impacting the rock surface at a distance of 1/8 inches from the bit tip. At a 0.20 inch depth of penetration, the bit force reductions achieved with the same test parameters were lower, averaging 30 to 35 percent.
7. Although no quantitative measurements were made, a drastic reduction in airborne dust was observed with jet assisted cutting compared to dry cutting. In some cases, almost no dust production could be detected when jets were turned on.

8. Visual observations of bit wear patterns showed a marked reduction in bit wear with jet assist. Wear reductions mainly were found to occur on bit shank.

5.0. RECOMMENDATIONS

Based on the results of this research effort, the following areas are recommended for further investigation:

1. For the case of jet behind the plow bit, the force reductions brought about by jet assist were found independent of jet pressure. The reasons for this are not clearly understood and additional tests are needed to further explore this arrangement of jets with the plow bit. In particular, tests should be run in different rock types to determine if pressure effects on the degree of bit for a reduction is dependent on the properties of rock used for testing.
2. Quantitative studies are needed to develop an accurate assessment of bit life improvements resulting from jet assisted cutting. If feasible, tests should be carried out on a field operating machine to better simulate the in-situ conditions affecting bit wear and performance.
3. Further experimental and theoretical investigations should be pursued to provide a better understanding of the mechanism involved in jet assisted cutting. Presently, various theories exist as regards to the mechanism by which water jets are believed to assist cutting, but additional analyses are needed to verify or disapprove their validity.

6.0. REFERENCES

1. Handewith, H., "Traverse Speed Tests", Report to U. S. Bureau of Mines, Contract No. J0333956, Boeing Services International, Inc., 1985.

2. Ropchan, D., et al., "Application of Water Jet Assisted Drag Bit and Pick Cutter for the Cutting of Coal Measure Rocks", Final Report to U.S. Department of Energy, April, 1980, DOE Contract No. FE-0982-1.

3. Dubugnon, D., "An Experimental Study of Water Jet Assisted Drag Bit Cutting of Rocks", Justitut Cerac SA., Switzerland, First U. S. Water Jet Symposium, Golden, Co., 1980.

APPENDICES

APPENDIX A

Description of German Sandstone

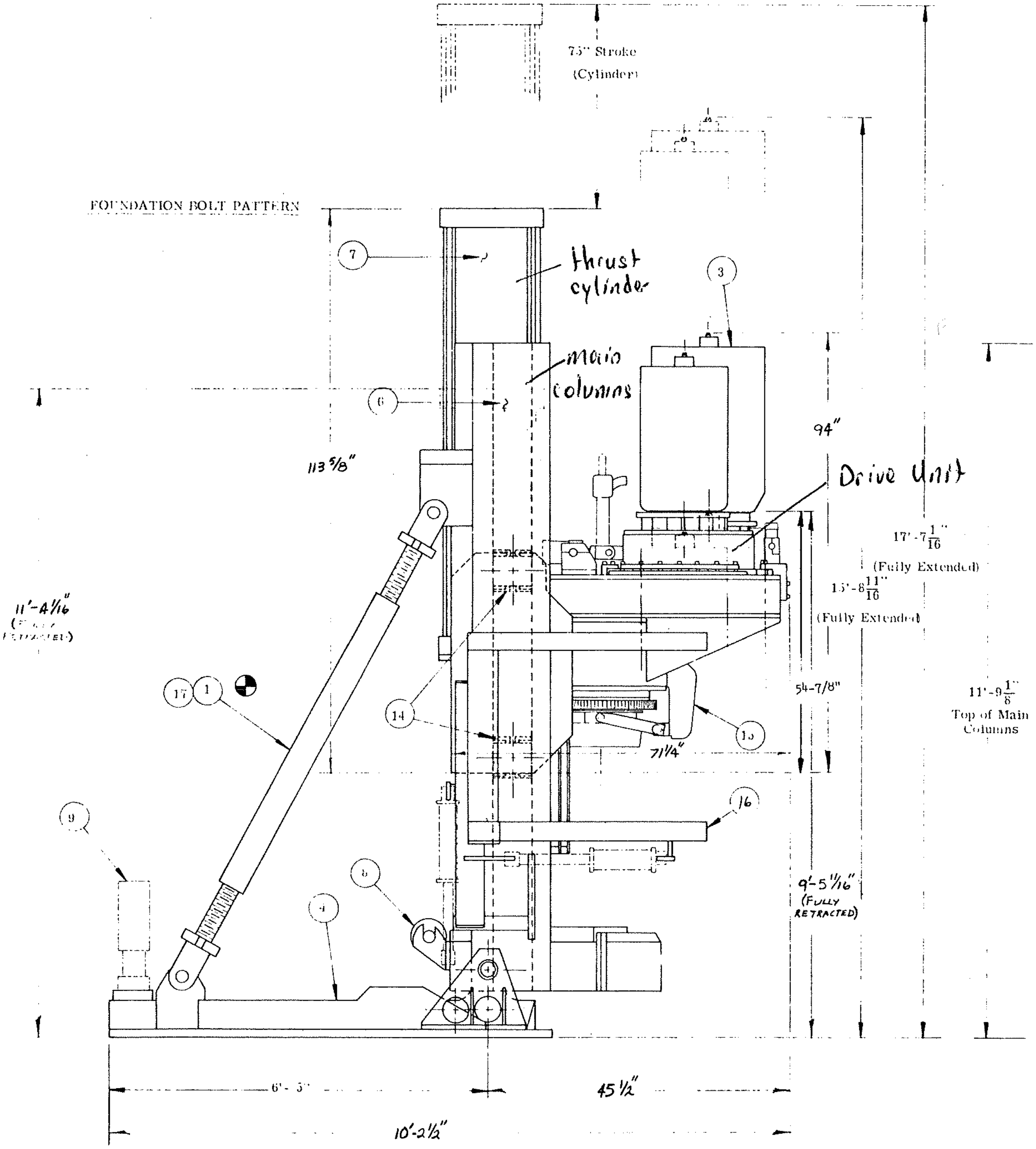
GERMAN SANDSTONE

This is a light gray, fine to medium grained, quartz sandstone. Quartz grains are well rounded and cemented with silica. The samples exhibited indistinct lamination and some broad band stainings with limonite. The samples of this rock were obtained from a quarry near Dortmund, West Germany.

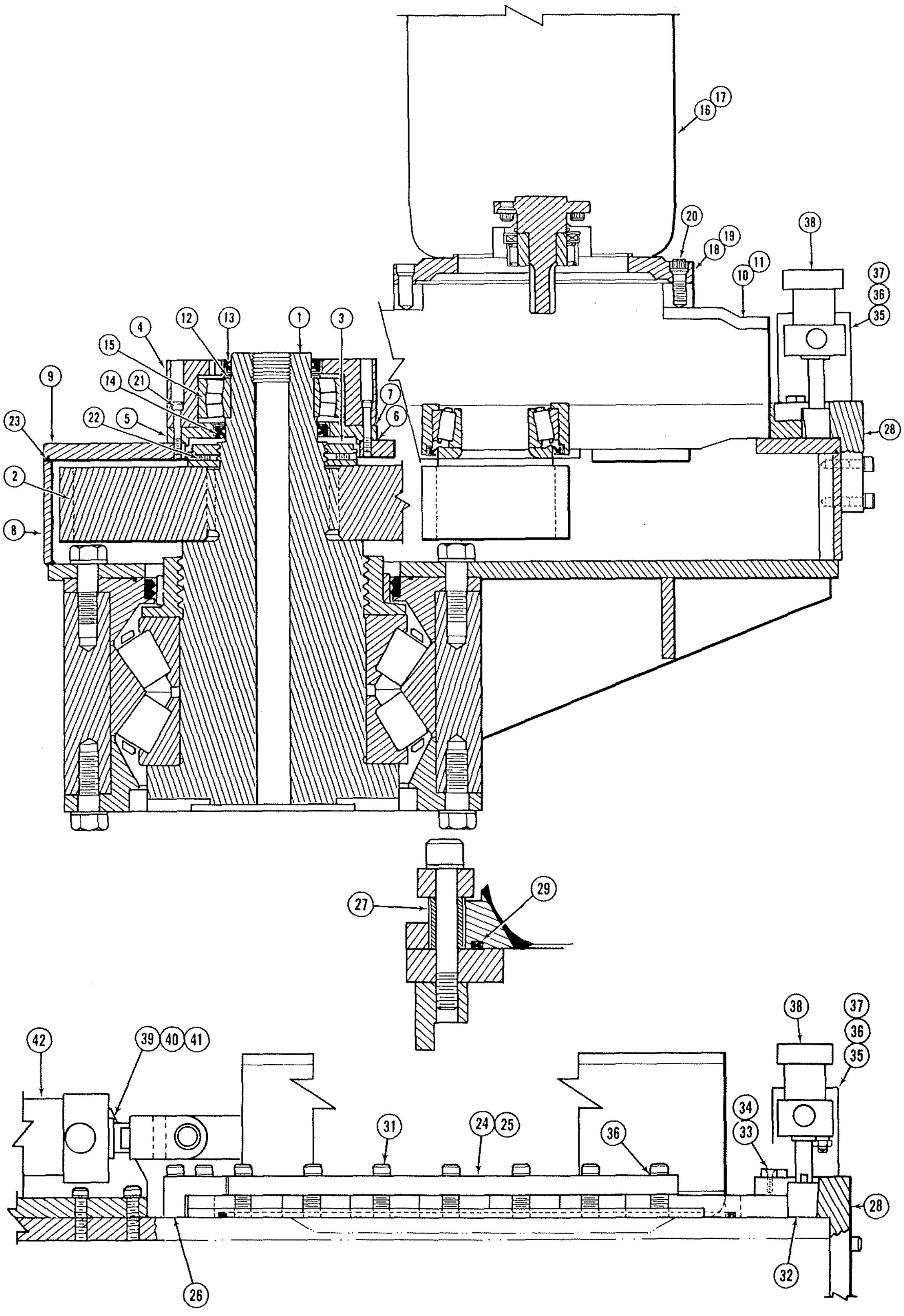
Uniaxial compressive strength : 19,000 psi
Brazilian tensile strength : 1,350 psi
Porosity (%) : 4.9
Density : 2.41 gm/cc

APPENDIX B

Drawings of the dresser model 800 raise bore drive and guide system used in the rotary cutterhead test facility



The drive system and the main guide columns used in the construction of the rotary cutterhead test facility.



The raise bore drive system used for the rotary cutter.