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PRELIMINARY STUDIES OF THE EFFECTIVENESS OF WATER JET CUTTING ON FROZEN GROUND

by

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PRELIMINARY STUDIES OF THE EFFECTIVENESS OF WATER JET CUTTING ON FROZEN GROUND

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FOREWORD

This report was prepared by the Mineral Industry Research Laboratory, University of Alaska, Fairbanks, under the U.S. Bureau of Mines contract entitled "Underground Placer Mining Project", project B2, "Effectiveness of Water Jet Cutting on Frozen Ground". The program is part of a continued research cooperation between the U.S. Bureau of Mines, AFOC Fairbanks and the Mineral Industry Research Laboratory, UAF, undertaken in order to develop an underground mining system for deep placer deposits in frozen ground.

This report is a summary of the work recently completed under this program during the period February, 1982 through July, 1983.

The laboratory studies undertaken within this project were conducted at the beginning of 1982 in Rolla, Missouri with participation of Drs. Clark Barker and Marian Mazurkiewicz. In-situ testing was performed in the CRREL Permafrost Tunnel in Fox, Alaska. The valuable discussions, suggestions and help received from Messrs. Jim Barker and Will Sprout of the U.S. Bureau of Mines are gratefully acknowledged. Also participation in this project of Mineral Engineering Department student Andy Folly, is acknowledged.

TABLE OF CONTENTS

ABSTRACT

Cutting of artificially frozen gravel and ice was performed under laboratory conditions at pressures ranging from 3000 to 15000 psi (20.7 to 103.5 MPa) and flow rates below 4 gpm (0.24 L/s). During the second stage of this preliminary study additional cutting and "drilling" were conducted in the permafrost tunnel at Fox, at pressures ranging from 2000 to 4400 psi (13.8 to 30.4 MPa) and flow rate up to 40 gpm (2.4 L/s). The erodability of the material (energy required to remove a unit volume of material) was calculated and used as a basis for finding the optimum conditions for frozen gravel disintegration. Recommendations for further studies are also included.

1.0 INTRODUCTION

1.1 Background

Hydraulic mining has a long history and has been used to remove a variety of minerals, ores and other materials from the earth. These range from gold, uranium and coal mining to cutting slots in wells for solution mining. High pressure water jets have found application in cutting concrete, wood and other materials.

The U.S. Bureau of Mines was for many years the supporter of research and development having the objective of improving the state of the art in hydraulic coal, uranium and gold from frozen placer. As part of the Bureau of Mines program, J.W. Chester and J.M. Flank conducted the first frozen placer framentation research in the late 60's using a high pressure, low volume water technique which they found promising. Prior studies were conducted by Foster Miller Assoc. for the U.S.A CRREL in 1966 through 1968. They concluded that continuous water jets were unlikely to be of value. They concentrated the research efforts on discontinuous jets and found that further development work on the rapid fire devices for high speed droplet impact was worthwhile, but no action has been taken since then to implement this recommendation. Other investigators (Drs. M. Mellor, U.S. Army CRREL; David R. Summers, University of Missouri, Rolla; M.C. Franz, Univ. of Michigan) conducted further research in application of high pressure water jets to permafrost cutting. The pressure range was between 5,000 and 15,000 psi (34.5 to 103.5 MPa) with emphasis on higher pressure in this range, whereas the flow rate was at or below 5 gpm (0.3 L/s). The reported results were considered encouraging, although no major breakthrough in terms of developing commercially valuable equipment for underground mining in frozen placers has been reported.

At the beginning of 1982 the U.S. Bureau of Mines, FOC Fairbanks revived interest in this area and initiated research in cooperation with the Mineral Engineering Department of UAF. The research undertaken over a period of time from February, 1982 to July, 1983 concentrated on defining the optimum parameters in terms of pressure and flow rate for efficient cutting of frozen gravel. The first part of this preliminary study consisted of laboratory cutting of artificially frozen gravel and ice in order to obtain better insight into the possible range of parameters, safety and related topics. This part of testing was conducted at the University of Missouri, Rock Mechanics and Explosive Research Center in Rolla where the high pressure-low volume water jet equipment was available. The second part of this project was conducted in 1983 after assembling the necessary equipment in the CRREL Permafrost Tunnel in the second part of 1982. The cutting and "drilling" at low pressures from 2,000 to 4,400 psi (13.8 to 30.4 MPa) and high volume water flow (about 40 gpm or 2.4 L/s) were conducted in the lower portion of the winze next to the U.S. Bureau of Mines room. Cutting of slots and "drilling" of holes with stationary nozzles were tried in the frozen gravel and bedrock.

1.2 Literature

Selected papers are reviewed here which were presented during the last 15 years dealing with the developments in high pressure water jet technology as applied to both rock and frozen ground disintegration.

A study of excavation concepts was carried out for U.S.A. CRREL by Foster Miller Assoc. (1971, Ref. 1) between 1966 and 1968. Using the available data on rock cutting Foster Miller concluded that continuous water jets were unlikely to be of value in excavating permafrost because of low energy effectiveness, high power demands and large volume of water requirements.

They further concentrated on discontinuous jets and ran a series of tests at -5^{o}C on frozen fine grain soils with uniaxial compressive strength on the order of 2,000 psi (13.8 MPa). The final conclusion of the Foster Miller team was that further development work on rapid fire devices for high speed droplet impact was worthwhile but no action was taken to implement this recommendation.

Interest in continuous jets revived in 1969 when tests were made for U.S.A. CRREL by M.C. Franz of the University of Michigan. About a hundred tests were made on frozen specimens of silt, sand and gravel with pump pressure of 6,000 to 10,000 psi. (41.4 t 68.9 MPa), nozzle diameters from 0.022 to 0.0556 in. (0.559 to 1.45 mm) and traversing speeds from 11 to 104 ft/min (0.0559 to 0.528 m/s). A few tests were also run with sand injected into the cutting jet. Although the nozzles used in this test were not of optimum design, the results showed quite conclusively that small diameter jets of moderate pressure are capable of making useful penetrations into frozen soils with slots up to 12 in. (305 mm) deep in sand, up to 3.5 in. (89 mm) deep in silt, and up to 3 in. (76 mm) deep in gravel. The specific energy based on jet power and volumetric excavation rate for the slot only was 14,000 lbf/in.^{2} for sand, 27,000 lbf/in.^{2} for silt, 70,000 lbf/in.^{2} for gravel (96.6, 186, 483 MJ/m^3 respectively). In 1968 the U.S. Bureau of Mines, stimulated by renewed interest in the frozen gold bearing gravels of Alaska, undertook a field study of jet cutting experiments (Chester, J.W., Ref. 2) which were made on test blocks of frozen coarse gravel at -4^{o}C using nozzles of approx. 0.5 in. (12.7 mm) diameter with a traverse rate of 3 in./sec (0.0762 m/s) and pump pressures of 1,500, 2,400 and 4,500 psi. (10.3, 16.5 and 31 MN/m^2). Penetrations up to 8.4 in. (214 mm) were achieved with specific energy averaging 35,000 lbf/in.^{2} (242 MJ/m^3). Field trials were made in Alaska at the U.S.A. CRREL Permafrost

Tunnel using a 0.148 in. (3.76 mm) diameter nozzle with pump pressures of 2,500, 3,500, 4,200 psi. (17.2, 24.1 and 29.0 MN/m^2). Penetrations were not reported but a test block simulation gave penetrations up to 2.5 in. (63.5 mm) at 4,500 psi (31 MN/m^2) pressure and 3 in./sec. (0.0762 m/s) traverse rate. Specific energy for excavation of the Alaskan gravel ranged from 16,000 - 35,000 lbf/in.^{2} (100 to 242 MJ/m^3). It was concluded that hydraulic cutting holds definite promise for working frozen gravels.

Further tests were made for U.S.A. CRREL by D.A. Summers of the University of Missouri in 1971. Specimens of frozen gravel were traversed by a continuous jet (0.023 in. or 0.584 mm nozzle diameter) at pressures of 2,500, 4,000, 6,000, 9,000, 12,000 and 24,000 psi (17.2, 27.6, 41.4, 62.1, 82.8, 165 MN/m^2), with traversing speeds of 3, 7, 15 and 30 ft/min (0.0152, 0.0356, 0.0762, 0.152 m/s). Multiple pass traversing was investigated by passing the jet 1, 2, 5 and 10 times and effects of adding polyethylene oxide to the jet water were studied. Several shots were made with a water cannon, firing six gallon (22.7 L) slugs at approximately 10,000 psi (69 MPa) through nozzles of 0.2, 0.5 and 1 in. (5.08, 12.7, 25.4 mm) diameter. Maximum penetration achieved in a single pass with the continuous jet was 2.6 in. (66 mm), and penetration of 6.7 in. (170 mm) was reached in 3 passes. Specific energy ranged from 15,000 to 100,000 lbf/in^2 (100 to 700 MJ/m^3). Penetration depth for the water cannon shots exceeded 12 in. (305 mm), which was the thickness of the test blocks. Multiple pass traversing with the continuous jet did not appear to have much effect on the specific energy, but it did seem to increase the penetration per unit time of application, e.g. 10 passes at 30 ft/min (0.152 m/s) gave significantly greater penetration than one pass at 3 ft/min (0.0152 m/s). Addition of polyethylene oxide to the cutting water did not give significant improvement in performance. The gravel used in these tests contained bigger particles and the large pebbles deflected the jet at random angles leading to undermining and enlargement of slot width.

In the period from 1972 to the present no further papers have been published at the international jet cutting symposiums regarding jet cutting of frozen gravel, although many interesting papers were published concerning both the developments in the high pressure technology as well as new applications of high pressure water jets.

In 1980 Hydronautics, Inc., in their reports submitted to the U.S. Department of Energy (Ref. 3), reported the development and application of the Cavijet which produced disintegration of sedimentary rocks at much below the pressures reported earlier. The Cavijet cavitating fluid jet is a turbulent jet in which vapor and gas cavities are deliberately stimulated to enhance the erosion action of a relatively low velocity liquid jet. The destructive action of cavitation has been known for years, often to the disappointment of designers and users of pumps, propellors and other hydraulic components. The Cavijet cavitating fluid jet is one of the few useful applications of this phenomenon. In contrast to non-cavitating jets the cutting or drilling is achieved by the energy generated from collapsing cavitation bubbles. The pressure from these imploding bubbles is extremely high and is focused at many small areas on the eroding surface. In materials which are prone to cracking such as rocks and coal and possibly ice, the extremely high localized pressure causes rapid fracturing which greatly enhances the erosion mechanism. A typical configuration of the cavitating nozzle is shown in Figure 1. The nozzle has to have a suitable shape which maximizes the pressure reduction at the center of vortices created within the jet or on its periphery and hence induces the growth of vapor or gas cavities in the fluid. It has been found that the center-body configuration of the nozzle is best for in-air applications, namely drilling, cutting or cleaning. For operation on submerged surfaces as in deep-hole drilling or underwater cutting, either the turning vane or "plain" (without vanes or center-body) Cavijet nozzle designs usually provide better results, namely, greater volume removal. Figure 2 provides comparison of the ability of a cavitating water jet, to amplify the pressure and therefore deliver a considerably higher impact pressure to a surface, to a steady jet at the same velocity. The curve for impact pressure, Pi, for the steady jet was calculated from the equation for the stagnation pressure, Po:

$$p_i = p_o = \frac{1}{2}\rho v^2$$

where

ρ = mass density of water, and

v = velocity of the jet.

The envelope of curves in Figure 2 for the cavitating water jet is based on Rayleigh's single cavity spherical collapse theory, with gases in the cavity assumed to follow an isothermal compression. Hydronautics has derived a formula for the collapse pressure as a function of gas content in the cavities. Based on it, the important pressure is:

$$p_i = \frac{Po}{6.35} \exp\left(\frac{2}{3\alpha}\right)$$

where $\alpha = Q_o/p_o$, is the gas content of the cavities

Q_o = partial pressure of gas

p_o = local pressure in the surroundings of the cavity at the beginning of the collapse.

Additional developments in the area of high pressure technology were reported during the Second U.S. Water Jet Conference held in Rolla, Missouri in May of 1983.

Knickmeyer and Baumann, (Ref. 4) reported an interesting attempt to combine high pressure water jets with roller tools and carbide picks on a full face tunneling machine. These tests were carried out with a TB-I-26060 tunneling machine having a cutting diameter of 8.5 ft. (2.6 m) in an upper carboniferous sandstone quarry within a project sponsored originally by the U.S. Bureau of Mines and later by the Department of Energy. The principle of a combined water jet - roller tool system for rock destruction consists of cutting kerfs by means of water jets, with the roller tool subsequently shearing off the rock rib left between the kerfs. Based on the compressive/tensile strength of the rock, the static forces required for the operation of the roller tools can be reduced by up to 50% as a result of the application of the water jets. The reduction of the necessary thrust forces is shown in Figure 4 as a function of a water jet pressure. The reduction of the necessary thrust forces, through adding the high pressure water jets over purely mechanical tools, would considerably reduce the weight of such road headers with all resulting advantages regarding their mobility. This positive influence of high pressure water jets added to a conventional tunneling machine can also be utilized through an increase in the rate of machine advance. The rate of advance with unchanged thrust was doubled when using high pressure water jets.

Additional tests were conducted with a roadway profile cutting system, again equipped with high pressure water jets. This system, apart from its advantages regarding support requirement and rock stability, insures high profile accuracy. The tool consists of carbide cutting tips and high pressure nozzles, i.e., two leading and 3 trailing nozzles. The tests conducted in solid sandstone and softer stratified rock showed that the forces acting upon the carbide picks can be reduced on the average by 50% and at the same time the wear can be substantially reduced, (Figure 5). In final conclusions the authors stated that the high pressure water jets combined with carbide picks had proven to be highly effective. They found that water jets alone are not too efficient since they require an extremely high specific energy and thus are not suited for destruction of large rock volumes. Further tests conducted to improve the effect of high pressure water jets by adding additives have shown that the slot depth can be increased by up to 100% or the pressure can be reduced by 30% when the additives are being used.

Other developments in the area of underground mining machinery supported by high pressure water jets were described by Henkel, (Ref. 5). The jet miner was designed to mine coal in seams from 3.3 to 5 ft. (1 to 1.5 m). The power installed for the pumps was 224 hp. (300 kW). The flow rate was 59.8 gpm (3.59 L/s) and water pressure was 10,120 psi (70 MPa). The coal face was undercut by the oscillating high pressure water jets and subsequently broken off by the cutting heads. The cutting heads exhibited no wear which meant that the coal was entirely cut by water jets. The force analysis led to the conclusion that the power requirement for the high pressure pumps could be reduced from 224 to 164 hp. (300 to 220 kW) and the water flow could be reduced from 59.8 to 45 gpm (3.77 to 2.83 L/s). Comparative measurements have shown that the quantity of dust released corresponds only to approximately 30% of the dust produced by a shearer loader in the same seam. Altogether experiments with the jet miner were described as very successful.

In another paper presented Yie, a successful application of abrasive entrained water jet to cutting hard rock was reported (Ref. 6). It has been observed earlier that there exists for a given rock a "threshold pressure" below which water jet cannot cut the rock to any depth within practical dwelling time. This threshold pressure was believed to be a function of the compressive strength, permability, crystalline structure, and other properties of rocks. The exact relationship however, is not clearly understood. Some typical values of such threshold pressure are 5,000 psi (35 MPa) for sandstone, 7,000 psi (48 MPa) for limestone, 14,500 psi (100 MPa) for granite, and over 20,000 psi (138 MPa) for quartzite and basalt. However, to obtain significant cut depth and speed requires a water jet of a pressure level considerably higher than threshold pressure of a given rock. Thus, most of the past investigations on cutting or drilling hard rock with water jets involved pressure in access of 40,000 psi (276 MPa). Such a high pressure requires the use of special pressure intensifiers that are known to be very costly and have limited flow capacity. An abrasive water jet for cutting hard rock at moderate pressures was developed by Fluidyne and was found to be effective. The basic design of the jet nozzle is shown in Figure 6. Such nozzles can generate very strong negative pressure in the range of 25 to 30 inches (0.63 to 0.76 m) Hg inside the mixing cavity at water pressure of 15,000 psi (103.5 MPa) with a bore of nozzle cone as large as 0.4 in. Because of the shielding provided by the multiple water jets a tungsten carbide nozzle cone can last more than a day's operation without affecting the level of negative pressure inside the mixing cavity or the performance of the abrasive water jet. Since orifice cones are interchangeable, the same nozzle body can be used for a wide range of water pressure and flow rates as well as a wide variety of abrasive powder or slurry. Testing these orifice cones on concrete revealed that abrasive entrainment is significantly better with orifice cones having five or more water jets judged by the amount of abrasives introduced without choking and the depth of cuts produced. The five-parallel-jet nozzle, for example, was also found to be superior over a single jet nozzle of similar output in cutting concrete without abrasives. Figure 7 presents a comparison of cut depth obtained with various rock specimens without or with abrasives. The benefit of adding abrasives into the water jet is clearly demonstrated as is the effect of rock properties on depth of cut. Garnet abrasives have shown to be far superior to silica sand, copper slag and "green diamond" abrasives in cutting concrete and rock. Garnet grains are sharper and have several cutting edges due to their crystalline structure. It was found that the benefit of using hard and sharp abrasives was influenced by the type of rock being cut. Also it was reported that the nozzle standoff distance could be changed, depending on the type of rock being cut, from 1 to 2 in. without affecting the depth of cut. In summary the author stated that the data collected in his study showed that water jet of moderate pressure can effectively cut very hard rock without sacrificing the quality of the water jet, if suitable abrasives are added into the water jet.

2.0 LABORATORY STUDIES ON ARTIFICALLY FROZEN GRAVEL AND ICE.

2.1 Description of Material Tested

In general any testing program run under different than in-situ conditions and not employing a full size structure has to be considered a model study. In most cases this requires the development of an equivalent material which would closely simulate the properties of the structure. The purpose of the equivalent material development is usually to reduce the size and cost of the testing program, to have the material readily available, etc. For the purpose of this research it has been decided that artifically frozen gravel and ice would be produced because collecting the permafrost samples and shipping them to the laboratory intact would not be feasible. The development of the equivalent material is usually based on matching the real and the equivalent material properties which are the most pertinent to a phenomenon under consideration. However, since little has been known about the parameters which control the cutting of or drilling in the permafrost, and also because of the limited range of the attempted research at this stage, it has been decided to use, for the solid part of the equivalent material, a modified washed river gravel from the Gasconade River near Waynesville, Missouri. The modification of the river material in addition to washing it, consisted of limiting its size to 2 in. (51 mm) and increasing the content of larger grain size fractions. This gravel was not crushed, although the individual pieces were not fully rounded. The 2 in. limit on gravel size was chosen in connection with the maximum size of samples which could be handled during testing. The grain size distribution curve for the simulated gravel is showen in Figure 8 with data points listed in Table 1.

Ordinary tap water was mixed with the above gravel. The water content by weight was 18%.

2.2 Sample Preparation

As mentioned previously, two types of material were tested, frozen gravel and ice. The frozen gravel for water jet cutting was prepared in the shape of rectangular samples of the size of 1 x 1 x 3 ft. (0.305 x 0.305 x 0.915 m). They were frozen in wood forms lined with plastic sheets. The ice sample for water jet cutting was frozen in a plastic cylindrical container 18 in. (0.46 m) in diameter and 12 in. (0.305 m) high. The samples were frozen at the local freezer company at +5°F. After freezing the samples, they were covered with 2 in. thick fiber glass insulation and taken to the testing facility.

In general the quality of samples produced was very satisfactory. However, a few ice samples showed cracking which very likely resulted from freezing too quickly.

2.3 Equipment Used

All cutting tests were performed using a Kole 3J triplex pump driven by an electric motor as shown in Figure 9. This setup can produce various combinations of water pressure and flow rate by changing the diameter of the 3 plungers to achieve a pressure and flowrate combination equal to the rated capacity of the pump, which is 60 hp. (80.4 kW). However, different pressures and flow rates can also be achieved by varying the nozzle exit diameter and quantity of the low pressure discharge of the pump. The latter procedure was followed in performing the cutting tests.

The discharge of high pressure water from the pump was carried inside a 0.5 in. (12.7 mm) ID flexible hose with a rated burst pressure of 30,000 psi (207 MPa). This type of hose is in common usage in the water blasting industry and because of its flexibility it is a very convenient component for high pressure work. A mechanism shown in Figure 10 was used to oscillate the nozzle across the sample. This device is a three dimensional four bar linkage which, when the input flywheel is rotated by a small hydraulic motor at a constant angular speed, executes a motion which is approximately sinusoidal in nature. The nozzle moves smoothly across the sample, stops and swings back across the sample to the other extreme position, producing two cutting passes per revolution of the input link. The nozzle is clamped to the end of the swinging arm by a threaded holder which produces a metal to metal seal to contain the high pressure water. The nozzles used in this study are patterned after a design proposed by Leach and Walker. They suggested an inlet cone of 13^{o} degree included angle followed by a cylindrical exit section whos length is 3 to 4 times the exit diameter as shown in Figure 11. The design evolved from a large number of tests performed on different nozzle shapes to determine the effective cutting range of each design. In some cases a dual orifice diverging nozzle was used to cut slots in the frozen gravel. With this arrangement two jets are placed in a plane as shown in Figure 12, and moved across the sample to cut two parallel grooves. The jets can frequently work together to remove all of the material in between their parallel paths.

2.4 Test Procedures

The frozen samples were positioned with respect to the oscillating nozzle system as shown in Figure 13. The distance "d" is the standoff distance, while "L" is the width of a sample. "R" and "ψ" are constants and "ψ" varys according to the standoff distance used for a particular test.

With the nozzle arm at the extreme position so that the water jet would not touch the sample, the high pressure pump was started and the bypass valve adjusted to produce the correct pressure for the particular test run. When this adjustment was completed, the hydraulic drive was turned on and the arm began to swing across the sample. After the required exposure (usually 30 seconds) the power was turned off and the arm motion was stopped and the measurement of the penetration depth and width across the slot produced were recorded. If additional cutting was desired at this location the procedure was repeated for an additional exposure time and the data recorded. Usually it was possible to cut 4 to 5 slots across one sample tested.

It should be mentioned that the samples were taken from the freezer locker just prior to the cutting tests. During the time of the test the samples were exposed to the ambient air temperature of approximately 70°F and consequently the sample temperature was gradually increasing. However at the conclusion of each test the samples were still very solid and no significant reduction in strength was noticed.

As mentioned previously, different pressures and flowrates result depending upon the size of the nozzle exit and the amount of water bypassed. For this preliminary test it was decided that a pressure measurement taken from the pump manifold would suffice and that the flow rate and cutting power would be calculated from the measured pressure and known nozzle exit diameter. This procedure would not account for pressure losses between the pump and the nozzle nor any variation in the nozzle discharge coefficient. However, this effect will be present in any mining high pressure equipment and can never be totally eliminated. With these assumptions the equations used for power and flow rate calculations are:

$$Q\ (\text{gpm}) = 29.84\ \sqrt{p} \cdot D^2$$

$$\text{Power (hp.)} = 0.0174 \cdot p^{3/2} \cdot D^2$$

where

D = nozzle exit diameter in inches,

p = pump pressure in psi.

For specific energy calculations the energy input was then computed using

$$\text{Energy (in.lbs.)} = 114.91 \cdot p^{3/2} \cdot T \cdot \text{Factor}$$

where T = length of test in seconds

Factor = the term based on the relationship between standoff distance and the portion of the test time that the jet was actually cutting the sample.

$$0 \leq \text{Factor} \leq 1$$

The value of the term "Factor" was determined with reference to Figure 14 by noting that for a given standoff distanced, the angle /2 is found from

$$\tan \frac{\psi}{2} = \frac{L}{2(R+d)}$$

The jet will be on the sample during the time the arm position is inside the range $\psi/2$ and off the sample for the remaining time. In terms of the mechanisms kinematics this yields an expression for the factor of the form

$$\text{Factor} = 2 \sin^{-1}[L/(2(R+d) \cdot \tan \beta/2]/\pi$$

where for the actual mechanism

$L = 12$ in.

$R = 28$ in.

$\beta = 40^{\circ}$

which yields values for various standoff distances as calculated in Table 2. Thus when a stand of distance of 4 in. was used the jet was only on the sample 34.4% of the time. The specific energy required to cut the material was then computed from energy divided by the volume of the slot expressed in cubic inches.

2.5 Range of Parameters Tested

In general the water jet cutting action is more pronounced close to the nozzle exit. This results from the fact that the jet becomes less coherent and more dispersed as it travels away from the nozzle exit. For this test the stand of distances were maintained in the range from 0 up to a maximum of 12 inches.

The exit velocity of the jet increases with increasing pump pressure. There is no known method of predicting the optimum pressure to use for cutting a particular material. There usually is however, a threshold pressure below which little or no cutting takes place. Above this threshold pressure the effectiveness of the cutting depends on many factors, two of which (pressure and flow rate) determine the specific energy requirement which is the energy input required to excavate a given volume of material. In the test conducted, pressures up to 15,000 psi (103.5 MPa) were used to cut the samples. This pressure is well below the threshold pressure required to actually cut the individual pieces of gravel embedded in the ice. The method of generating the slot relies upon freeing the gravel from the parent body of ice so that subsequently the jet can wash the freed material from the slot. The threshold pressure for the ice itself appears to be quite low and good results on the ice alone could be obtained at pressures below 5,000 psi (34.5 MPa).

With the various combinations of pressure and nozzle diameter tested, the calculated power input ranged from a maximum of 51.1 hp. on run #11 to a minimum of 9.8 hp. on run #12. These values coupled with the fact that the jet was actually on the sample approximately 1/3 of the time suggests that the input power levels were relatively moderate for these cutting trials.

2.6 Test Results

The cutting test results on the samples of frozen gravel are quite interesting in that they exhibit some characteristics which are different from typical water jet cutting data available for rocks. For example, for rock samples, it is normal that the penetration rate of the jet would decrease uniformly with increase in the stand off distance. In the conducted tests this pattern was not observed and the penetration rate was fairly constant.

Figure 14 shows the depth of cut for nozzle number 370 (0.062 in. dia.) at 5600 psi after exposure time of 30, 60 and 90 seconds for three different stand off distances. It is interesting that the slope of each curve is the same which means that the penetration rate does not depend on the stand off distance. Surprisingly the penetration at 12 in. standoff distance was better than at 8 in. This suggests that the standoff distance does not have a major influence on the efficiency of cutting and that the grain size distribution at a particular slot may have influenced the results. Since the water jet is not cutting the gravel, the slot depth is increased by freeing pieces of gravel and washing them out. It would suggest that the slot width depends rather on the grain size than the geometry of the nozzles, and also that the volume of water supplied at a given energy level may play an important role in overall efficiency.

The same type of results were obtained for other nozzles and pressure values, as shown in Figures 15 through 19. Figure 18 and 19 show cutting results for 2^{o}, 8^{o} and 12^{o} deverging nozzles, no. 300, 330 and 350 at 6,000 psi pressure. These nozzles produce two jets whose cross section is equivalent to the area of the 370 nozzle exit. When the standoff distance was small, the results were similar to the single 370 orifice nozzle results. If the stand off distance is increased to allow the jets to cut two separate slots, the penetration decreases slightly due to the smaller size of the jet. However, this effect deserves further study because in some instances the individual slots joined together to form a single larger slot. This could work well when the water jets were used to support a mechanical tool of some type for excavating in frozen gravel.

The specific energy required to excavate the material is of great interest when planning a full scale mining system. The specific energy values were calculated for the jet cutting trials based on the input energy and the volume of the slot generated. The slot volume was calculated using the average depth and width measured after each cut. These results are shown in two Figures 20, and although there is some scattering of the data, they suggest a lower specific energy volume as the pressure is reduced. Two functions were fitted to the experimental data; namely a straight line $y = ax + b$ and an exponential curve $y = ae^{bx}$. The latter fits the data best with the coefficient of correlation $r = 0.5274$. The minimum average specific energy value at 3000 psi is $E_s = 0.174$ in.lb./in^3. This trend must seize at some pressure below 3,000 psi since the threshold pressure for the material must lie somewhere around this value. These results suggest that there is a good potential for designing a water jet mining system for permafrost where the operating pressure would be below 5,000 psi.

Figure 21 shows the arrangement of the nozzle relevant to the face of the sample on test run 23 and 24. In these two cases, the nozzle was held stationary relative to the sample so that the "drilling" effect of the jet could be investigated. In run 23 the nozzle 430 was used at 3,000 psi to wash out a cavity 5 in. in diameter and 8 in. deep in less than 1 minute of operation. On run 24 the same nozzle was moved about 7 in. away from the previous position and was used to cut a cavity which connected into the previous one in 25 seconds of operation. This technique may have some advantages in working to a "free face" after the initial cavity is formed.

2.7 Conclusions Regarding Laboratory Jet Cutting Tests

The lowest specific energy value resulted for the case of water pressure of 3,000 psi. This suggests that it would not be necessary to use very high pressure to effectively cut the frozen gravel. Considerations which must be made are to decide what volume of water could be tolerated in mining underground and how much power the system should be designed to consume.

For the range of standoff distances tested, the nozzles cut effectively and were able to free gravel pieces up to 2 in. in diameter and wash them from the slot. This suggests that the standoff distance has no major influence on the efficiency of cutting and both slot cutting and drilling are worthy of consideration when planning further in-situ studies.

In a few trials, slots were positioned to excavate frozen gravel by combining an old slot with a new one. This appears to have some potential-to work toward a free face. The same statement applies for holes which overlap.

The test run with the dual orifice divergent nozzles indicates that the two jets can work to cut around and free pieces of gravel which can result in a slot wider than from a single orifice nozzle. This would be a possible solution when large pieces of gravel are encountered.

Based on the ability of the jets to clear the free pieces of gravel from the slot, it would appear that the nozzle could enter the slot in order to increase the depth as desired.

With limited amount of tests run, the general conclusions regarding feasibility look promising. Therefore further jet cutting tests of frozen gravel should be conducted under field conditions to gain additional data for the possible design of a mining water jet system for placer deposits in frozen ground.

3.0 HIGH PRESSURE WATER JET FIELD STUDIES

3.1 Test Facility Description

The test equipment consisted of a water pump system, a water supply system and a nozzle traverse system.

A triplex plunger pump rated at 40 gpm and 4,500 psi driven by a 125 hp. 440 VAC electric motor was rented for these studies from the U.S. Bureau of Mines office in Minneapolis. The pump was equipped with a pressure gauge and an overload safety valve. Pump and motor, which were skid mounted, were placed in the lower portion of the winze in the vicinity of the U.S. Bureau of Mines chamber in the U.S.A. CRREL Permafrost Tunnel at Fox (Figure 22A). After the first unsuccessful test, heating tapes were applied to the inlet and outlet pipes of the pump and an infrared heater was used to keep the pump warm. Fiberglass insulation was used to keep the valves and pump from freezing.

Water was supplied from a tank truck parked outside the portal to a 500 gal. capacity tank in the tunnel. From there water was gravity and/or pump fed to a high pressure pump by 100 ft. 2 in. ID steel pipe. A 20 ft. long 0.5 in. ID high pressure hose was used between the pump outlet and the nozzle. A bronze 0.138 in. diameter straight nozzle was used in these experiments. The hose was connected to the nozzle holder and pump's high pressure outlet through 0.225 in. ID fittings. The water discharged during testing was collected in a small sump below the testing stand and after each series of tests was pumped to either the main tank underground when additional tests were planned, or directly disposed outside.

The 0.138 in. diameter nozzle was connected through the nozzle holder to the hose which was fixed inside the steel tube attached to the tiltable feed as shown in Figure 23. This arrangement allowed for the nozzle to be moved forward and backward, rotated by ± 180° and oscillated in a horizontal plane.

3.2 Testing Program

The main purpose of the undertaken pilot in-situ studies was to evaluate:

- the overall performance of the high pressure water jet system,

- the erodability of the frozen gravel and bedrock associated with gold placer deposits when being cut and "drilled" with high volume medium pressure (below 5000 psi) water jets,

- and through the gained experience and accumulated pilot results to suggest 2nd stage of the testing program.

Cutting of slots and drilling of holes in the bedrock and frozen gravel was done in 1 to 4 min. steps at pressures ranging from 2000 to 4400 psi. After each cutting period the size of the cavity was measured. Any changes in water pressure, air and rock temperature were recorded during the testing period. The rock temperature was monitored at the roof surface, whereas the air temperature was measured 4 ft. above the floor. Both temperature transducers were placed about 15 ft. from the pump, in the vicinity of the area where the cutting took place.

3.3 Test Results

Two sets of experiments (Table 4) were run to evaluate the cutability of frozen gravel. In the first set the average water gravel and air temperatures were $34^{\circ}F$, $25.8^{\circ}F$, $26.8^{\circ}F$, respectively. Four tests were run, each lasting 60 seconds at pressures varying from 2000 to 2300 psi. During the second series, three tests were run, each for about 4 minutes with pressure varying from 2300 to 3550 psi. At that time the average water, gravel and air temperatures were

50^{o}F, 25^{o}F and 25^{o}F respectively. During cutting the nozzle advancement (along the cut surface) rate varied from 1 to 2 in./min.

The location of the slots is shown in Figure 22B, whereas size and shape of the slots obtained during successive cutting in frozen gravel are shown in Figures 24B and 26. The maximum depth of cutting during the first series was 31 in., whereas during the second series it was 58 in. Based on the accumulated data, the specific energy was calculated and was found to vary from $0.84 \cdot 10^5$ to $8.9 \cdot 10^5$ in.lb./in.^{3}.

A similar series consisting of four tests was run for slot cutting in bedrock. At that time water, gravel and air temperatures were 33^{o}F, 26.4^{o}F and 27.7^{o}F respectively, while the water pressure varied from 2400 to 3200 psi and the nozzle was moved at constant velocity of 4 in./min. as indicated in Table 4. The specific energy for high pressure water jet cutting in bedrock varied from $(6.6$ to $8.9).10^5$ in.lb./in^3. The location of the slot is shown in Figure 22B, and its size and shape are shown in Figure 25.

Two additional series of tests were run with stationary nozzle. The first series consisted of three tests run 60 seconds each at pressures varying from 2200 to 2700 psi., whereas, in the second series six tests were run at pressures from 2600 to 4100 psi with duration time for each test from 1 to 2 min. (Table 4). In both cases the water used was at temperature close to freezing, although the gravel and air temperature were similar to the ones reported earlier. The specific energies were from $(0.32$ to $34.25) \cdot 10^5$ in.lb./in.^{3} The size and shape of "drilled" holes are shown in Figure 27 and their location in Figure 22B.

The grain size distribution curve for the cut gravel is shown in Figure 24A. The sample tested for grain size distribution represents most of the material removed from slots and holes cut in the frozen gravel.

3.4 Analysis of Data and Observation

As it usually happens when running tests under in-situ conditions the obtained data are scattered, still they show quite interesting relationships.

First of all, the specific energies are much higher than those obtained under laboratory conditions during the testing program in Rolla. At least two factors seem to be contributing to this fact:

- Diameter of the hose and fittings as well as type of the nozzle used in the Permafrost Tunnel very likely contributed to substantial energy loss in the system itself.
- Material tested in the Permafrost Tunnel contained much larger pieces of rock, which very likely contributed to greater values of the specific energy.

The calculated specific energy variation with the standoff distance does not confirm the commonly accepted view that with increase in the standoff distance above about 4 in. a substantial loss of high pressure water jet energy is observed. This is not to say that we have clearly demonstrated that the energy of the water jet does not decrease with the standoff distance. Very likely additional factors such as (1) the increasing pump pressure with the increase in testing time, as well as (2) the fact that at greater distances from the opening's surface the concentration of compressive stresses in the side-wall might have been lower, very likely contributed to this fact. This may mean that if the pump delivered higher pressures at smaller standoff distances, the specific energies would be smaller indicating that the overall cutting efficiencies would be better.

Looking at the obtained results quantitatively, the optimum specific energy is $0.32 \cdot 10^5$ in.lb./in.^{3}. at 4100 psi. At this point (four from the nozzle) the rate of material removal was 37.5 ft^3/hr. or in terms of drilling a 6 in. diameter hole, the rate of drilling would be 191 ft/hr. or 3.18 ft/min.

When analyzing the accumulated data in terms of pressure/specific energy relationship it is quite clear that at lower pressures, in the range of 2000 to 3000 psi, the efficiencies are generally much lower than at pressures around 4000 psi. It would suggest that based on both laboratory and in-situ data, the optimum specific energy can be obtained for pressures around 3,000 to 4,000 psi for a system with minimum pressure loss.

The overall performance of the equipment used under the low temperature conditions was satisfactory. Except for the initial problems with water freezing no major obstacles were encountered. This include, the equipment freeze-up, fog and mist generation, noise level etc. However a shield protecting the operator from flying rocks and debris is needed.

4.0 CONCLUSIONS AND RECOMMENDATIONS

Based on the conducted laboratory and field experiments run at different conditions in terms of type of gravel, pressure, temperature and flow rate, the pressure for optimum specific energy seems to be in the range between 3000 and 4000 psi. Further field studies are needed to confirm this conclusion. They should be run at 1000 to 15000 psi pressures and 1 to 50 (if possible) gpm flow rates with better documentation of such parameters as grain size distribution, ice content, water and frozen gravel temperatures, standoff distance and pressure loss.

In addition to the better evaluation of the pressure loss and the standoff distance influence, the time of testing and the traverse velocity of the nozzle should be taken into account. Altogether these recommendations call for better control and monitoring equipment.

Cavijet cavitating nozzles should also be tested to evaluate the efficiencies in cutting and drilling in frozen ground.

The size of the second stage field studies should be increased so that the overall number of data points would be sufficient for reliable conclusions based on experiments conducted in this highly none-uniform material. Testing of artificially made samples with strictly controlled ice content and grain size distribution should be considered when the data to be collected will not be consistent.

The water used in testing should be recirculated through some sort of settling containers. The anti-freezing agents should be considered and their feasibility of application and impact on the frozen environment tested before they are used full scale.

A device which would allow controllable nozzle movements (constant traverse and rotational velocity) and protection shield for the operator should be incorporated in the second stage of testing.

LIST OF FIGURES

LIST OF FIGURES (cont.)

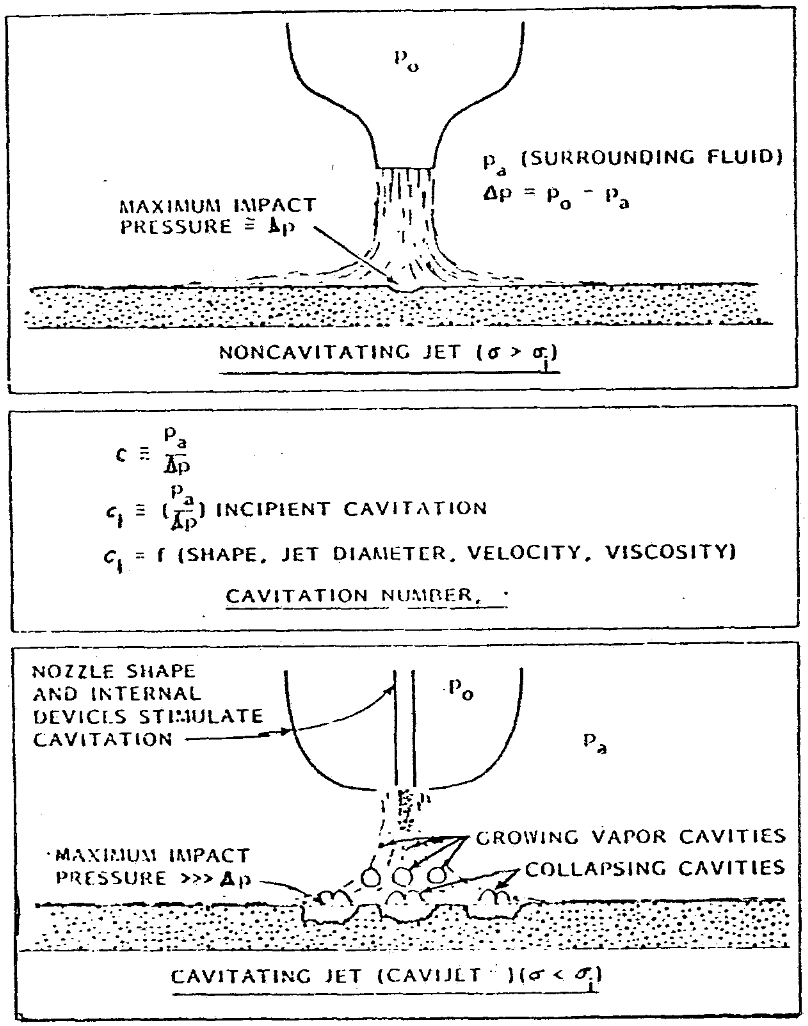


FIG. 1 THE EFFECT OF CAVITATION ON EROSION BY JETS.

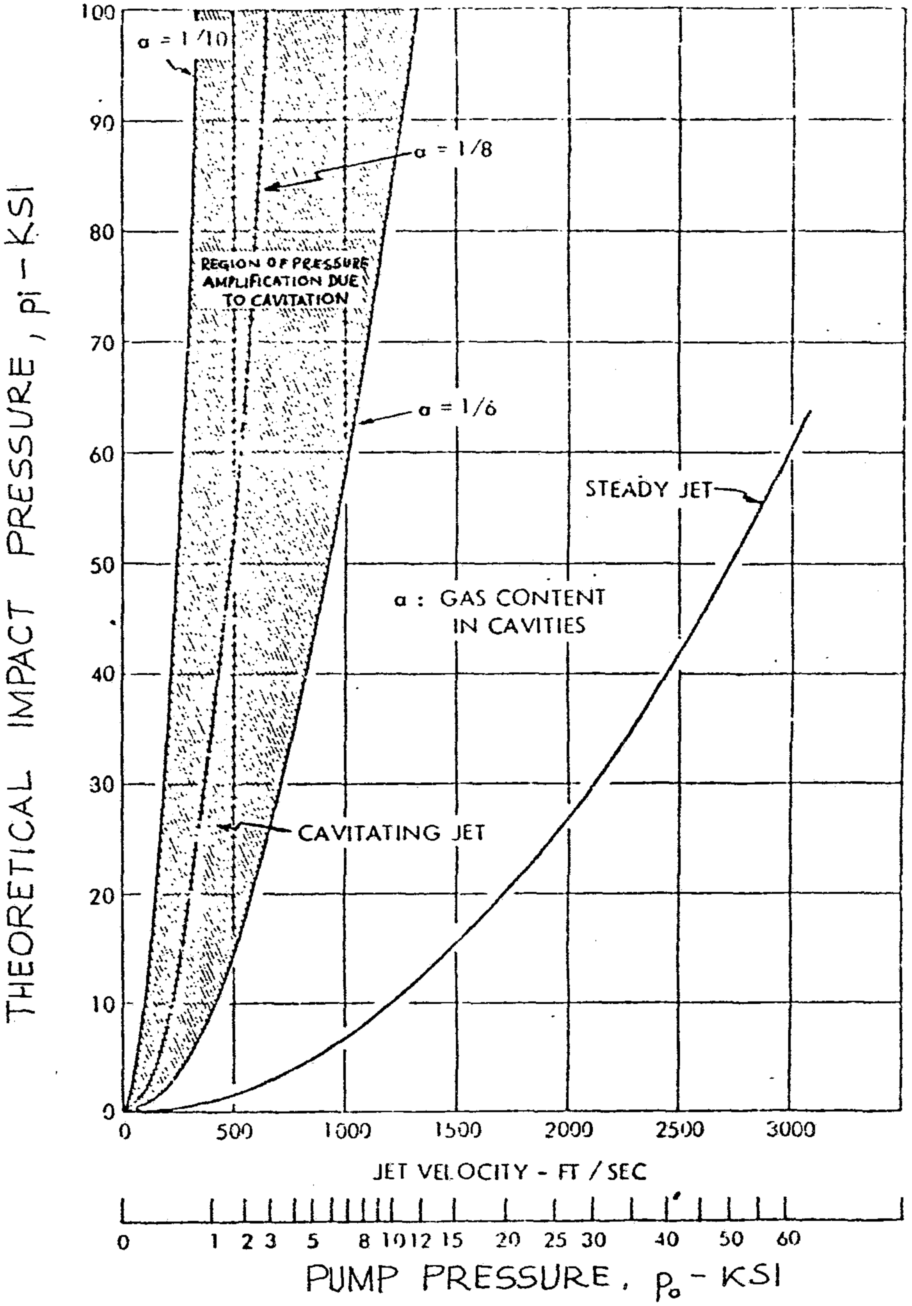


FIG. 2 THEORETICAL COMPARISON OF CAVITATING AND STEAD
WATER JETS.

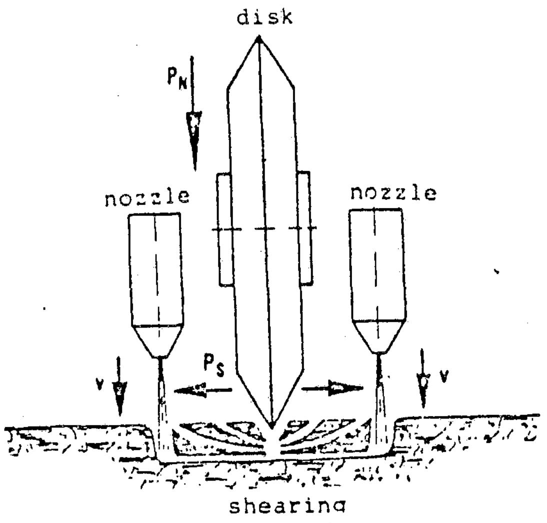


FIG. 3. COMBINED CUTTING SYSTEM

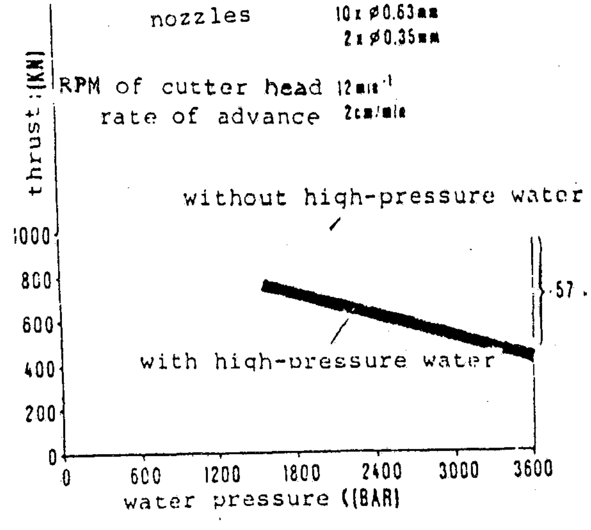


FIG. 4 TUNNELLING MACHINE THRUST AS A FUNCTION OF WATER JET PRESSURE.

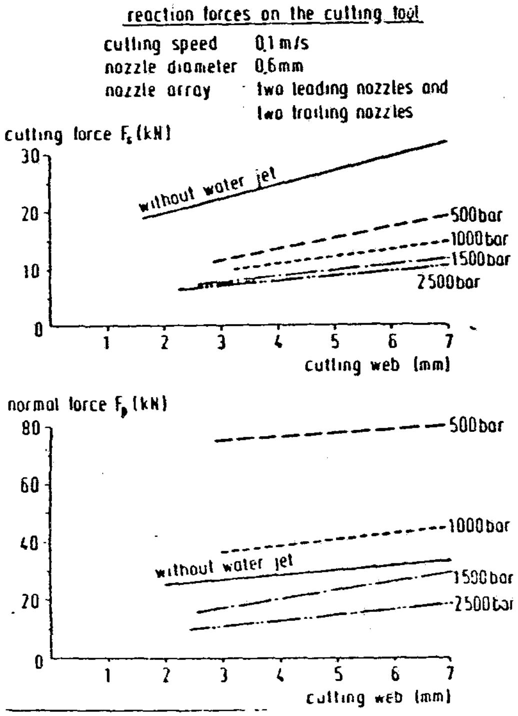


FIG.5 REDUCTION IN CUTTING AND NORMAL FORCES OF A ROADWAY PROFILE SYSTEM CAUSED BY WATER JET APPLICATION

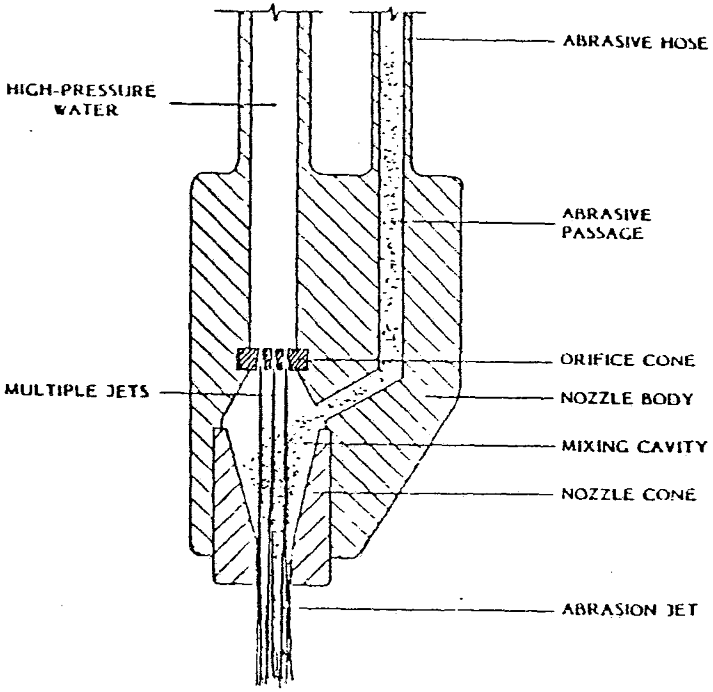


FIG.6 SCHEMATIC ILLUSTRATION OF FLUIDYNE'S ABRASION-JET NOZZLE

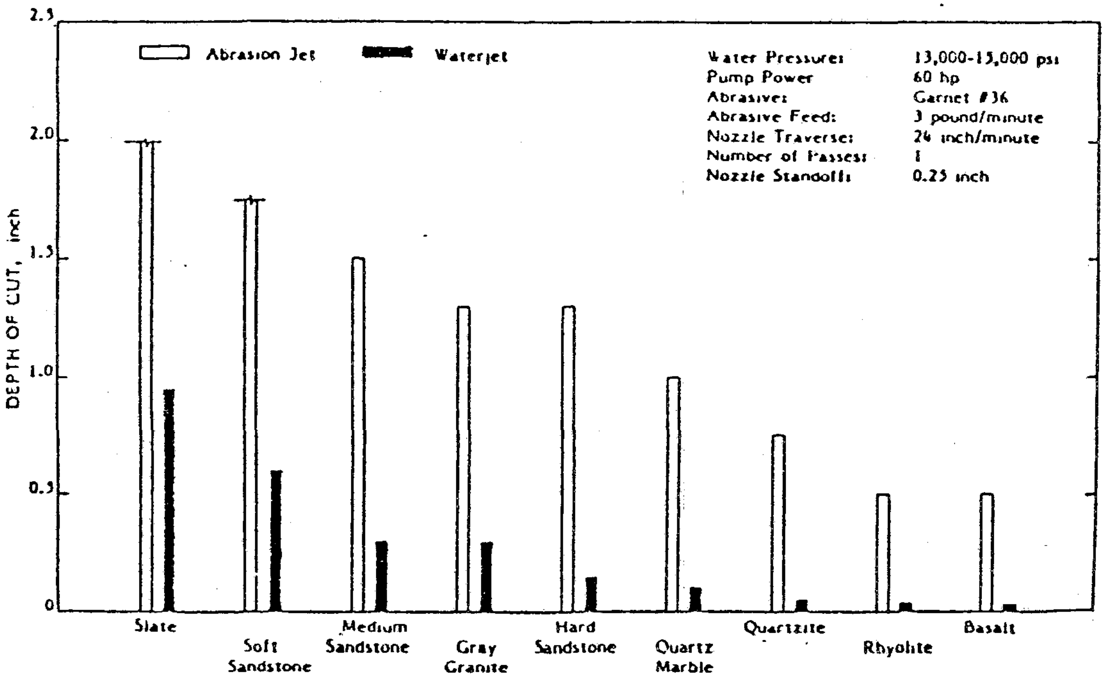


FIG. 7 COMPARISON OF DEPTH OF CUT MADE ON VARIOUS ROCK SPECIMENS

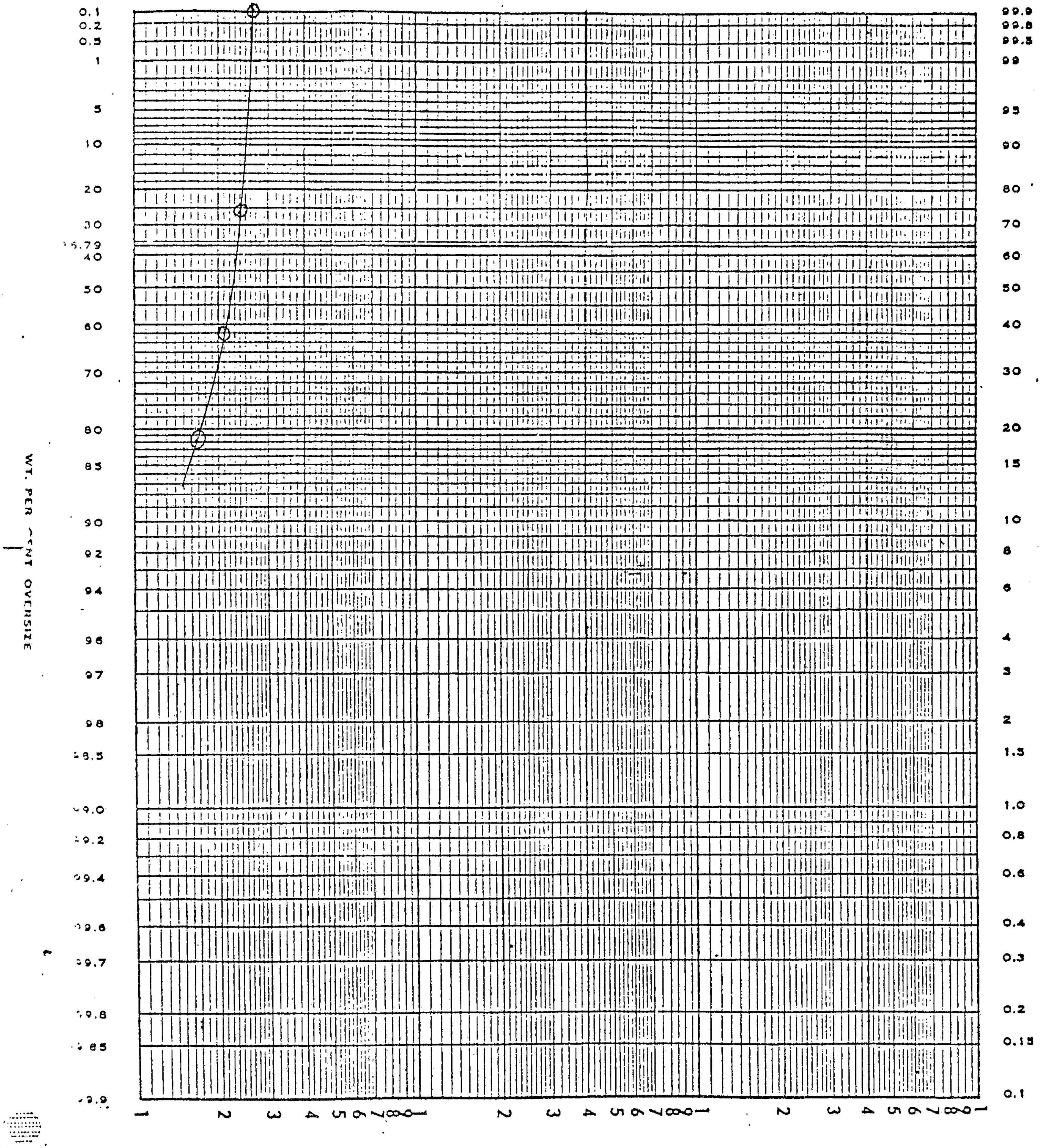


FIGURE 8. GRAIN SIZE DISTRIBUTION CURVE FOR GRAVEL SAMPLE

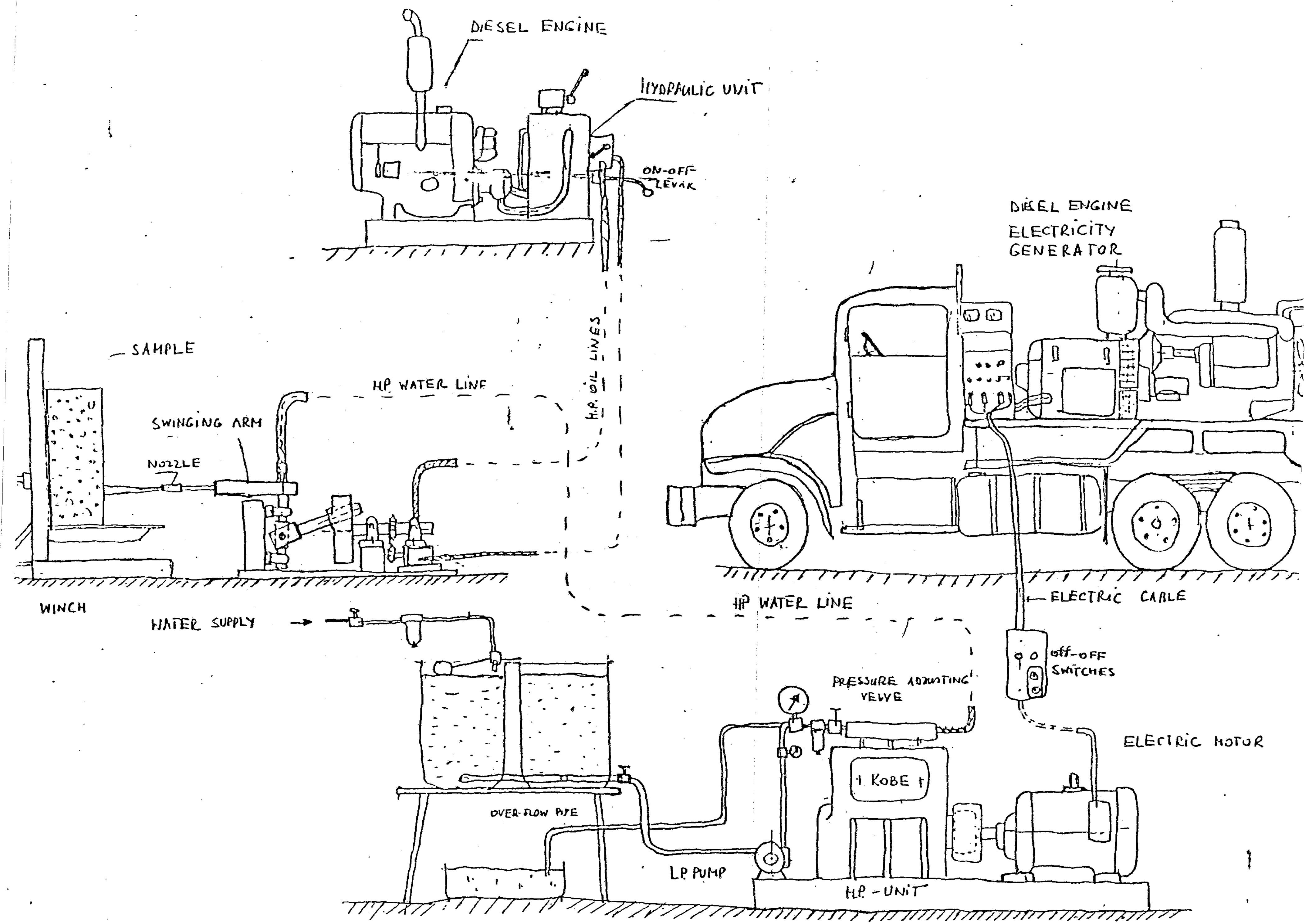


FIG. 9. GENERAL LAYOUT OF EQUIPMENT.

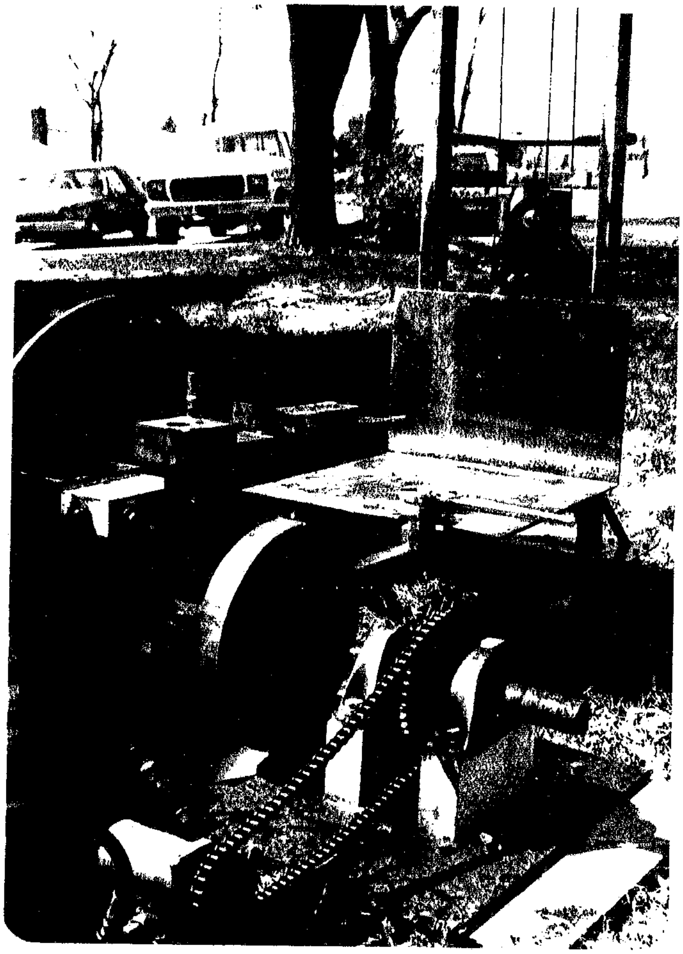


FIG.10 MECHANISM USED TO OSCILLATE THE NOZZLE

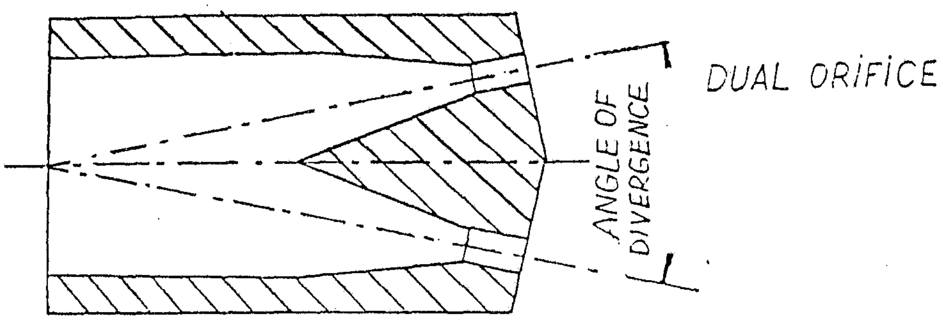


FIG.11 SINGLE ORIFICE

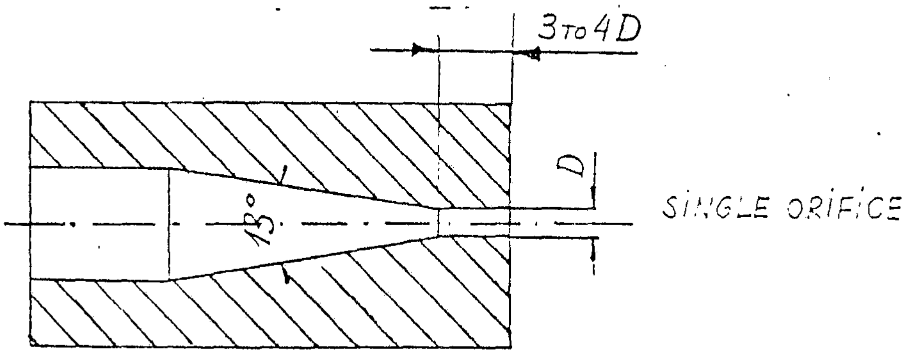
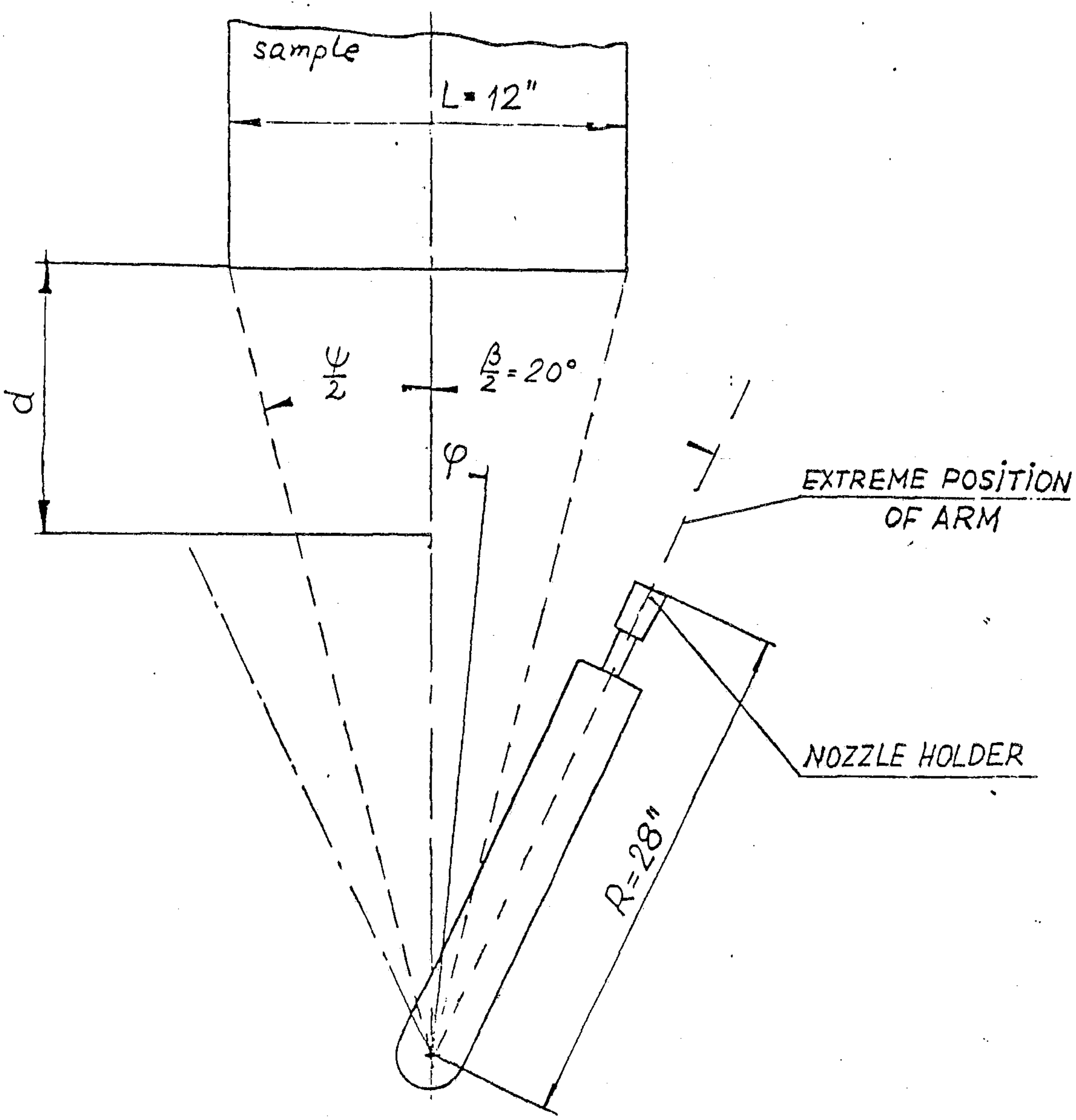


FIG.12 DUAL ORIFICE



ARM MOTION IS GIVEN BY $\varphi = tg^{-1}[tg\, 20° \sin \omega t]$

FIG. 13 POSITION OF THE SAMPLE WITH RESPECT TO THE OSCILLATING NOZZLE

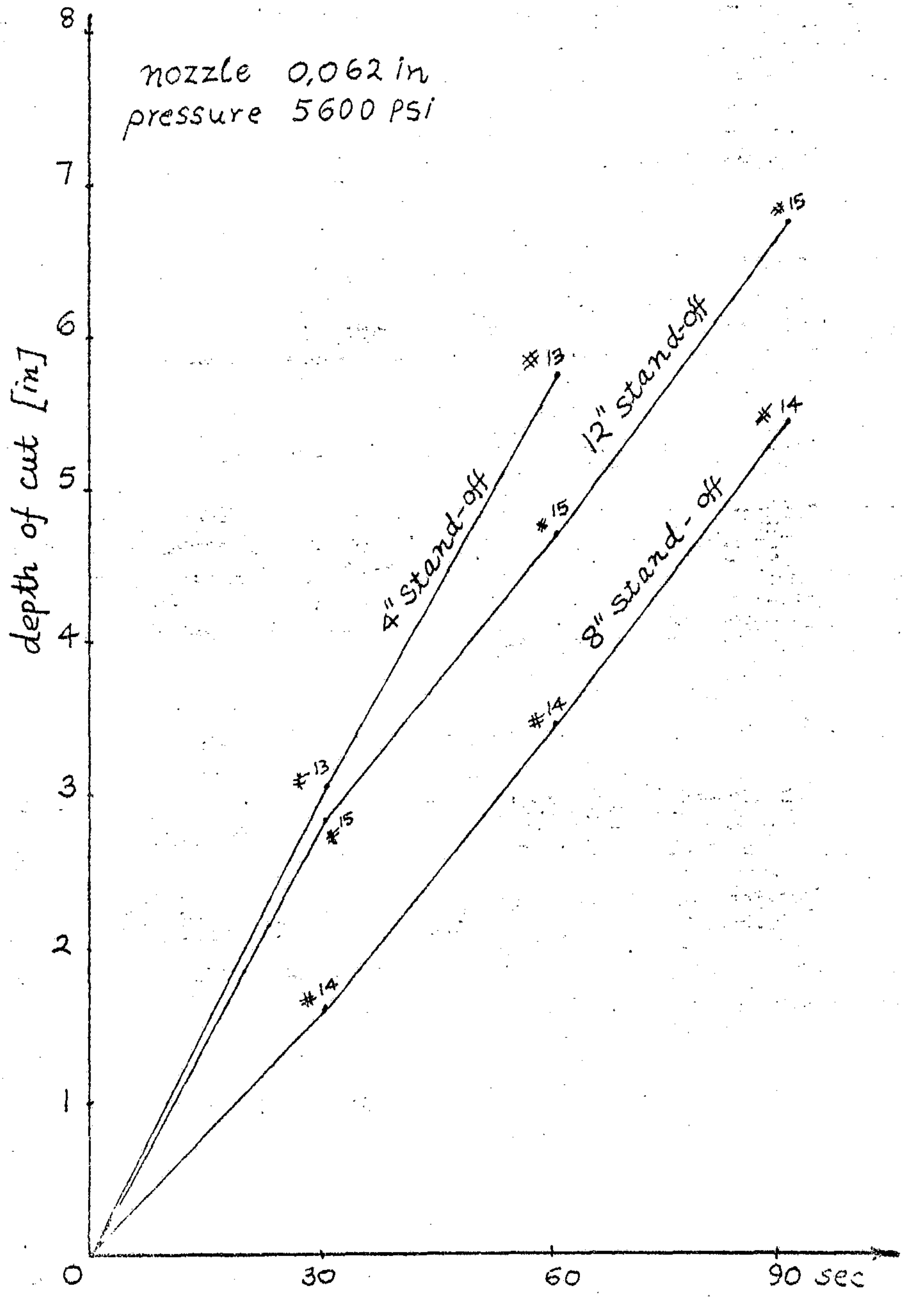


FiG.14 PENETRATION DEPTH FOR NOZZLE 370 AT 5600 PSi

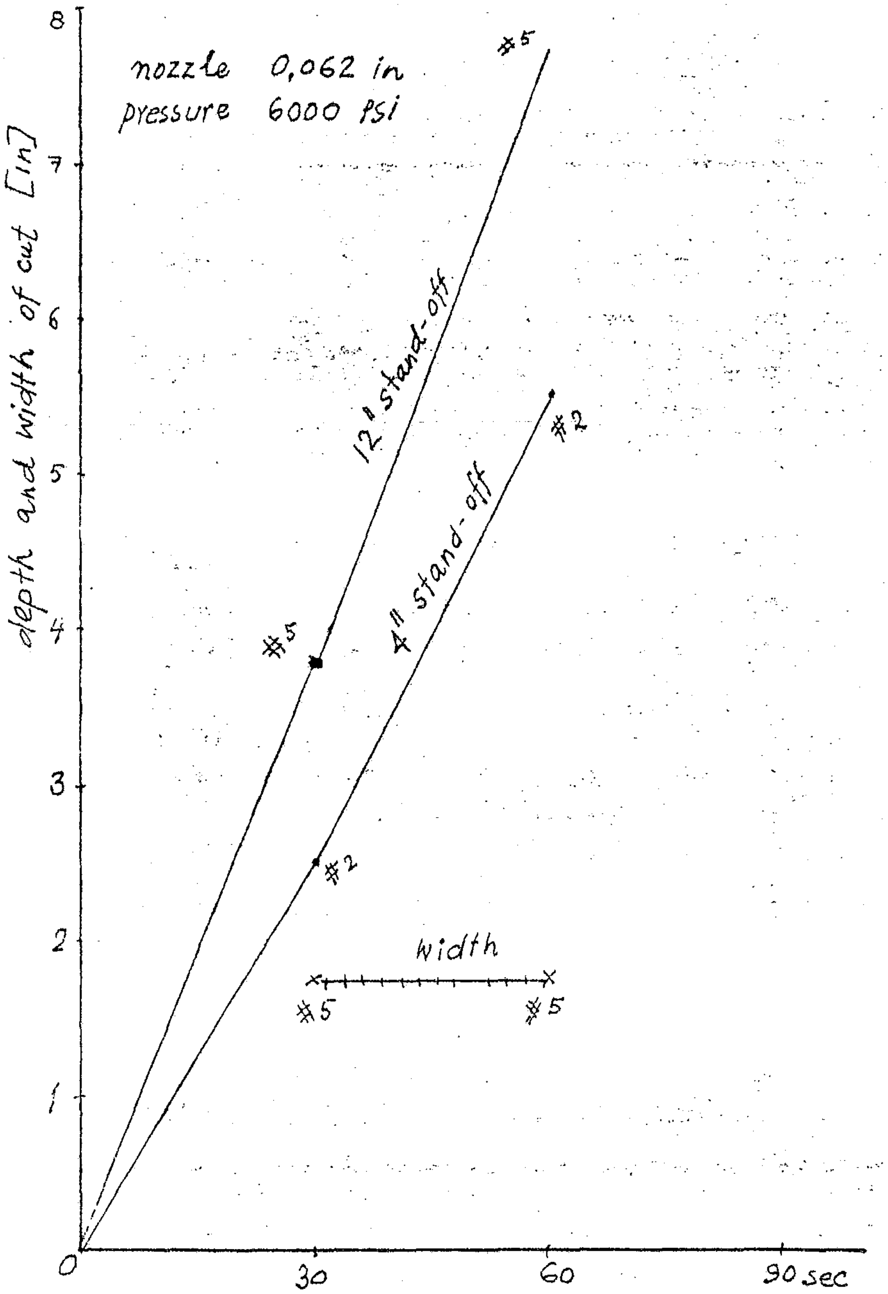


FIG. 15. PENETRATION DEPTH FOR NOZZLE 370 AT 6000 psi.

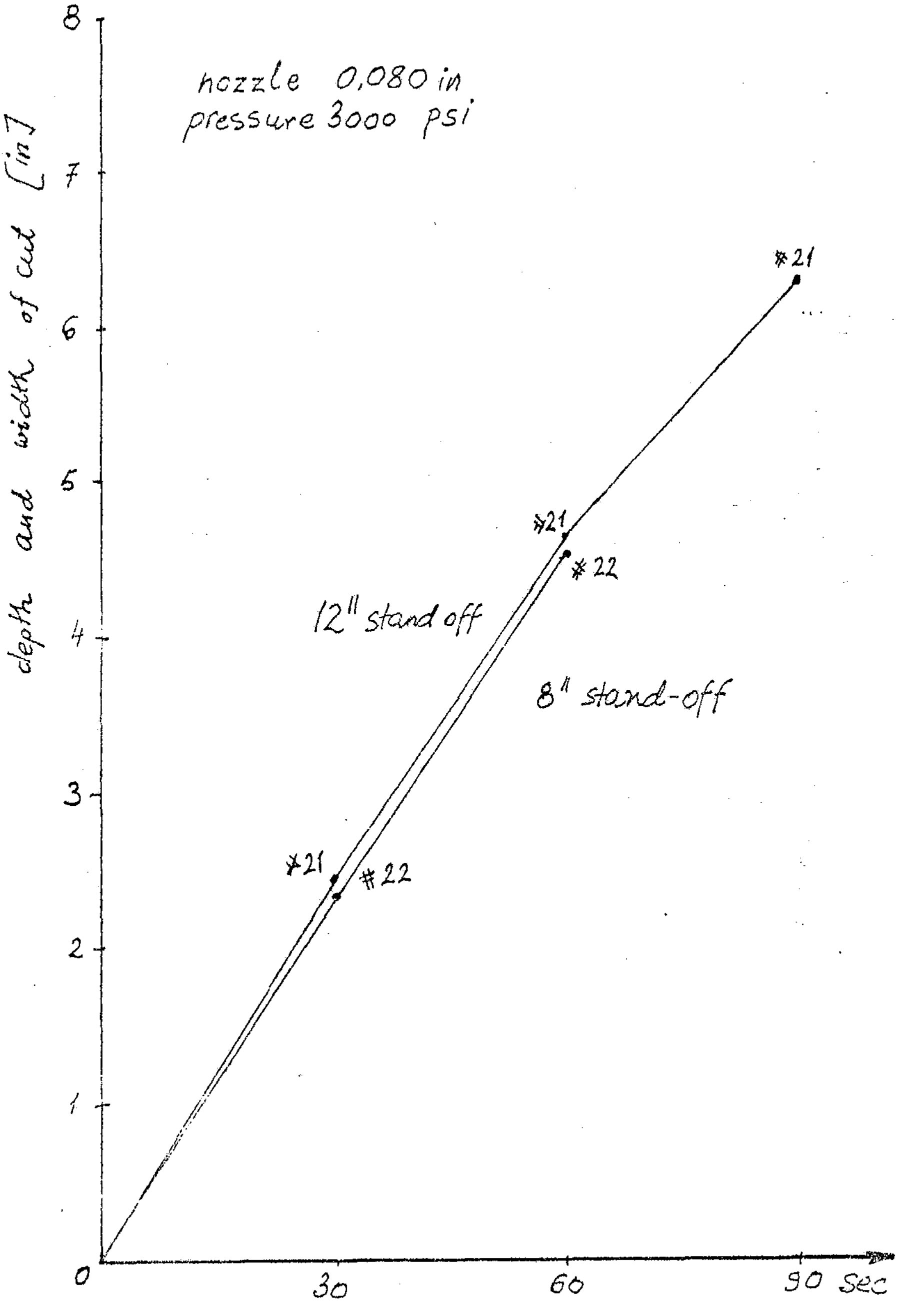


FIG. 16. PENETRATION DEPTH FOR NOZZLE 430 AT 3000 PSI.

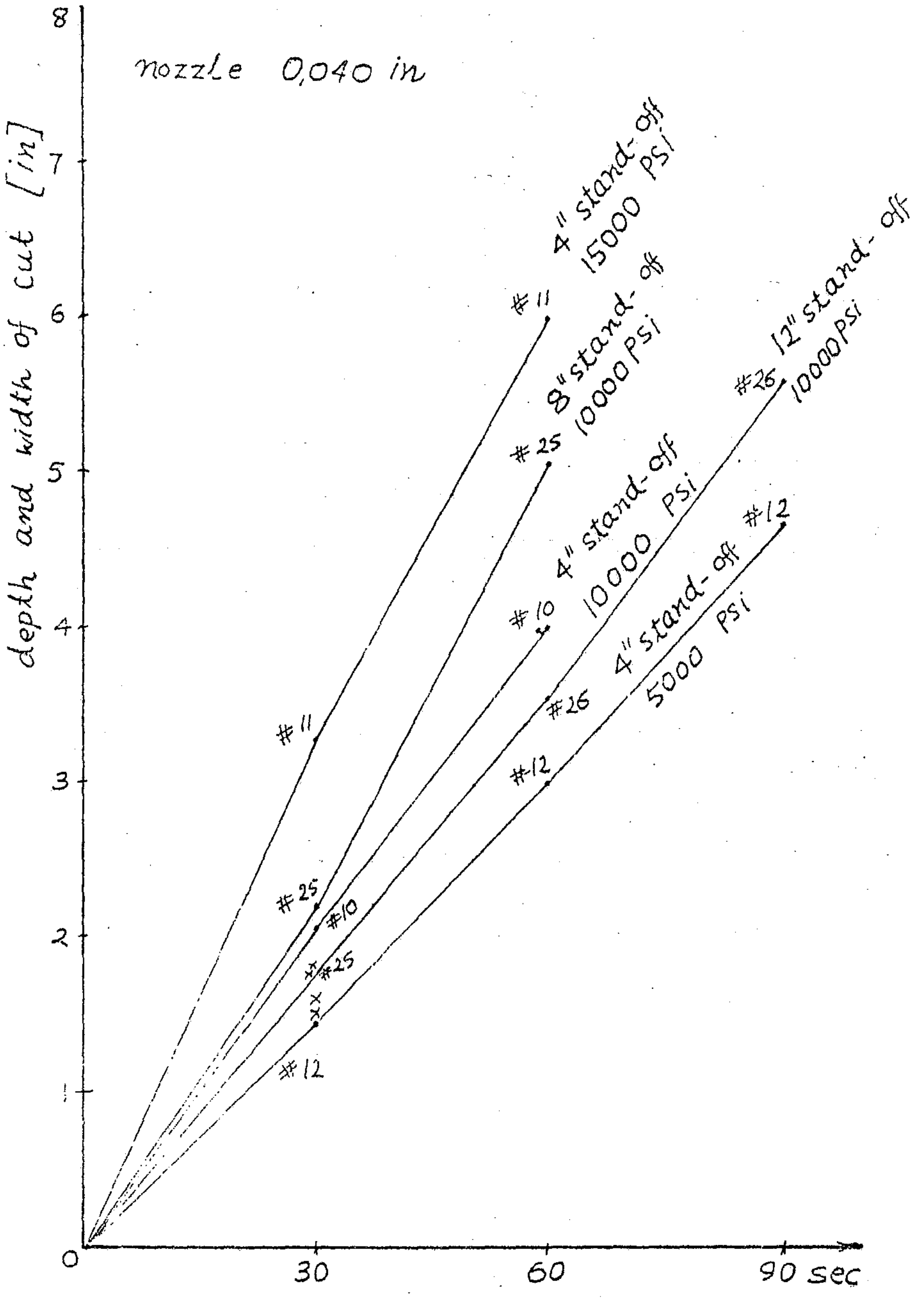


FIG 17 PENETRATION DEPTH FOR NOZZLE 400 AT 5000, 10000 AND 15000 PSI

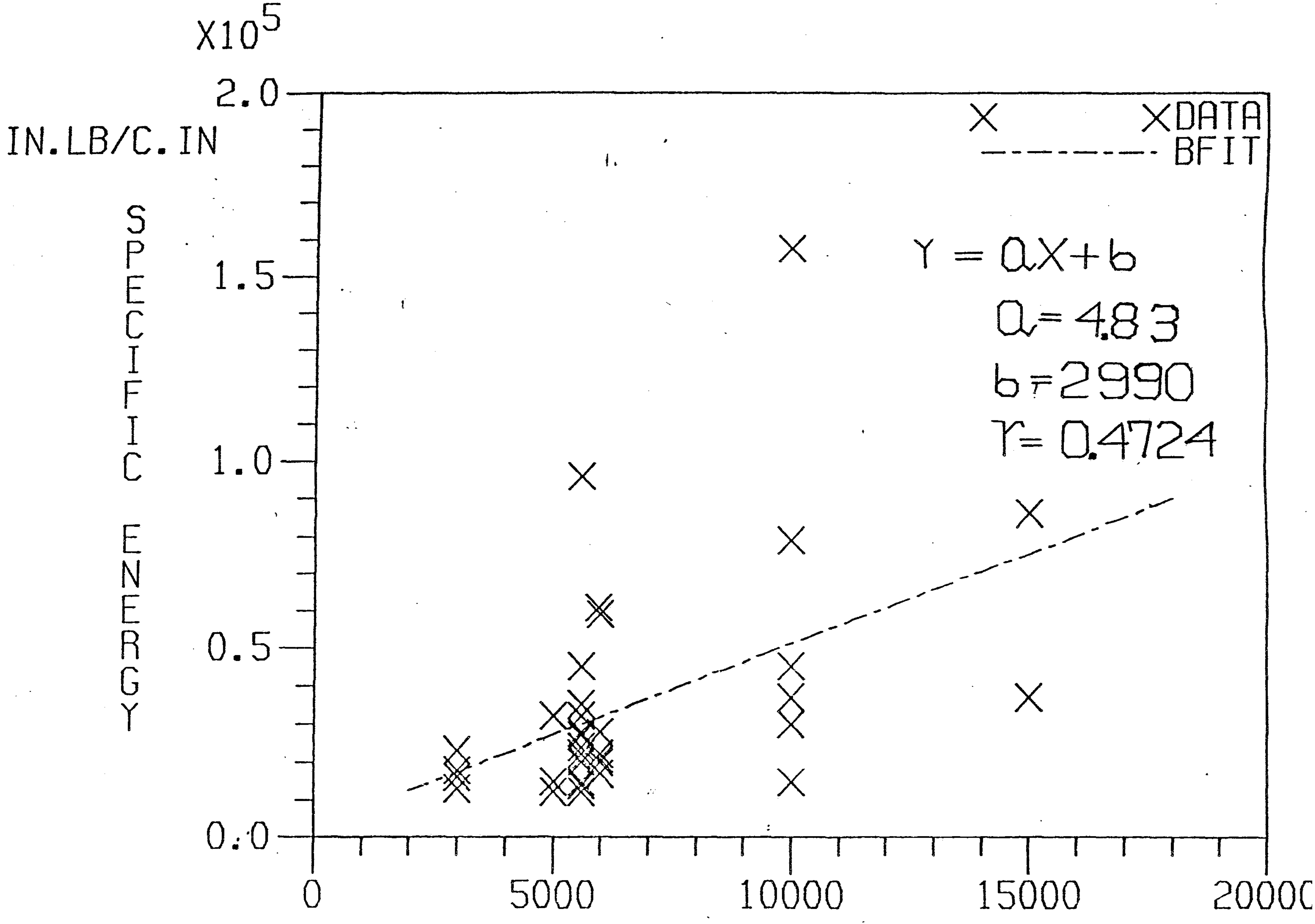


FIG. 20 SPECIFIC ENERGY VS PRESSURE

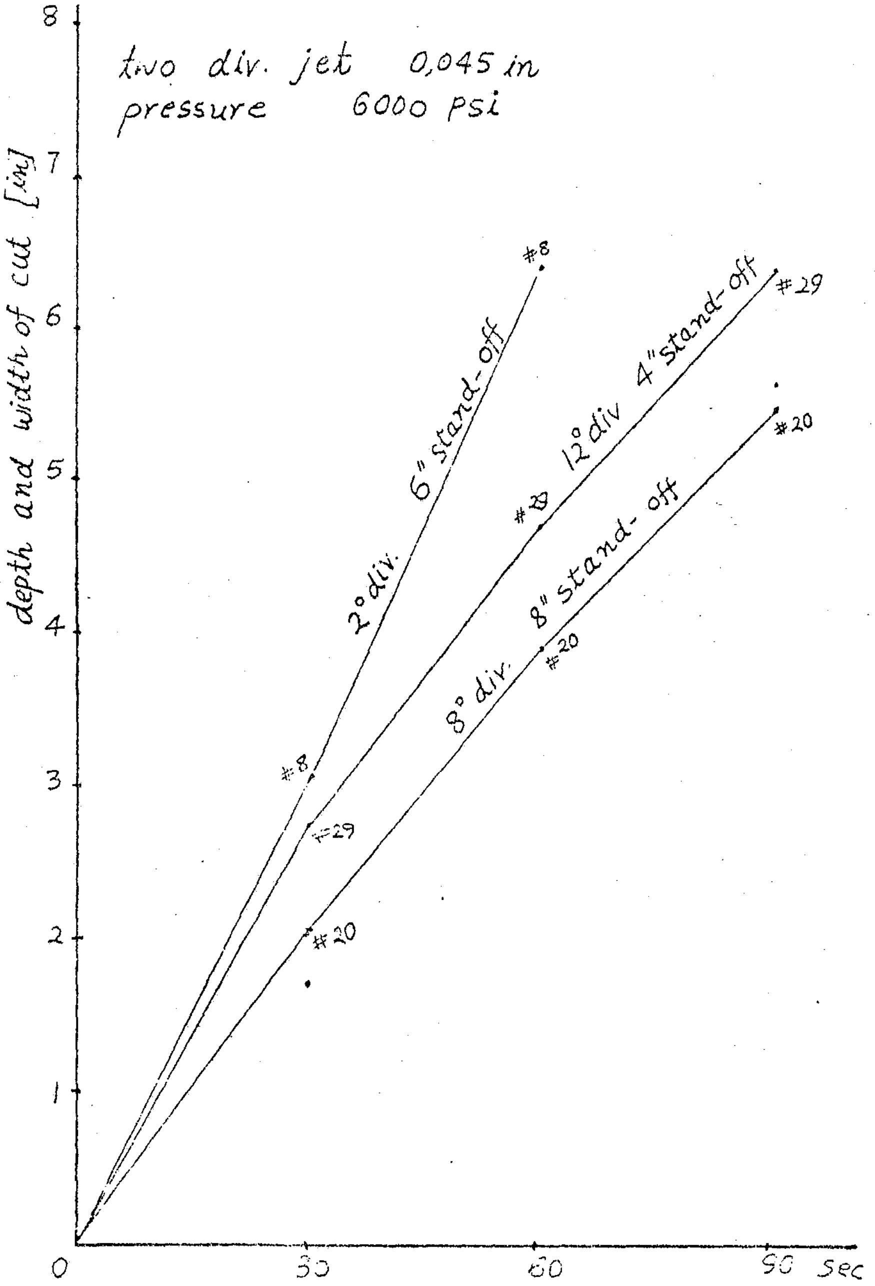


FIG. 18 PENETRATION DEPTH FOR DUAL ORIFICE NOZZLE

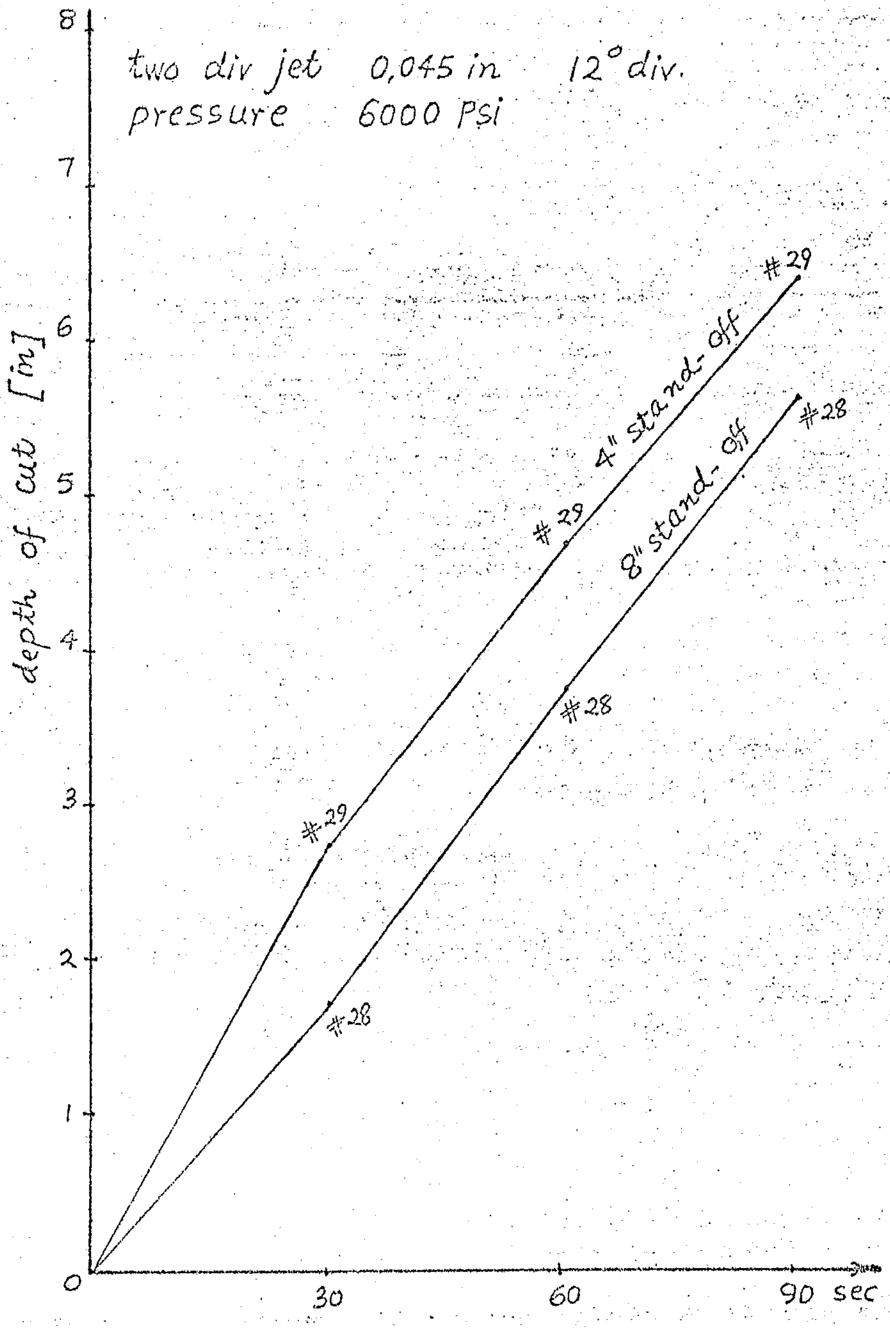


FIG. 19 PENETRATION DEPTH FOR 12° DIVERGING NOZZLE

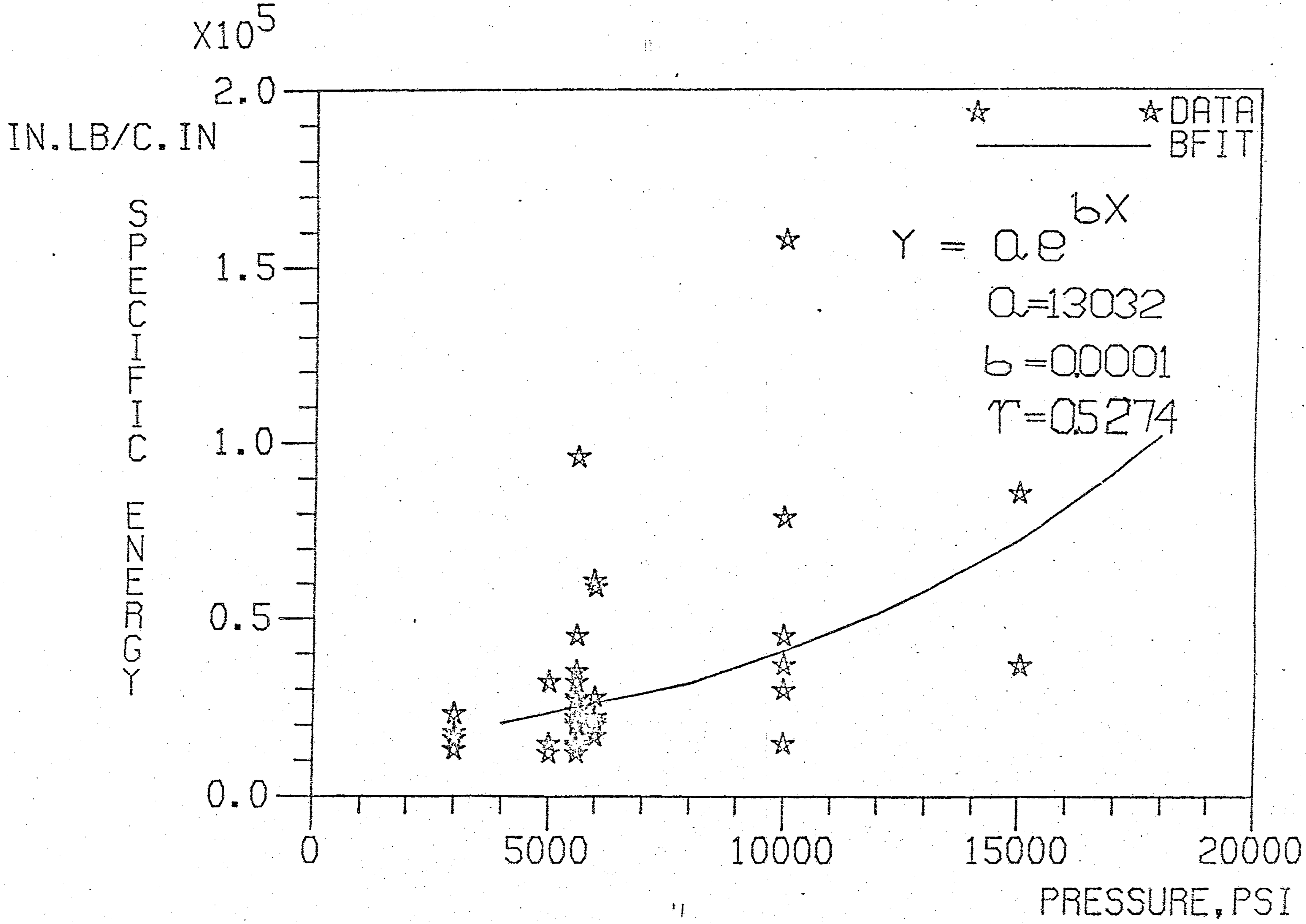


FIG. 20A SPECIFIC ENERGY VS PRESSURE

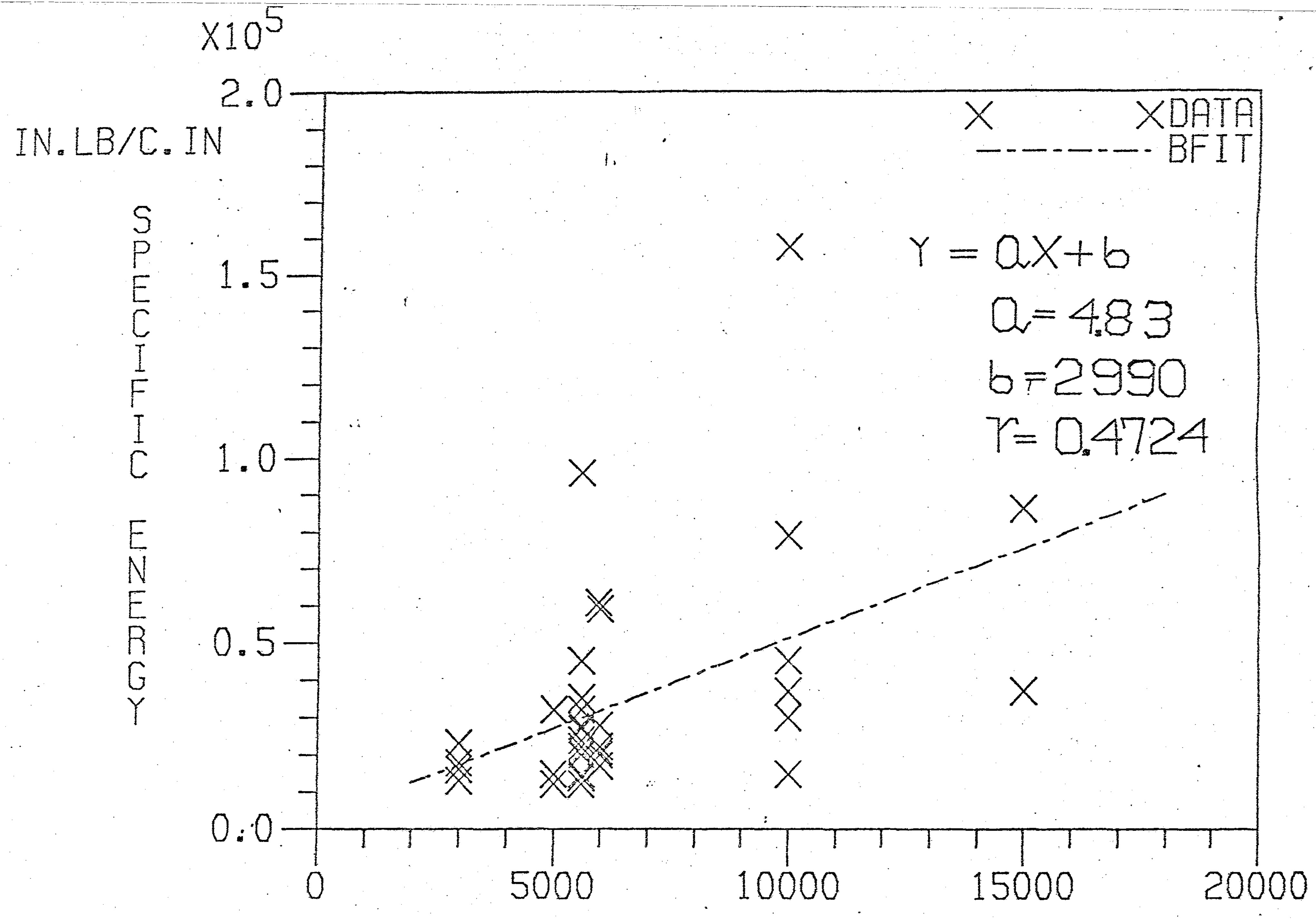
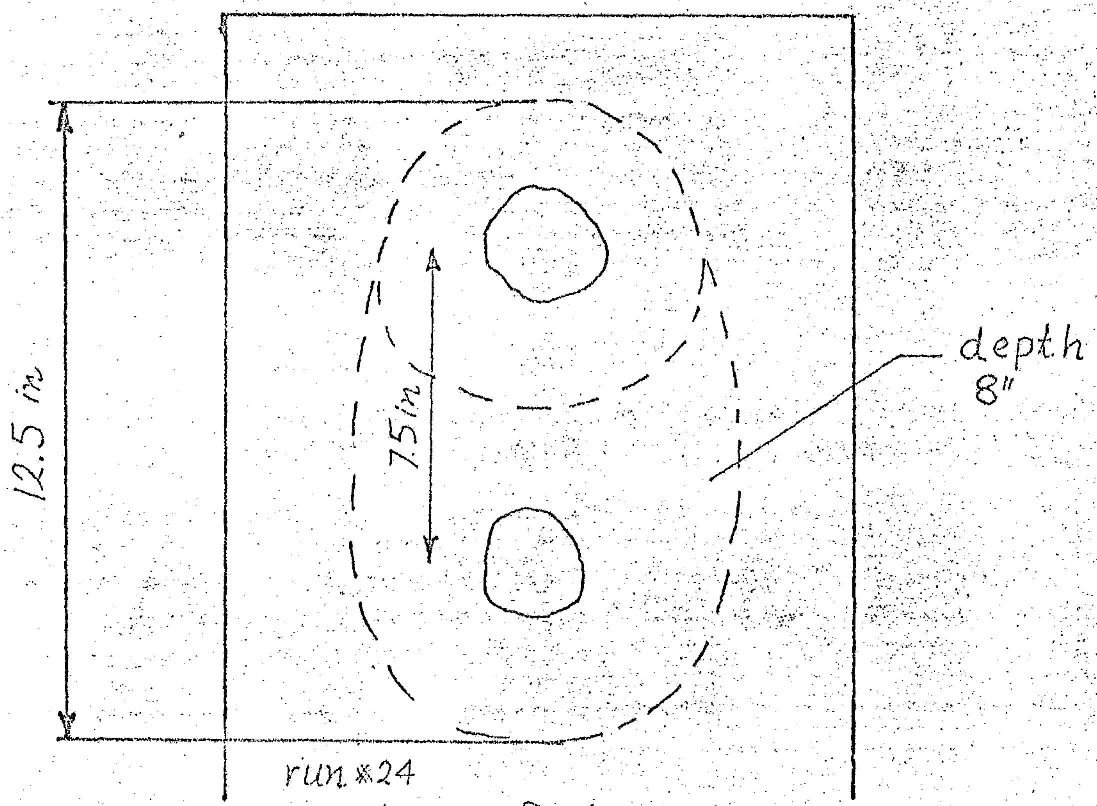
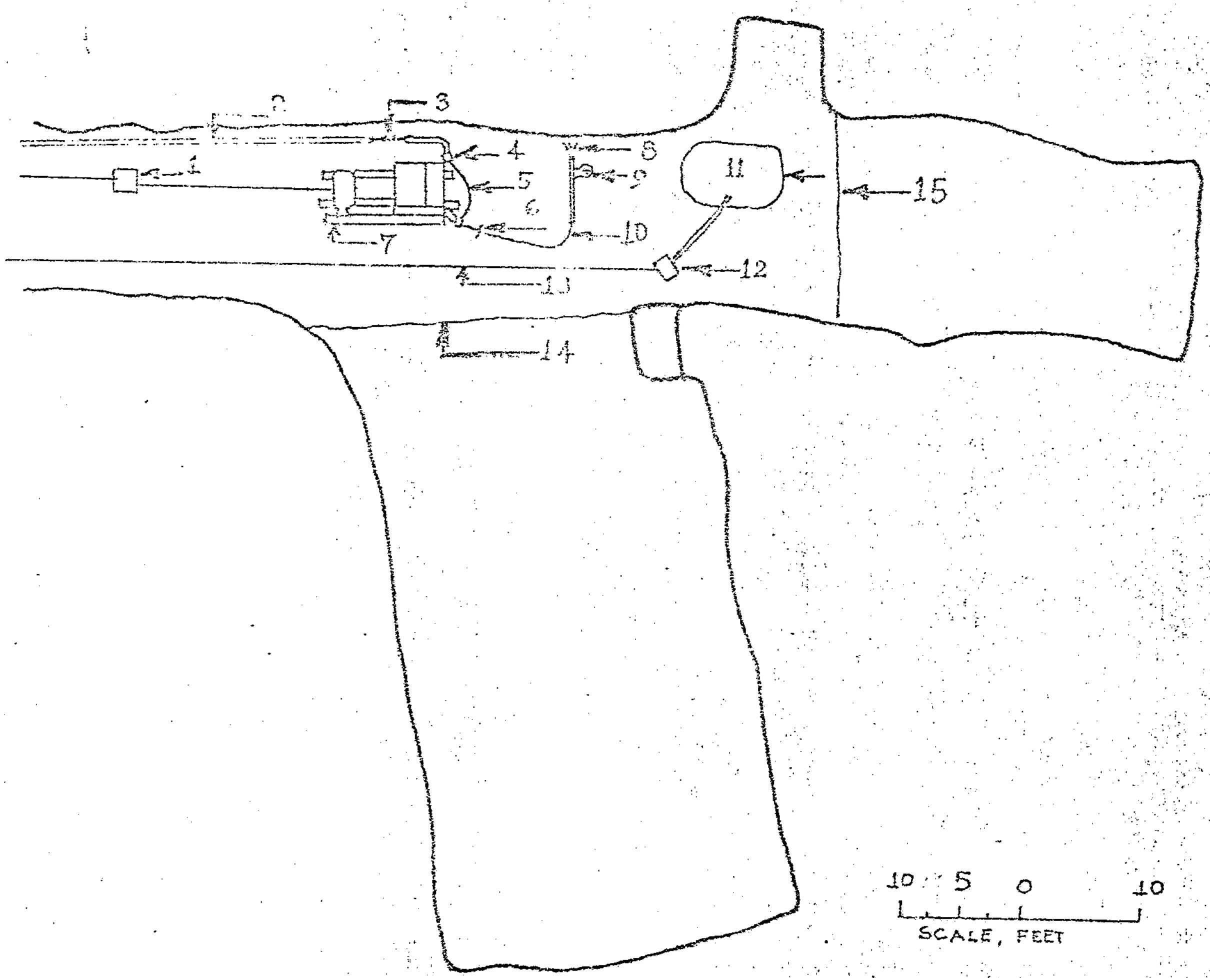


FIG. 200 SPECIFIC ENERGY VS PRESSURE



run #24
nozzle 0.080 in
steady nozzle
stand-off distance — 0 in
time of cut — 25 sec.

FIG. 21 COMBINED EFFECT OF TWO CUTS

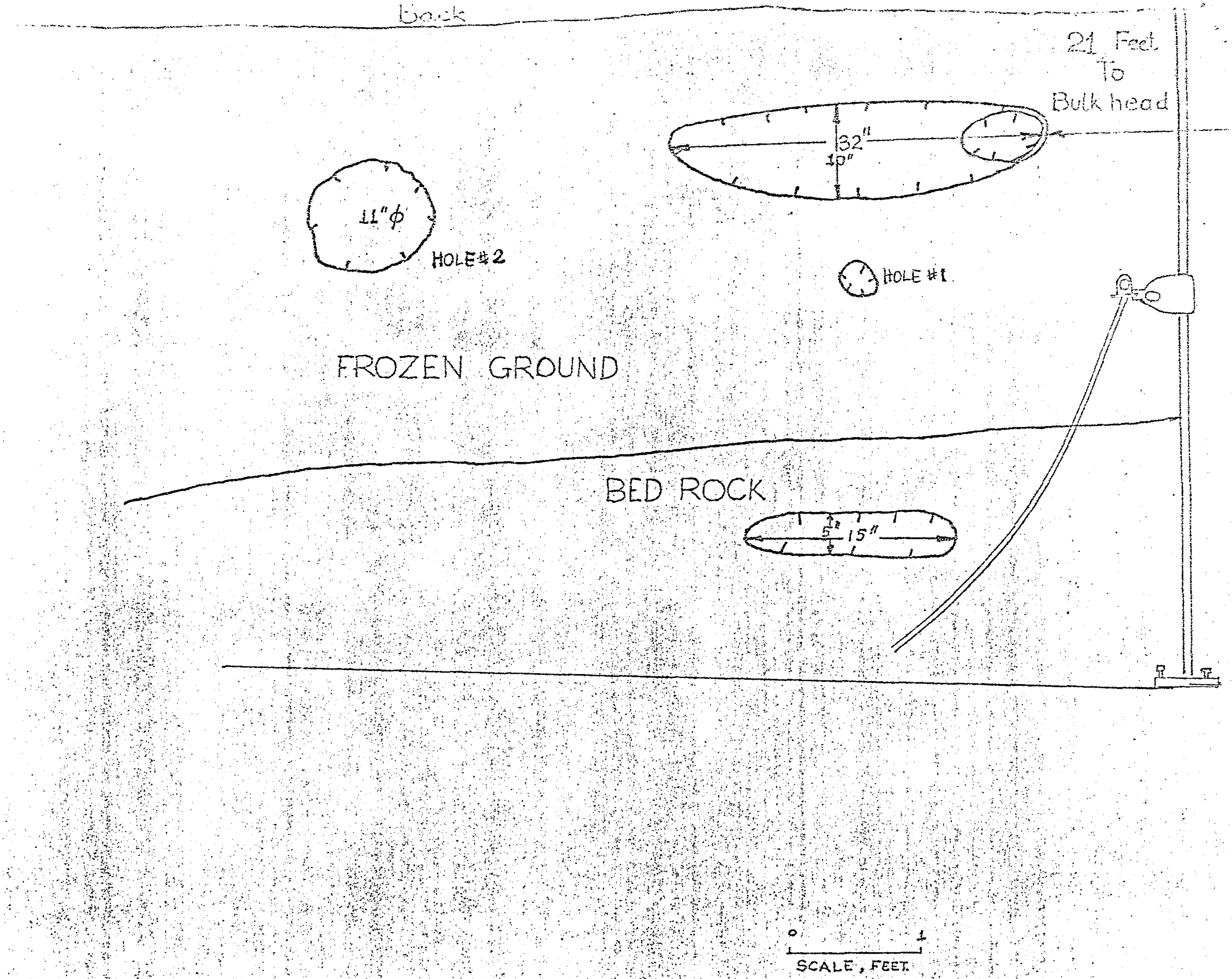


INDEX

1. Junction Box
2. 2" Line
3. Flow Meter
4. Filter
5. Bleed Line
6. Pressure Gauge
7. Motor 125 hp
8. Nozzle
9. Pole
10. Flexible Hose
11. Sump
12. Low pr. pump
13. 1" ϕ Line
14. Bulkhead
15. Bulkhead L 2'10"
H 7'9"

EXPERIMENTAL SET UP IN THE PERMAFROST TUNNEL

FIGURE 22A



HOLES AND SLOTS CUT INTO PERMAFROST

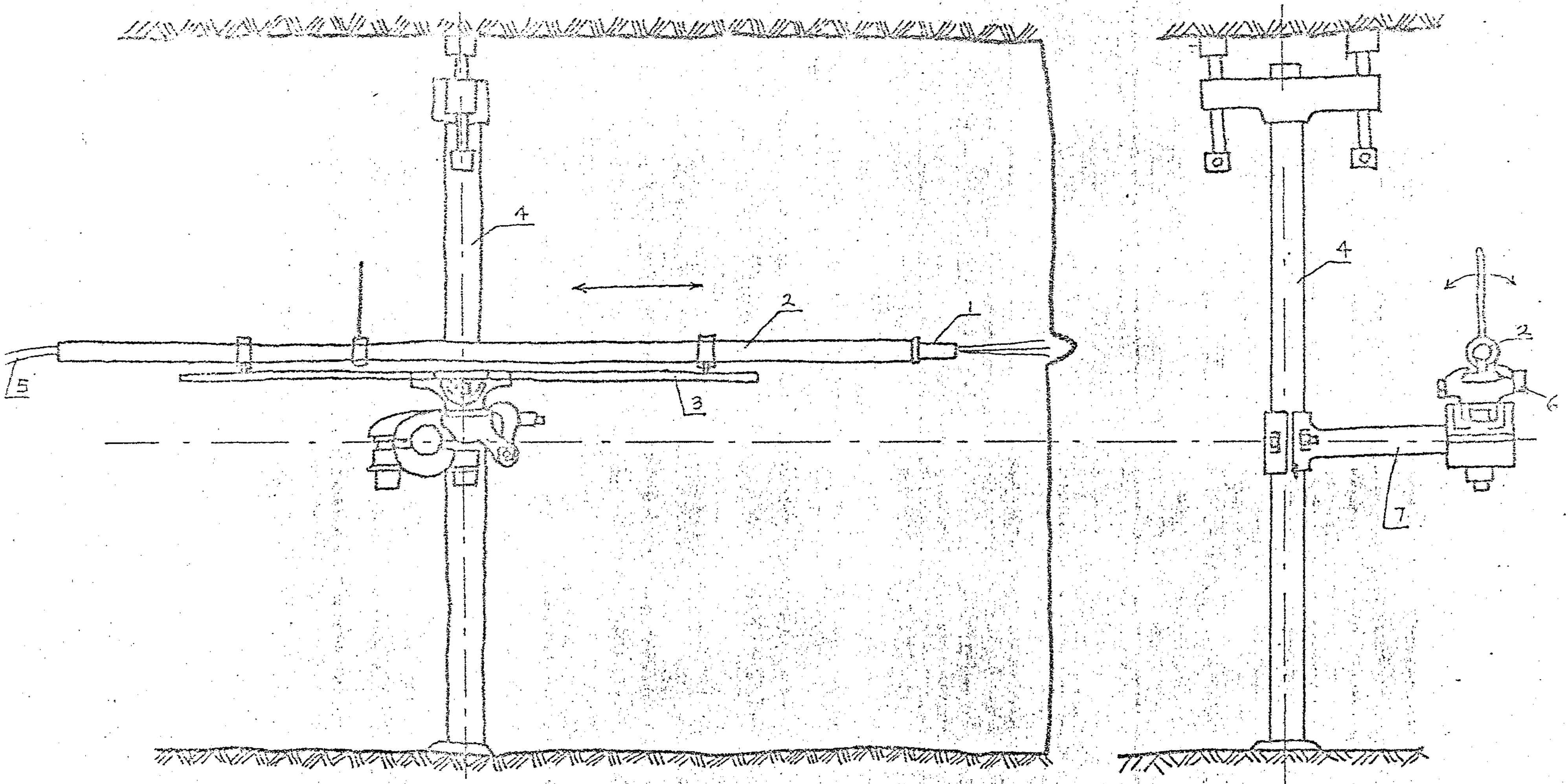


FIGURE : 23 NOZZLE TRAVERSE SYSTEM

INDEX :

(1) NOZZLE HOLDER
(2) STEEL TUBE
(3) STEEL BASE
(4) COLUMN
(5) H. P. HOSE
(6) TILTABLE FEED
(7) TEE - CLAMP JOINT

Rosin - Rammler

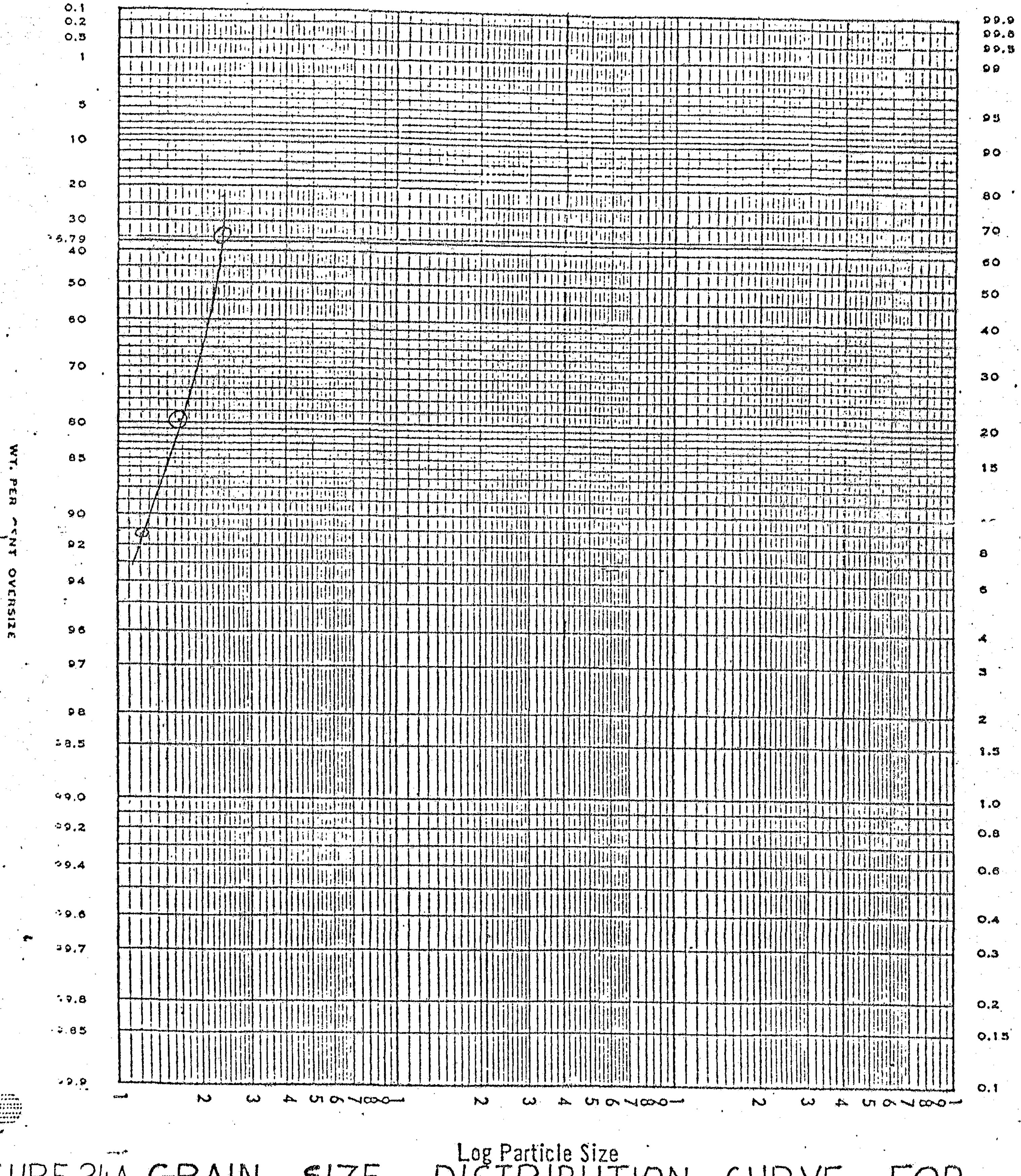
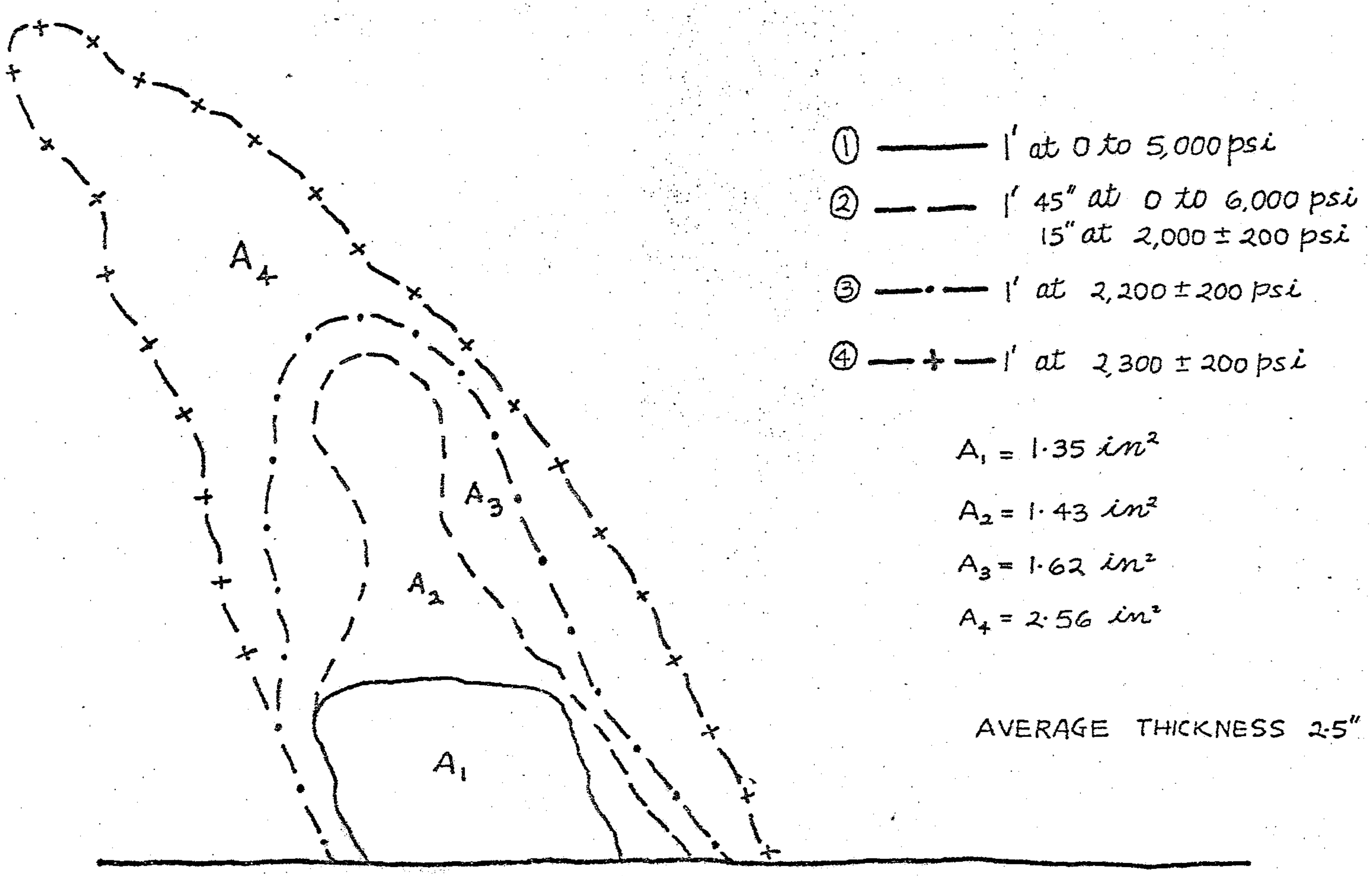


FIGURE 24A. GRAIN SIZE DISTRIBUTION CURVE FOR GRAVEL



$A_1 = 1.35\ in^2$

$A_2 = 1.43\ in^2$

$A_3 = 1.62\ in^2$

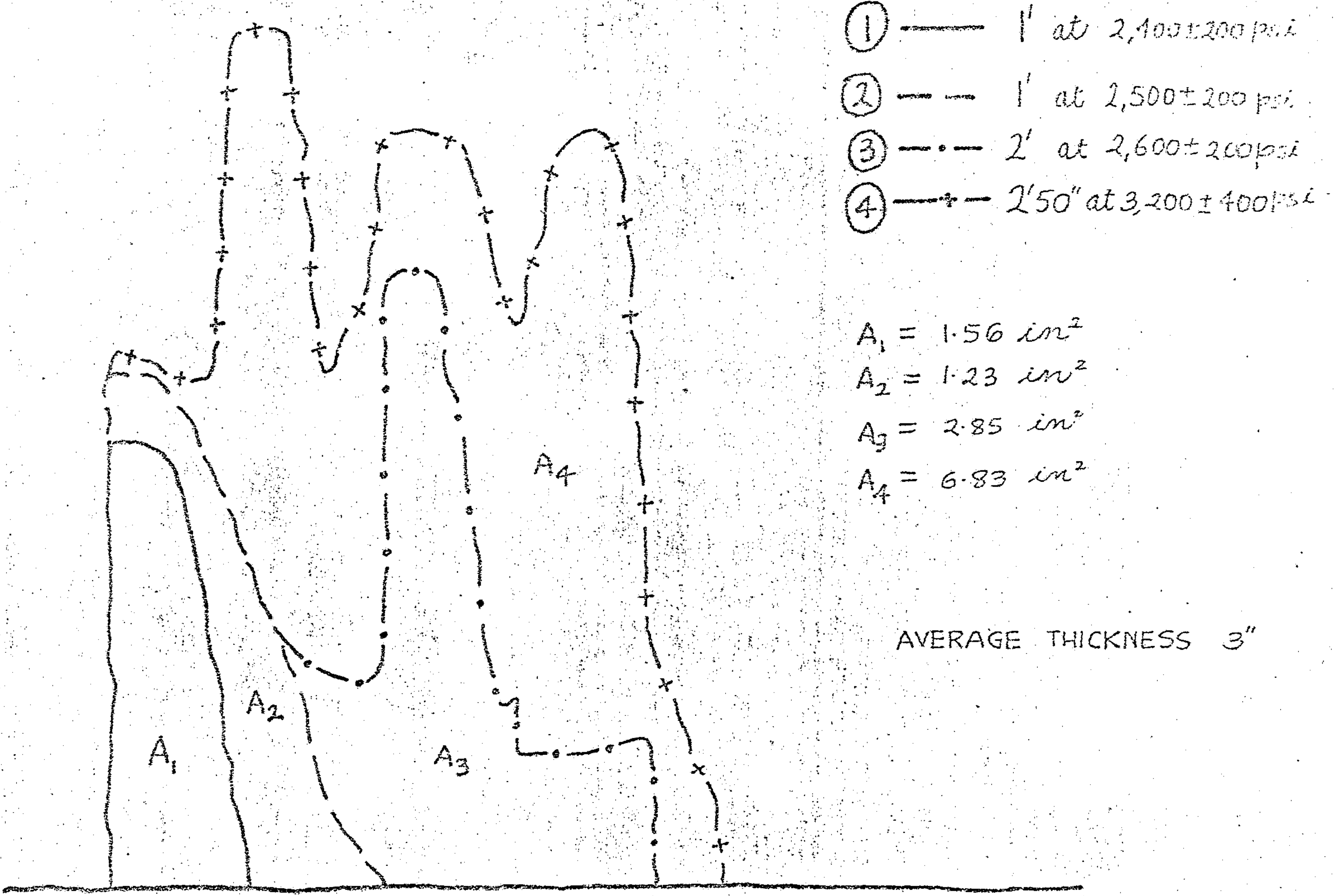
$A_4 = 2.56\ in^2$

AVERAGE THICKNESS 2.5"

FIGURE: 24B SLOT CUTTING IN FROZEN GRAVEL

SCALE 1:5

GROUND I



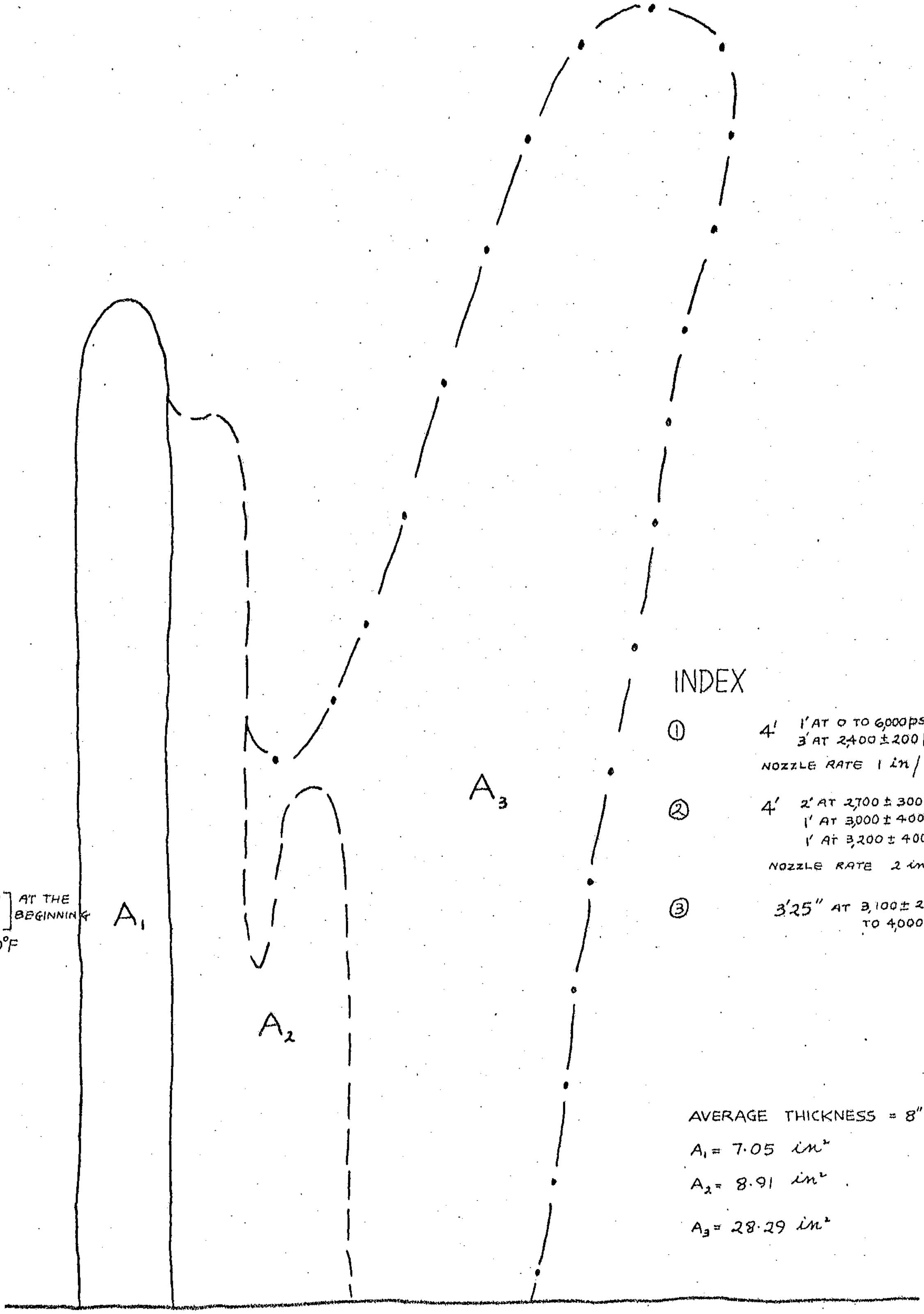
$A_1 = 1{\cdot}56\ in^2$
$A_2 = 1{\cdot}23\ in^2$
$A_3 = 2{\cdot}85\ in^2$
$A_4 = 6{\cdot}83\ in^2$

AVERAGE THICKNESS 3"

5/24/83
WATER TEMP = 33°F

FIGURE: 25 SLOT CUTTING IN BEDROCK

SCALE → 1:5



6/8/83

AIR TEMP. -4°C ⎤ AT THE
ROCK TEMP. -4°C ⎦ BEGINNING
WATER TEMP. 50°F

INDEX

① 4' 1' AT 0 TO 6,000 psi
3' AT 2,400 ± 200 psi
NOZZLE RATE 1 in/min

② 4' 2' AT 2,700 ± 300 psi
1' AT 3,000 ± 400 psi
1' AT 3,200 ± 400 psi
NOZZLE RATE 2 in/min

③ 3'25" AT 3,100 ± 200
TO 4,000 ± 200 psi

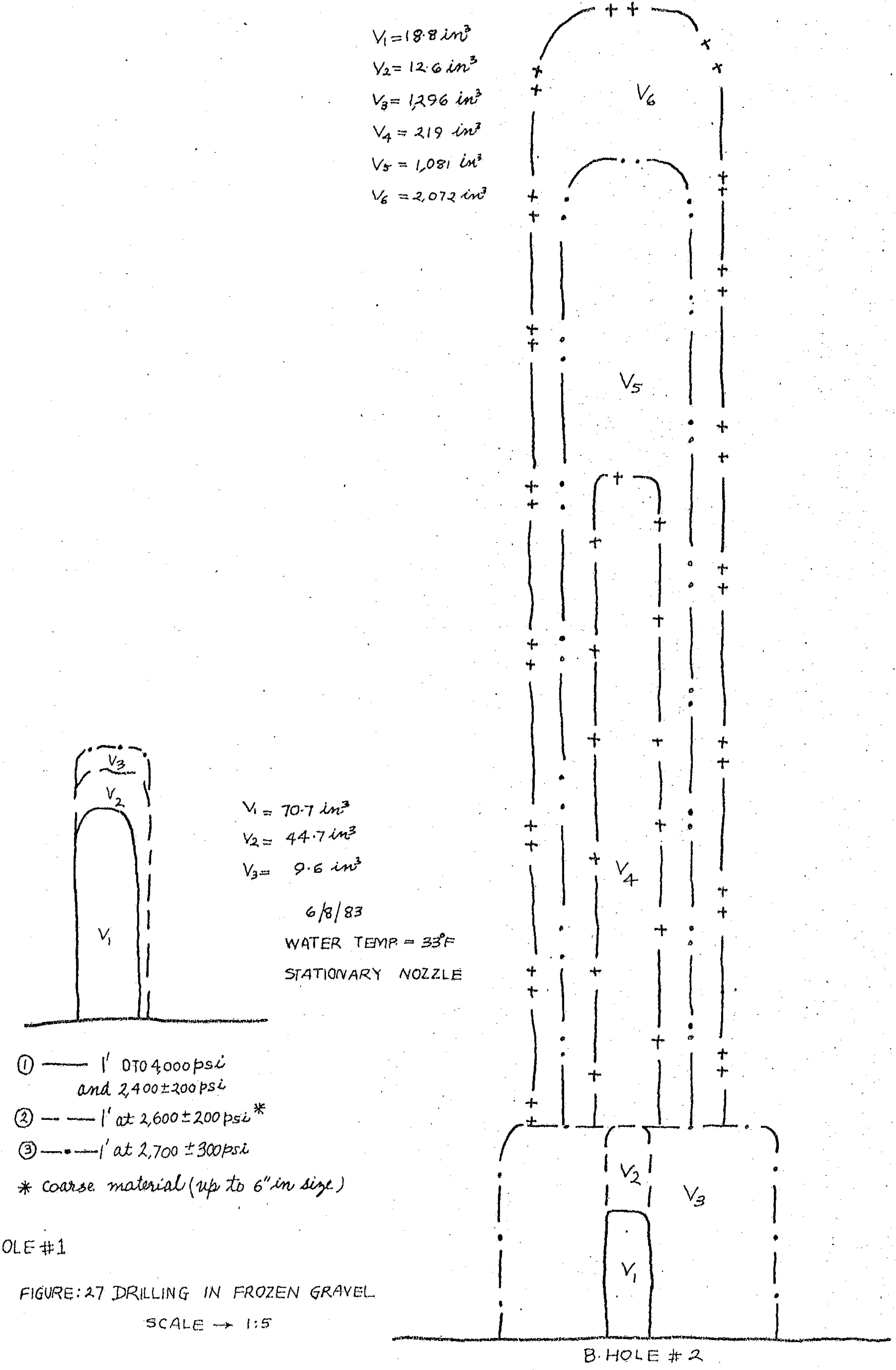
AVERAGE THICKNESS = 8"

$A_1 = 7.05\ in^2$

$A_2 = 8.91\ in^2$

$A_3 = 28.29\ in^2$

FIGURE : 26 SLOT CUTTING IN FROZEN GRAVEL SCALE → 1:5



V1 = 18.8 in³
V2 = 12.6 in³
V3 = 1,296 in³
V4 = 219 in³
V5 = 1,081 in³
V6 = 2,072 in³

V1 = 70.7 in³
V2 = 44.7 in³
V3 = 9.6 in³

6/8/83
WATER TEMP = 33°F
STATIONARY NOZZLE

① —— 1' 0 TO 4,000 psi and 2,400 ± 200 psi
② - - - 1' at 2,600 ± 200 psi *
③ —•— 1' at 2,700 ± 300 psi
* coarse material (up to 6" in size)

A. HOLE #1

B. HOLE # 2

FIGURE: 27 DRILLING IN FROZEN GRAVEL
SCALE → 1:5

LIST OF REFERENCES

1. Foster-Miller Associates, Fundamental Concepts for the Rapid Disengagement of Frozen Soil, U.S.A. CRREL Technical Reports 233 and 234, (1971).
2. Chester, J.W., Hydraulic Fragmentation of Frozen Gravel, USBM Report of Investigations (copy of the report sent for field review) (1971).
3. Hydronautics, Inc., Evaluation of Cavijet Cavitating Jets for Cutting Coal-associated Rocks, DOE/ET/12514-T1, (1980).
4. Knickmeyer, W., Bauman, L., High-Pressure Water Jet Assisted Tunneling Techniques, 2nd U.S. Water Jet Cont., May 24-26, Rolla, Mo., (1983).
5. Henkel, E.H., Jet-Miner Surface and In-Seam Trials Run by Burgbau-Forschung GMBH, Germany, 2nd U.S. Water Jet Cont., May 24-26, Rolla, Mo., (1983).
6. Yie, G.G., Cutting Hard Rock with Abrasive Entrained Waterjet at Moderate Pressures, 2nd U.S. Water jet Cont., May 24-26, Rolla, Mo., (1983).
7. Skudrzyk, F.J., Barker, C.R., Mazurkiewicz, M., Preliminary Studies of Frozen Gravel Properties Related to Underground Mining, Report for the Mineral Eng. Dept., UAF, April 26, (1982).
8. Skudrzyk, F.J., Impact of Permafrost on Placer Mining, 5th Annual Conference on Alaskan Placer Mining, March 30-31, (1983).

LIST OF TABLES

Table 1

Sieve Analysis of Gasconade River Gravel

Sieve Number	Size, inches			%	%
	1	-	2	26.5	100.0
	0.525	-	1	35.4	73.5
4	0.185	-	0.525	20.1	38.1
28	0.0232	-	0.185	9.7	18.0
50	0.0116	-	0.0232	6.9	8.3
	0.0	-	0.0116	1.4	1.4
			TOTAL	100.0%	

Total weight of the sample 14,334 g.

Water Content: dry gravel weight 4397.5 g.
water weight 965.0 g.

% water content in "permafrost" 18.0% by weight.

Table 2. Cutting of Frozen Gravel Samples

	Number of run	Nozzle dia. [in]	pressure [psi]	time of action [sec]	Standoff correction factor	Volume of material removed [in^3]	Specific Energy Esp [in. lb/in^3]	Remarks
1	3	0.062	6000	30	6/0.322	89.25	$0.22\ 10^5$	
2	4	0.062	6000	60	6/0.322	180.60	$0.22\ 10^5$	
3	5a	0.062	6000	30	12/0.270	78.75	$0.21\ 10^5$	
4	5b	0.062	6000	60	12/0.270	162.75	$0.20\ 10^5$	
5	6	0.062	6000	30	6/0.322	120.00	$0.17\ 10^5$	Web 1 1/4 in.
6	7a	0.062	6000	30	6/0.322	33.25	$0.59\ 10^5$	
7	7b	0.062	6000	30	6/0.322	70.00	$0.28\ 10^5$	
8	10a	0.040	10000	30	4/0.344	24.00	$0.79\ 10^5$	
9	10b	0.040	10000	30	4/0.344	63.00	$0.30\ 10^5$	
10	11a	0.040	15000	30	4/0.344	40.25	$0.86\ 10^5$	
11	11b	0.040	15000	30	4/0.344	94.00	$0.37\ 10^5$	
12	12a	0.040	5000	30	4/0.344	21.00	$0.32\ 10^5$	
13	12b	0.040	5000	30	4/0.344	43.75	$0.15\ 10^5$	
14	12c	0.040	5000	30	4/0.344	57.25	$0.12\ 10^5$	
15	13a	0.062	5600	30	4/0.344	42.00	$0.45\ 10^5$	
16	13b	0.062	5600	30	4/0.344	69.40	$0.27\ 10^5$	
17	14a	0.062	5600	30	8/0.303	17.50	$0.96\ 10^5$	
18	14b	0.062	5600	30	8/0.303	52.50	$0.32\ 10^5$	
19	14c	0.062	5600	30	8/0.303	80.00	$0.21\ 10^5$	
20	15a	0.062	5600	30	8/0.303	47.25	$0.35\ 10^5$	
21	15b	0.062	5600	30	12/0.270	53.75	$0.28\ 10^5$	
22	15c	0.062	5600	30	12/0.270	110.00	$0.14\ 10^5$	
23	16a	0.062	5600	30	12/0.270	120.90	$0.12\ 10^5$	Web 2 1/2 in.
24	16b	0.062	5600	60	12/0.270	197.10	$0.15\ 10^5$	Web 2 1/2 in.
25	19	0.062	5950	40	0/1.00	100.53	$0.61\ 10^5$	steady nozzle
26	20a	0.045 x 2	5600	30	8/0.303	73.81	$0.24\ 10^5$	8° Div.
27	20b	0.045 x 2	5600	60	8/0.303	161.70	$0.22\ 10^5$	8° Div.
28	20c	0.045 x 2	5600	90	8/0.303	259.20	$0.20\ 10^5$	8° Div.
29	21a	0.080	3000	30	4/0.344	79.65	$0.16\ 10^5$	
30	21b	0.080	3000	60	4/0.344	138.00	$0.18\ 10^5$	
31	22a	0.080	3000	30	8/0.303	69.60	$0.16\ 10^5$	
32	22b	0.080	3000	60	8/0.303	163.80	$0.13\ 10^5$	
33	23	0.080	3000	30	0/1.000	157.08	$0.23\ 10^5$	
34	25a	0.040	10000	30	8/0.303	36.00	$1.58\ 10^5$	
35	25b	0.040	10000	60	8/0.303	90.00	$0.37\ 10^5$	
36	25c	0.040	10000	30	8/0.303	114.00	$0.15\ 10^5$	
37	26	0.040	10000	60	12/0.270	66.00	$0.45\ 10^5$	

Table 3

Sieve Analysis of the Permafrost Tunnel Gravel

Size (mm)	%	%
50.8 - 25.4	26.5	100.0
25.4 - 13.34	35.4	73.5
13.34 - 4.69	20.1	38.1
4.69 - 0.0	18	18

Table 4. Cutting of Frozen Gravel

	Step	Area in.^{2}	Width in.	Volume in.^{3}	Time Sec.	Pressure psi	Nozzle dia. in.	Specific Energy in.lb/in.^{3}	Remarks
Slot Cutting in Gravel I	1	6.75	2.5	16.88	60	2,000	0.138	6.96×10^5	Water temp. 34°F gravel temp. 25.8°F air temp. 26.8°F
	2	7.15	2.5	17.88	60	2,000		6.57×10^5	
	3	8.1	2.5	20.25	60	2,200		6.69×10^5	
	4	12.8	2.5	32.00	60	2,300		4.53×10^5	
Slot Cutting in Bedrock	1	7.8	3	23.4	60	2,400	0.138	6.60×10^5	Water temp. 33°F gravel temp. 26.4°F air temp. 27.7°F
	2	6.15	3	18.45	60	2,100		8.90×10^5	
	3	14.25	3	42.75	120	2,600		8.14×10^5	
	4	31.9	3	95.70	170	3,200		7.04×10^5	
Slot Cutting in Gravel II	1	35.25	8	282.00	240	2,300	0.138	2.05×10^5	Water temp. 50°F gravel temp. 25°F air temp. 25°F
	2	44.55	8	356.40	240	2,900		2.30×10^5	
	3	141.45	8	1131.60	205	3,550		0.84×10^5	
Drilling Hole #1	1			70.7	60	2,200	0.138	1.92×10^5	Water temp. 33°F
	2			44.7	60	2,600		3.89×10^5	
	3			9.6	60	2,700		19.19×10^5	
Drilling Hole #2	1			18.8	60	2,600	0.138	9.26×10^5	
	2			12.6	120	3,000		34.25×10^5	
	3			1,296	120	3,550		0.43×10^5	
	4			219	120	3,800		2.81×10^5	
	5			1,081	120	4,000		0.59×10^5	
	6			2,072	115	4,100		0.32×10^5	