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PRELIMINARY STUDIES OF FROZEN GRAVEL PROPERTIES RELATED TO UNDERGROUND MINING

by

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prepared for
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by

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1. Introduction

This report describes research conducted by Drs. Frank J. Skudrzyk, Clark R. Barker and Marian Mazurkiewicz over a period of time from February 15 to April 15, 1982 for the University of Alaska, Fairbanks. The scope of the project, established through discussions with Dr. Chris Lambert, representing the UA, was to conduct pilot studies of frozen gravel properties related to underground mining in permafrost: high pressure water jet cutting characteristics and uniaxial compressive test (uniaxial compressive strength and Young's modulus measurement). It has been agreed that the tests would be conducted on an artificial material simulating the frozen gravel.

In addition to water jet and uniaxial testing of simulated frozen gravel, uniaxial tests were run on frozen pea-gravel and ice as well as a single water jet test was conducted on ice. These tests were carried out to gain insight into the interaction between the components of the permafrost samples as well as to establish some guidelines for the future studies.

The assumed testing program has been successfully carried out. The material tested, testing procedures, and results obtained are described in this report.

2. Literature Review

Jet cutting of frozen soil, frozen gravel, and ice has been investigated and studied by several researchers at various locations over the last decade. During this period continuing development has occurred on high pressure pumping equipment and accessories. In addition a better, although still not complete, understanding of some of the significant parameters of jet cutting has evolved. Therefore, it is difficult to review the literature and select concrete facts which would necessarily apply to a current project without qualification. For this reason it should be adequate here to provide a cursory review than an in depth review.

Dr. Malcolm Mellor of the U. S. Army Cold Regions Research and Engineering Laboratory seems to have studied in some detail the problem of jet cutting of frozen gravel. In his paper (1972, Ref. 1) he presents the following review of literature:

" A study of excavation concepts was carried out for USACRREL* by Foster-Miller Associates (1971, Ref. 4) between 1966 and 1968. Using the rock cutting data of Farmer and Attewell (1963, Ref. 3) and Leach and Walker (1966, Ref. 5), Foster-Miller concluded that continuous water jets were unlikely to be of value in excavating

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* U.S. Army Cold Regions Research and Engineering Laboratory.

permafrost because of low energy effectiveness, high power demands and large water requirements. They then concentrated on discontinuous jets and commissioned a number of tests from Exotech, Inc.

Tests were made on frozen fine-grained soils at approximately -18°C; uniaxial compressive strengths of the order of 2000 $\mathrm{lbf/in.}^2$ (14 $\mathrm{MN/m}^2$) can be assumed. Water slugs with length/diameter ratio of approximately 70 and mean mass velocity of approximately 2000 ft/sec (610 m/s) were fired by a 20 mm gun through a nozzle of 0.22 in. (5.59 mm) diameter, giving specific energy values from 1100 to 6300 $\mathrm{lbf/in.}^2$ (i.e. $\mathrm{in\text{-}lbf/in.}^3$ -- 7.6 to 43.4 $\mathrm{MJ/m}^3$). Other tests with nozzle diameter 0.157 in. (3.99 mm), length/diameter ranging from 80 to 180, and mean mass velocity 1700 to 2300 ft/sec (520 to 700 m/s) gave specific energy values from 2800 to 7600 $\mathrm{lbf/in.}^2$ (19.3 to 52.4 $\mathrm{MJ/m}^3$). A single test with nozzle diameter 0.157 in. (3.99 mm), length/diameter 60 and velocity 1200 ft/sec (366 m/s) gave 1500 $\mathrm{lbf/in.}^2$ (10.3 $\mathrm{MJ/m}^3$). A single shot was made with an intensifier with a 0.055-in. (1.4-mm) diameter nozzle; it gave mean velocity of 3500 ft/sec (1070 m/s) with length/diameter of 1700 (virtually a continuous jet), yielding specific energy of 9400 $\mathrm{lbf/in.}^2$ (64.8 $\mathrm{MJ/m}^3$). Another single shot from a special accumulator device with slug diameter 0.05 in. (1.27 mm), length/diameter 30, and velocity 15,000 ft/sec (4570 m/s) gave specific energy of 7600 lbf/in.^{2} (52.4 MJ/m^3). A slight decrease in specific energy with decrease in length/diameter ratio was claimed.

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 USACRREL by N. C. Franz at the University of Michigan (Tousignant and Swensen, 1969, Ref. 8). About 100 tests were made on frozen specimens of silt, sand and gravel, with pump pressures of 6000 to 10,000 lbf/in.^{2} (41.4 to 68.9 MN/m^2), 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 these tests 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, and 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 (Chester, in press, Ref. 2). Experiments were made on test blocks of frozen coarse gravel at -4°C, using nozzles of approximately 0.5 in. (≈ 12.7 mm) diameter with a traverse rate of 3 in./sec (0.0762 m/s) and pump pressures of 1500, 2400 and 4500 lbf/in.^{2} (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 USACRREL permafrost tunnel using a 0.148-in. (3.76-mm) diameter nozzle with pump pressures of 2500, 3500 and 4200 lbf/in.^{2} (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 4500 lbf/in.^{2} (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 to 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 USACRREL by D. A. Summers at the University of Missouri in 1971 (Summers, 1971, Ref. 7). Specimens of frozen gravel were traversed by a continuous jet (0.023 in. or 0.584 mm nozzle diameter) at pressures of 2500, 4000, 6000, 9000, 12,000 and 24,000 lbf/in.^{2} (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 (0.152, 0.356, 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 6 gallon (0.0227 m^3) slugs at approximately 10,000 $lbf/in.^2$ ($\approx$ 69 MN/m^2) through nozzles of 0.2, 0.5 and 1.0 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 $lbf/in.^2$ ($\approx$ 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 had bigger particles than that used by Tousignant and Swensen, 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 articles have been published at the International Jet Cutting Symposium regarding jet cutting of frozen gravel. A careful review of the literature should be undertaken at some point to determine if other tests have been carried out than those reported by Dr. Mellor.

3. Testing

3.1. Description of Material Used

In general any testing program run under different than in situ conditions and not employing a full size structure has to be considered as 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 an artificial frozen gravel would be produced because both collecting of the permafrost samples and shipping them in the intact form would not be feasible. The development of the equivalent material is usually based on matching the real and equivalent material properties which are the most pertinent to a phenomenon under consideration. However, in this case little is known about the permafrost composition and its properties.

The properties pertaining to this project are:

- mechanical properties such as strength and deformation characteristics related to the stability considerations of underground openings in permafrost
- mechanical properties related to water jet mining
- thermal properties related both to stability and water jet cutting

Because of the limited data available on the frozen gravel composition, water content, properties in general etc., 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 materal a modified washed river gravel from the Gasconade River near Waynesville, Mo. The modification of the river material in addition to its having been washed consisted of limiting its size to 2 in. and increasing the content of larger grain-size fractions. This gravel was not crushed, although the individual pieces were not completely round. The 2 in. limit on gravel size was chosen in connection with the maximum size of samples which could be handled both in uniaxial and water jet testing. The grain-size distribution curve for the simulated gravel is shown in Fig. 1 with data points listed in Tab. 1. In addition to the above gravel a pea-gravel was used to make additional samples for uniaxial testing. Data concerning this material are given in Fig. 2 and Tab. 2.

Ordinary tap water was mixed with the above gravel. The water content by weight of the frozen samples was 18% for the gravel and 21.4% for the pea-gravel. These numbers may be a bit too high when compared to permafrost, but no reliable data was available. This information should be obtained in future research.

Table 1

Sieve Analysis of Gravel

Sieve Number	Size, inches	%	Σ%
	1 - 2	26.5	100.0
	0.525 - 1	35.4	73.5
4	0.185 - 0.525	20.1	38.1
28	0.232 - 0.185	9.7	18.0
50	0.0116 - 0.0232	6.9	8.3
	0.0 - 1.4	1.4	1.4
	TOTAL	100.0%	

Total weight of the sample 14,334 g.

Water Content: dry gravel 4397.5 g
water 965.0 g

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

Table 2

Sieve Analysis of Pea-Gravel

Size, inches	%	Σ%
3/8	0.0	0.0
0.187 - 0.375	53.8	100.0
0.132 - 0.187	37.4	46.2
0.937 - 0.132	6.5	8.8
0.0 - 0.0937	2.3	2.3
TOTAL	100.0%	

Total weight of the sample 5,491.5 g.

Water Content: dry pea-gravel 3,425.5 g
water 931.0 g

% water content in frozen pea-gravel 21.4% by weight.

3.2. Sample Preparation

As mentioned above three types of material were tested: frozen gravel, frozen pea-gravel and ice.

The frozen gravel samples for water jet cutting were prepared in the shape of rectangular samples of the size 1 x 1 x 3 ft. 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. in diameter and 12 in. high.

The samples for uniaxial testing made of gravel, pea-gravel and ice were frozen in the cylindrical forms 8 in. in diameter and 16 in. high. The side wall of the form was made out of 1/8 in. thick cardboard tube, whereas the bottom was a plexiglass plate with a groove to fit the tube. Both parts were "glued" together with hot wax.

This type of form provided maximum flexibility needed during freezing of the samples to avoid residual stresses. The samples were frozen in the local freezer company at +5°F. When the samples were removed for testing they were insulated with 2 in. thick fiberglass mat and taken to the testing facility. The upper ends of the samples were then cut with a band saw to produce a flat surface perpendicular to the axis of the sample. This procedure provided samples which conform to ASTM standards.

The quality of the insulation was checked for one of the samples in the following way. Six thermo-couples equally spaced along the radius were frozen inside the sample at its mid plane. The sample was then insulated, exposed to room temperature at 72°F and the variation in temperature at the thermocouple's locations record over a period of 3 h. and 24 min. Over this period of time the sample showed an average increase in temperature of 4°F per hr., whereas the difference between the innermost and outermost temperatures did not exceed ±0.2°F. With this slow increase in temperature we felt that the lack of an environmental chamber was not significant. The samples were left at room temperature for a specified time to let them warm up to a desired temperature.

In general the quality of samples produced was very satisfactory. However, in the case of ice samples, a few showed cracking which probably was a result of the rapid freezing process.

3.3. Uniaxial Compressive Tests

3.3.1. Testing procedure and test results

The samples were loaded to a failure point in the conventional Tinius Olson universal testing machine. The rate of loading was chosen in such a way that the test duration exceeded 5 min. each time. Over about 80% of the initial loading range the samples showed very small elastic deformation. Near the failure point and especially in the post-failure testing the samples showed large, probably both plastic and time dependent, deformations. This was especially true for higher temperatures. During the test the average axial displacement of the sample was recorded from four LVDT transducers along with its temperature.

The testing fixture with testing machine, samples tested, LVDT transducers and the data recording system is shown in Fig. 3. The side surface of the samples was covered with the fiberglass mat during the test, whereas the end surfaces were insulated with plexiglass plates. One of the gravel samples after testing is shown in Fig. 4. The accumulated data from uniaxial testing is listed in Tab. 3, and the uniaxial compressive strength, C_o, and Young's modulus, E, are plotted as a function of temperature in Fig. 5. The data both for C_o and E are scattered, reflecting considerable nonhomogeneity of the material. In general however, there is a clear decrease both in compressive strength and modulus of elasticity with increase in temperature for all three materials tested. Assuming, as a first approximation, that this relationship is linear the decrease has been calculated based on statistical analysis (Figs. 6 to 11) and is given in Tab. 4. The average values at 28°F both for compressive strength and Young's modulus are also included in this Table. The strength of frozen material increases with increase in gravel content. The C_o for frozen gravel tested is almost twice as high as for ice. The decrease in strength with increase in temperature is about 24 psi/°F for gravel and pea-gravel, but is much lower 6.3 psi/°F for ice. This means that the strength of ice is less influenced by temperature changes than the strength of frozen gravel.

3.3.2. Conclusions

Despite the scatter of data the relationship between both uniaxial strength and Young's modulus and temperature was clearly established for the material tested.

During the testing difficulties were encountered in loading the samples at near failure point and during the post-failure testing. A stiff testing machine is needed to load the frozen samples with constant strain rate.

During testing in the loading frame, samples were insulated with the fiberglass along their side surface and were separated by 1/2 in. thick plexigalss plates from machine's loading plattens. Though the temperature in the center of the sample remained fairly constant during the test, the situation at the ends might have been different and this would cause changes in the uniformity of loading especially in the case of frozen gravel samples. Loading the samples in temperature controlled chambers would solve the problem.

As mentioned above the samples showed large deformations at high loads and especially at higher temperatures.

These factors may be critical in consideration of the stability of underground openings and time dependent studies (creep test) are needed to better understand and cope with this problem.

For the purpose of the evaluation of permafrost roof stability flexural tests should be employed, again under controlled temperature conditions.

3.4. Water Jet Cutting Tests

3.4.1. Equipment Used

All cutting tests were performed using a Kobe 3J triplex pump driven by an electric motor as shown in Fig. 12 to produce the high pressure water. This unit can produce various combinations of water pressure and flow rate by changing the diameter of the three plungers to achieve a pressure and flow rate combination equal to the rated capacity of the pump which is 60 Hp. However, different pressures and flow rates can also be achieved by varying the nozzle exit diameter and the portion of the pump discharge which is bypassed from the nozzel. This procedure was followed in performing the cutting tests and will be described in more detail in a later section.

The discharge of high pressure water from the pump was carried inside a 0.5 in. ID flexible hose with a rated burst pressure of 30,000 psi. 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. Figure 13 shows the mechanism used to oscillate the nozzle across the samples. This device is a three dimensional four bar linkage which was developed for use in an underground longwall water jet coal mining machine. When the input flywheel is rotated by a small hydraulic motor at a constant angular speed, the output line (the nozzle arm) executes a motion which is approximately sinusoidal in nature.

The nozzle then 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 are patterned after a design proposed by Leach & Walker. They suggested an inlet cone of 13° included angle followed by a cylindrical exit section whose length is 3 to 4 times the exit diameter, as shown in Fig. 14. This design evolved from a large number of tests which they 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 Fig. 15 and move 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.

3.4.2. Test Procedures

Samples of frozen gravel in wooden forms 12 x 12 x 36 ins. were positioned as shown in Fig. 16 relative to the nozzle oscillation system. The distance d in the figure is called standoff distance while L is the width of a sample. R and β are constants and ψ would vary according to the standoff distance used for a particular test.

With the nozzle arm positioned so that the water jet was not touching 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 valve was positioned so that the arm would begin to swing across the sample exposing the sample to the water jet action. After the required exposure (usually 30 sec. was used) the power to the high pressure pump was turned off and the arm motion was stopped.

Measurements were then taken and recorded across the slot produced at several locations to determine the average depth of penetration and width of the slot produced. If additional cutting was desired at this location, the procedure was repeated for an additional exposure time and the data recorded. To begin a new test run, the sample was moved vertically to a fresh location far enough away from the previous cut to exclude any slot interaction effects. Usually it was possible to perform

4 or 5 test runs spaced along the longest dimension of the samples before it was necessary to use a new sample of the frozen gravel.

It should be mentioned that the samples were taken from the freezer locker just prior to the cutting tests. During the time of the tests, 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 the tests it was observed that the samples were still very solid and no significant reduction in strength or integrity was recorded due to the increasing temperature.

3.4.3. Details of Test Parameters

As mentioned previously different pressures and flow rates result depending upon the size of the nozzle exit diameter and the portion of the high pressure water which is bypassed from the nozzle. For these preliminary tests 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 the known nozzle exit diameter. This procedure would not account for pressure losses between the pump and nozzle or any variations in nozzle discharge coefficient. However these effects will be present in any mining equipment which maybe developed and they can never be totally eliminated.

With these assumptions the equations used for power and flow rate are

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

$$\text{Power(Hp)} = (0.0174)\ P^{3/2}D^2$$

where D = nozzle exit diameter in inches

P = pump pressure in psi

For specific energy calculations the energy input was then computed using

$$\text{Energy (in. lbs)} = (114.91)\ P^{3/2}D^2\ T \times \text{Factor}$$

where T = length of test in seconds

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

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

The value of the term Factor was determined with reference to Fig. 16 by noting that for a given standoff distance d the angle $\psi/2$ is found from

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

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

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

where for the actual mechanism $L = 12$ inches

$R = 28$ inches

$\beta = 40°$

which yields values for various standoff distances

Table 5

d(inches)	Factor
4	.344
6	.322
8	.303
10	.286
12	.270

Thus when a standoff distance of 4 inches was used, the jet was only on the sample 34.4% of the time.

The specific energy required to excavate the material was then computed from ENERGY divided by the volume of the slot expressed in cubic inches.

3.4.4. 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 disperse as it travels away from the nozzle exit. For these tests, standoff 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. For these tests, pressures up to 15,000 psi were used to cut the samples. This pressure is well below the threshold pressure required to actually cut the individual pieces of gravel imbedded in the ice. The method of generating the slot therefore relies upon freeing the gravel from the parent body of ice so that the jet can wash the gravel out of the sample. The threshold pressure for the ice itself appears to be quite low and good results on the ice alone could be obtained at below 5000 psi.

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 one third of the time suggests that the input power levels were relatively modest for these cutting trials.

3.4.5. 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. For example, it is normal for the depth of penetration of the jet into the sample to decrease uniformly with standoff distance for many materials. In the case of the frozen gravel this pattern was not the case as will be discussed in the following.

Figure 17 shows the depth of cut for nozzle 370 at 5600 psi after exposure times of 30, 60, and 90 sec. for three different standoff distances. It is interesting that the slope of each curve is nearly constant and that the most penetration for a given exposure time was obtained with the 4 inch standoff. Surprisingly, the penetration at 12 inch standoff was better than that at 8 inches. This suggests that the nozzle is cutting effectively at all three standoff distances and that the details of how each individual gravel is imbedded in the ice may influence the result. Since the water jet is not cutting the gravel, the slot depth is increased by freeing pieces of gravel and washing them out of the slot.

The same type of result is shown in Figure 18 where the same nozzle 370 was used at a pressure of 6000 psi.

In this case, the depth of penetration was higher for the 12 inch standoff than for the 4 inch standoff. In both cases the results suggest a linear relationship between depth of cut and exposure time.

Figure 19 shows the cutting result for a larger nozzle (number 430) with an operating pressure of 3000 psi. In this case the depth of penetration did not change with the two standoff distances of 8 and 12 inches. This suggests that the jet parameters are delivering a sufficient energy to the sample to excavate the gravel as it is encountered. Further tests need to be run to verify this situation.

In Figure 20 a smaller nozzle (number 400) was used at various pressures. Here at a 4 inch standoff distance, increasing the pressure from 5000 to 10000 to 15000 psi resulted in a significant increase in penetration. The input power level is of course much higher at the highest pressure. The results for the three standoff distances at 10,000 psi are following the same type of pattern as discussed previously.

Figure 21 and 22 show cutting results for 2°, 8°, and 12° diverging nozzles number 300, 330, and 350 at 6000 psi pressure. These nozzles have two jets whose cross section is equivalent to the area of the 370 nozzle exit. When the standoff is low, the results are similar to the single orifice nozzle 370 results. If the standoff 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 cases the individual slots join 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 the 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 Figure 23 and, although there is some scatter to the data, they suggest a lower specific energy value as the pressure is reduced. This trend must cease at some pressure below 3000 psi since the threshold pressure for the material must lie between 0 and 3000 psi. These results suggest that there is a good potential for designing a water jet mining system for permafrost where the operating pressure is below 5000 psi.

Figure 24 shows the arrangement of the nozzle relative 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 a "drilling" effect of the jet could be investigated. In Run 23, the nozzle 430 was used at 3000 psi to washout a cavity 5 inches in diameter and 8 inches deep in less than one minute of operation. Then on Run 24, the same nozzle was positioned about 7 inches away from the previous position and washed out a cavity which connected into the previous cavity in 25 seconds of operation. This technique may have some advantages in working to a "free face" after the initial cavity is formed.

3.4.6. Conclusions Regarding Jet Cutting Tests

The lowest specific energy values resulted for the case of a water pressure of 3000 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 the mining process 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 inches in diameter and wash them from the slot. This suggests that both a drilling and slot cutting system are worthy of consideration as candidates for a prototype mining system.

In a few trials, slots were positioned to excavate frozen gravel by combining an old slot with the new slot. This appears to have some potential to work toward a free face. This same statement applies for drilled holes that are overlapping.

The tests run with the dual orifice divergent nozzles indicate 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 important if 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 to extend the depth as desired.

With the limited amount of tests run, the general conclusions regarding feasibility look promising. Therefore further jet cutting tests of frozen gravel should be conducted to gain additional information.

4. Final Remarks and Conclusions

The materials tested in this pilot study were frozen gravel, frozen pea-gravel, and ice. It is not known if the freezing technique or the type of gravel used produced a good equivalent material for simulating a particular gold bearing sediment. Very little can be done at this point to improve the equivalent material until specific data concerning permafrost properties are available. A program should be initiated to study in situ mechanical properties and composition of permafrost which would allow a more accurate laboratory modelling to occur.

Based on the uniaxial studies, the uniaxial compressive strength and Young's modulus were evaluated for the three materials as a function of temperature in the range from 10°F to 28°F. The results indicate the need for further studies of time dependent behavior and strength under flexural loading.

The results from the water jet cutting tests are encouraging. The ice is easy to cut although the slot in ice alone tends to be very narrow compared to the width generated when the jet deflects off of the gravel particles. Samples need to be studied with larger pieces of gravel to see if the jet can still free bigger chunks of gravel than the 2 inch size used in these tests. There was no problem in these tests with washing the gravel out of the slot after it had been cut free.

The optimum pressure would appear to be below the 5000 to 15000 psi range, and further tests should be run at below 5000 psi to establish the threshold pressure for this material. The specific energy values required appear to be reasonable for effectively excavating the frozen gravel.

In future tests a method of controlling the sample temperature would be beneficial. Also, since the depth and width of the slot varies significantly, a method to accurately weigh the samples before and after cutting would improve the accuracy of the test procedure.

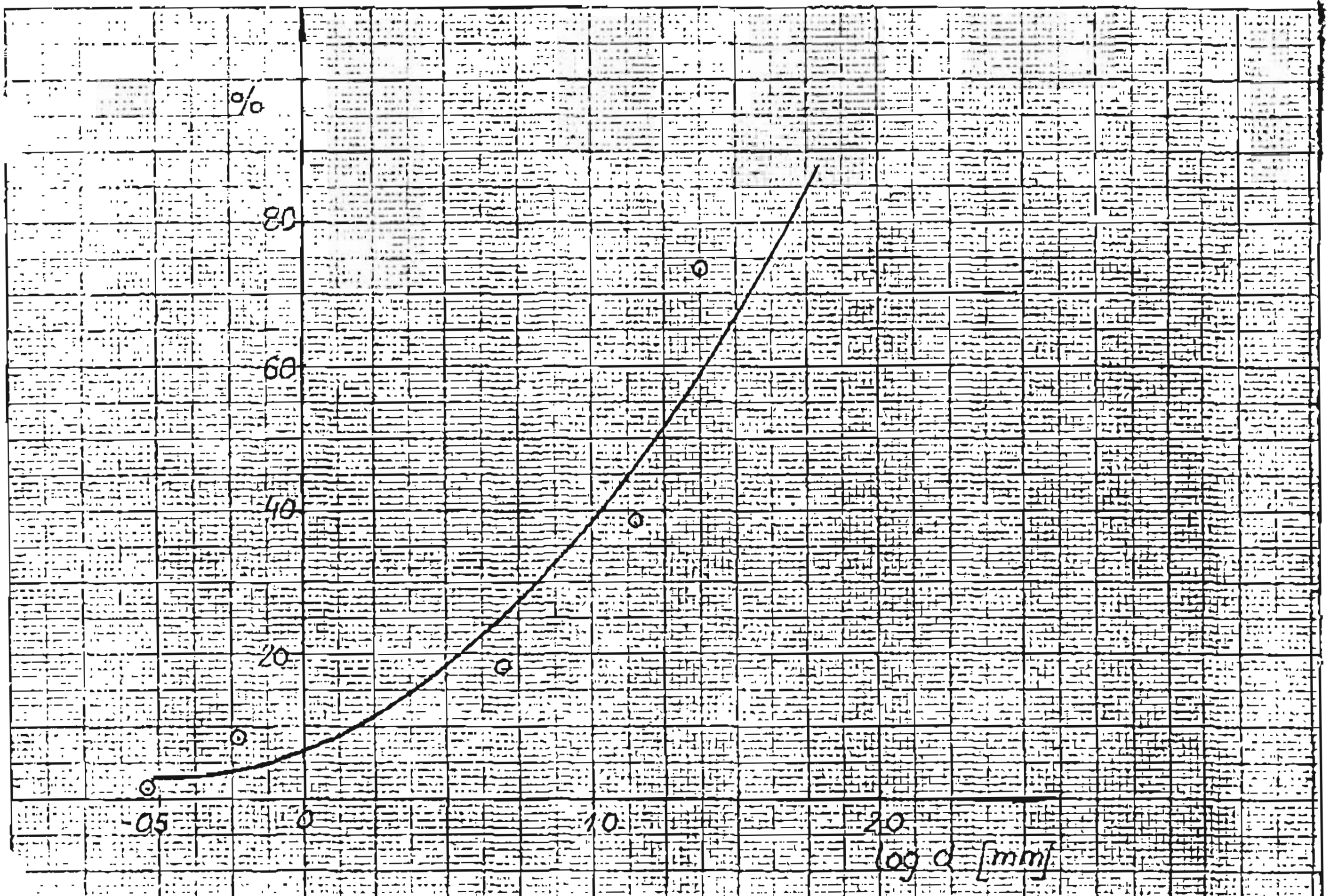


FIGURE 1 : GRAVEL SIEVE ANALYSIS

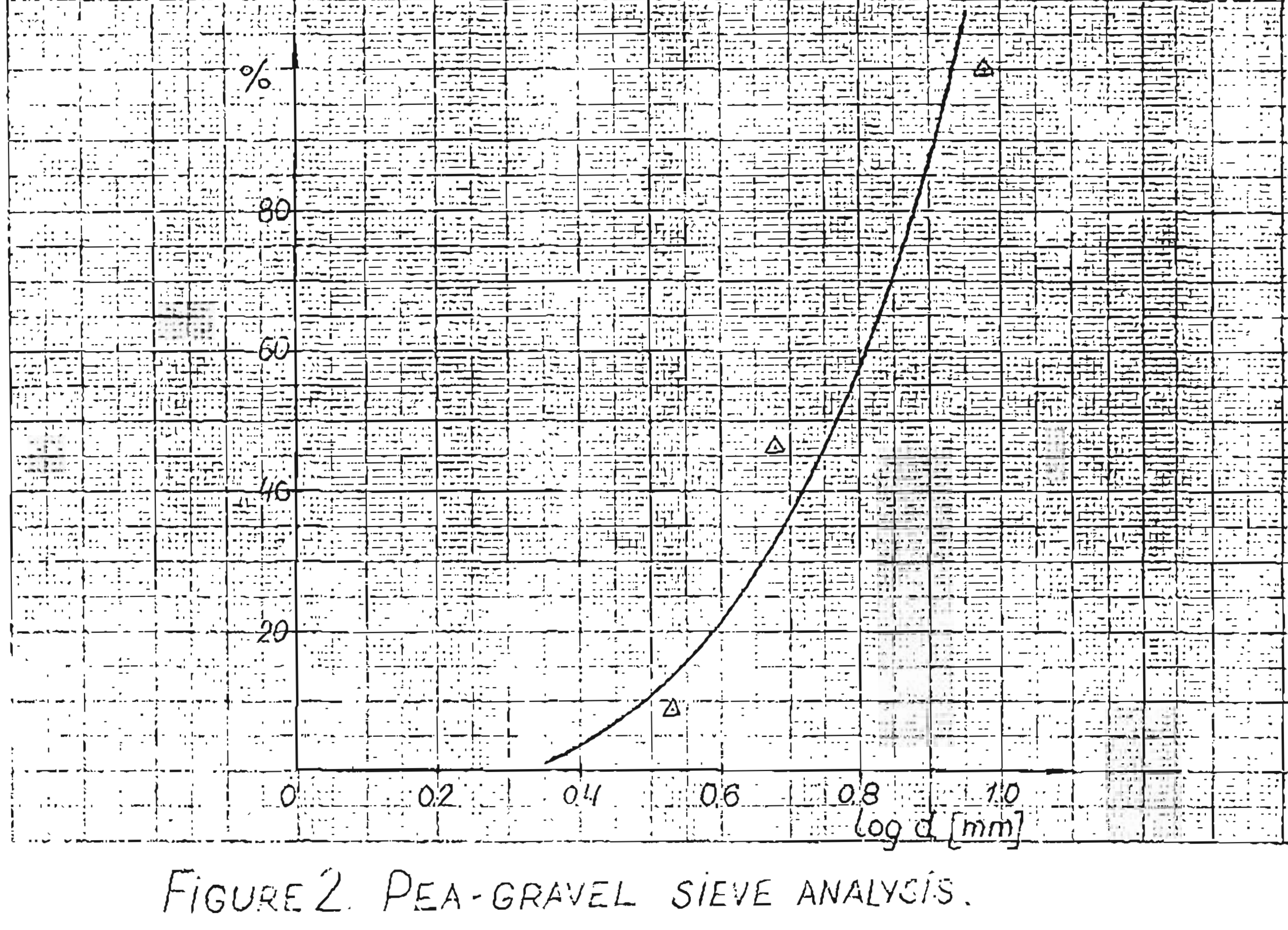


FIGURE 2. PEA-GRAVEL SIEVE ANALYCIS.

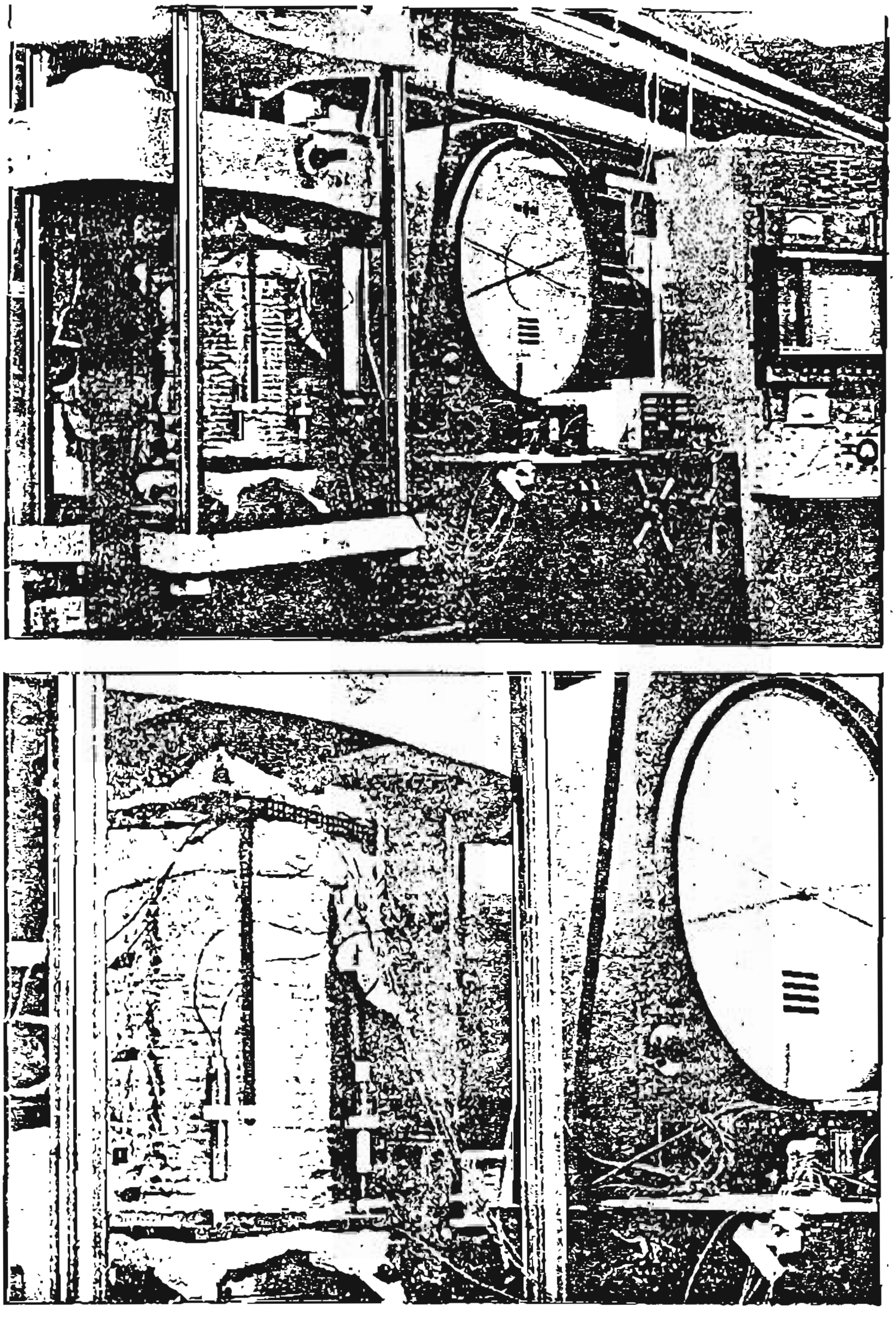


FIG. 3. TESTING FIXTURE FOR UNIAXIAL COMPRESSIVE TEST.

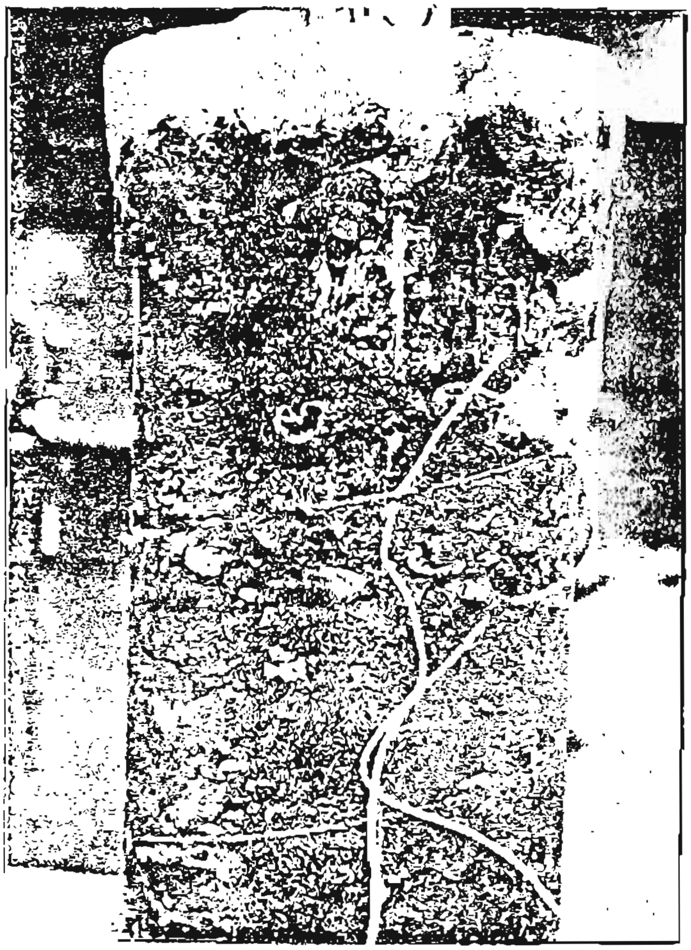


FIG. 4. #3 SAMPLE AFTER UNIAXIAL TEST.

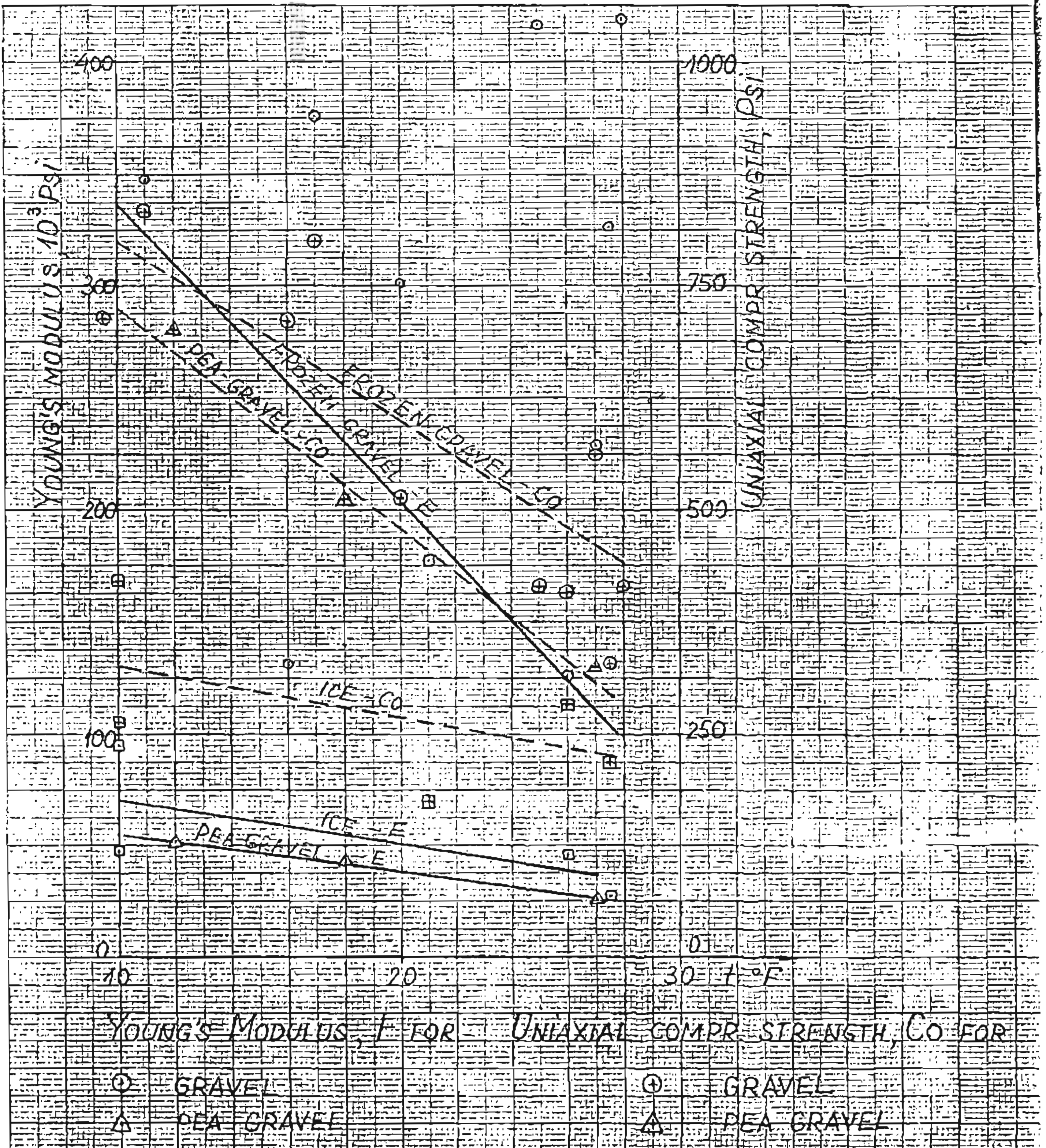


FIGURE 5 UNIAXIAL COMPRESSIVE STRENGTH AND YOUNG'S MODULUS AS A FUNCTION OF TEMPERATURE

```
Y = A + B*X

A =
 1060.6953125

B =
 -23.2026721015

R-SQUARE =
 0.768478862453

RES ERROR
 8953.10760587

MAX(ABS(RESIDUAL))
 146.776834239


 FROZEN GRAVEL,Co
```

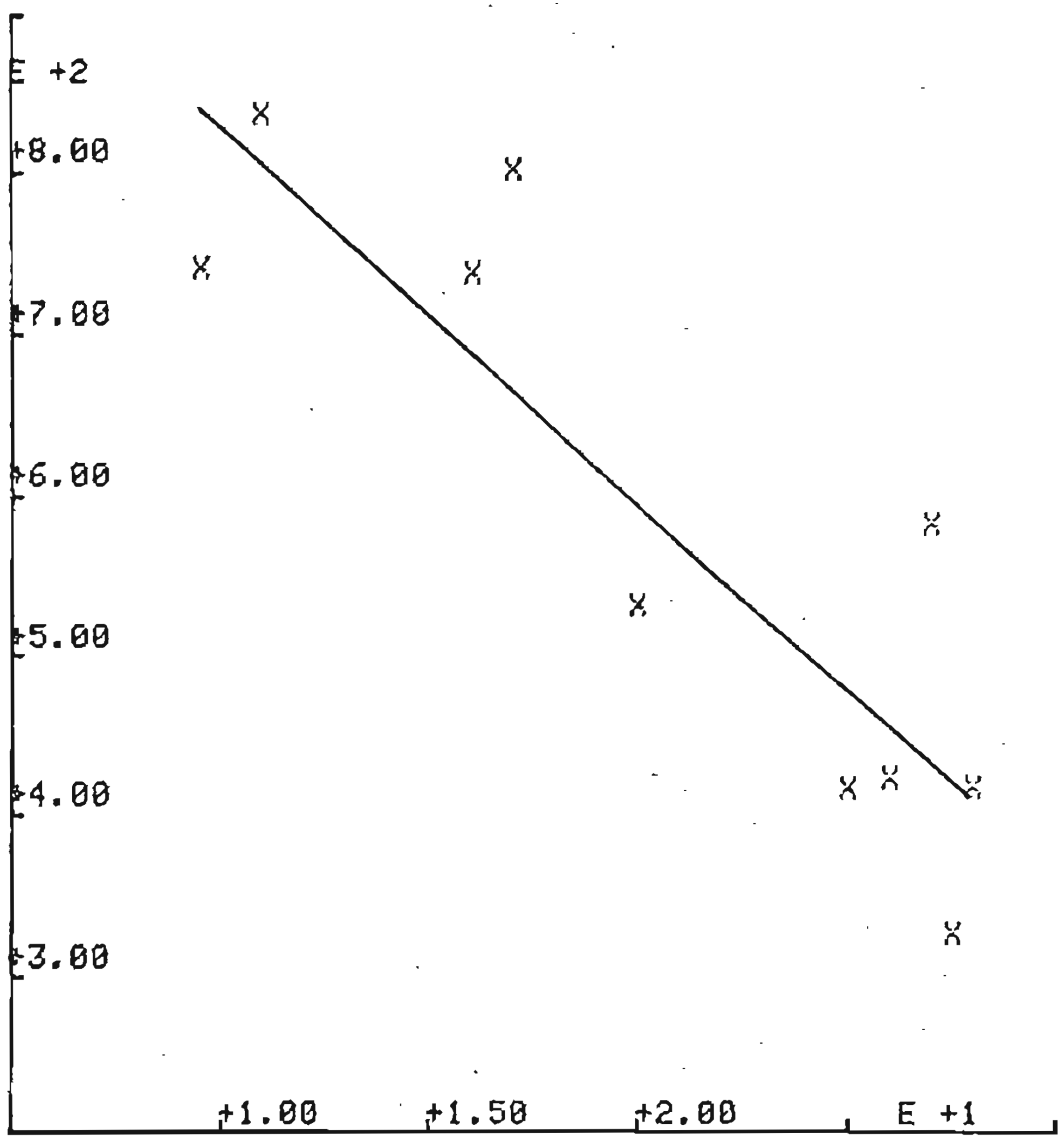


FIG.6. UNIAXIAL STRENGTH OF FROZEN GRAVEL.

```
Y = A + B*X

A =
 464739.84375

B =
 -12428.0117754

R-SQUARE =
 0.512332712605

RES ERROR
 8.115474687E+9

MAX(ABS(RESIDUAL))
 128691.655344


 FROZEN GRAVEL,E
```

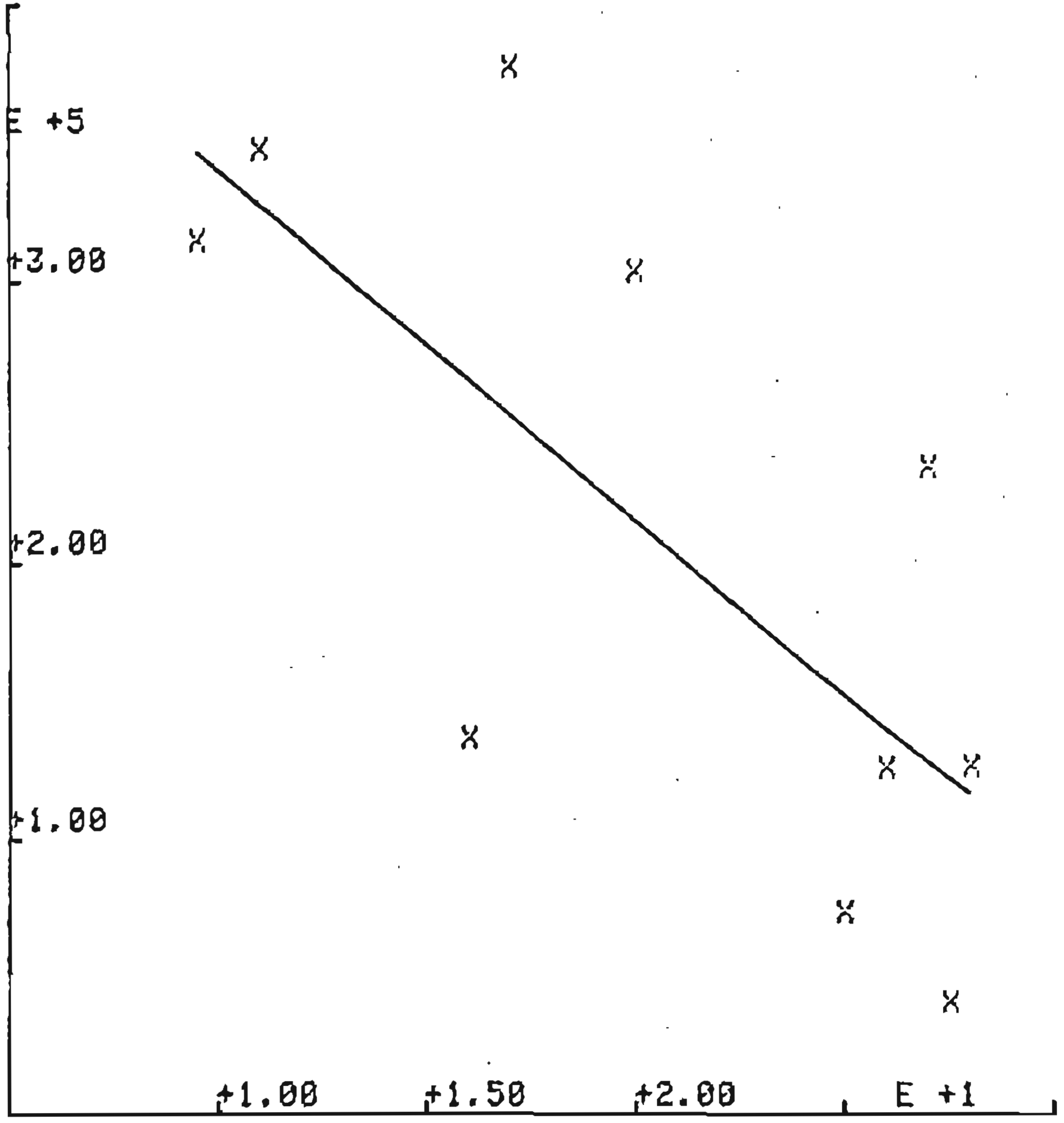


FIG. 7 YOUNG'S MODULUS OF FROZEN GRAVEL.

```
Y = A + B*X

A =
 987

B =
 -24.9473684211

R-SQUARE =
 0.987863270161

RES ERROR
 871.684210526

MAX(ABS(RESIDUAL))
 23.9473684211


 FROZEN PEA-GRAVEL,Co
```

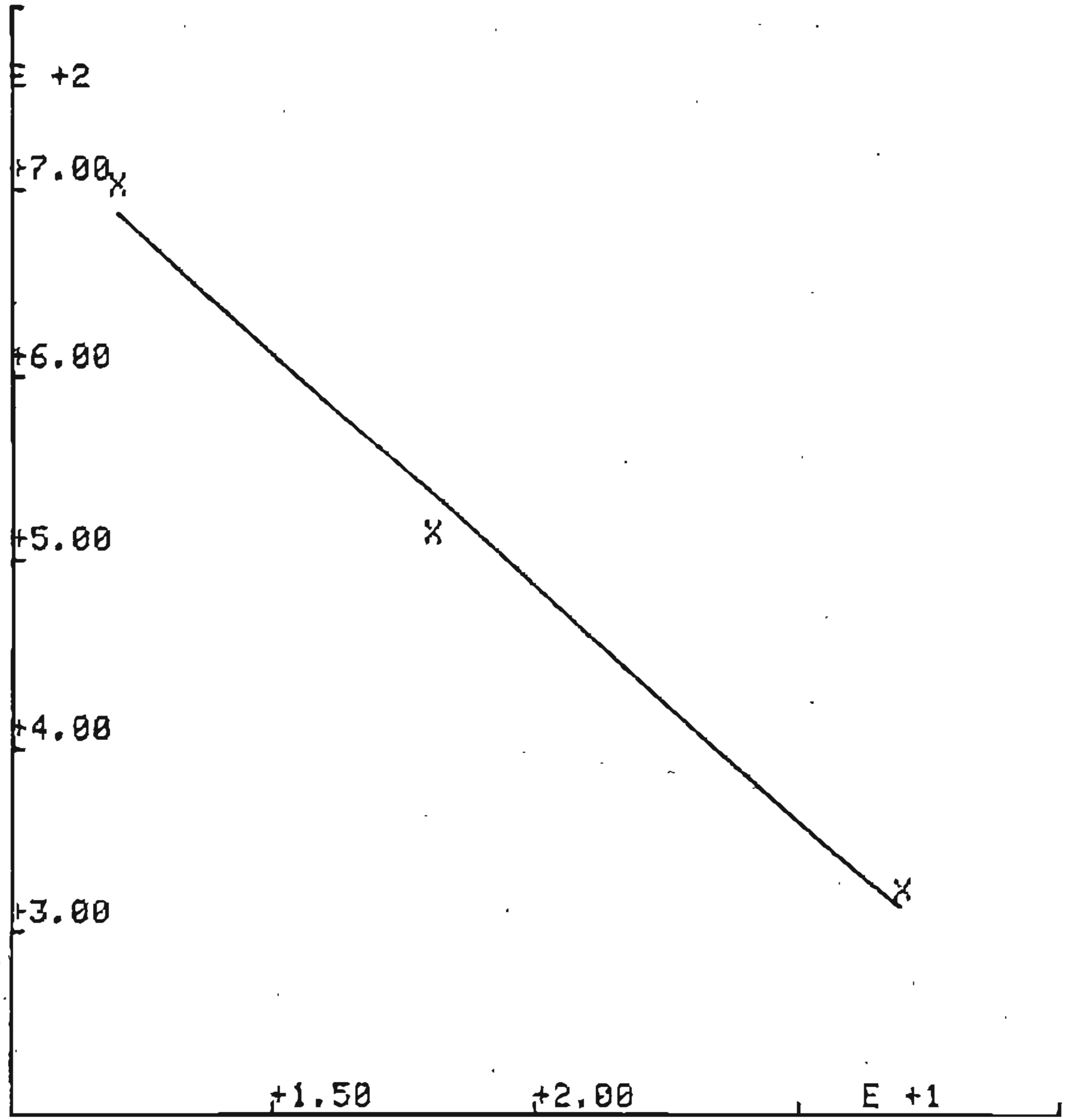


FIG. 8. UNIAXIAL STRENGTH OF FROZEN PEA-GRAVEL.

```
Y = A + B*X

A =
 72900

B =
 -1731.57894737


R-SQUARE =
 0.991741670662

RES ERROR
 2846315.78947

MAX(ABS(RESIDUAL))
 1368.42105263




FROZEN PEA-GRAVEL,E
```

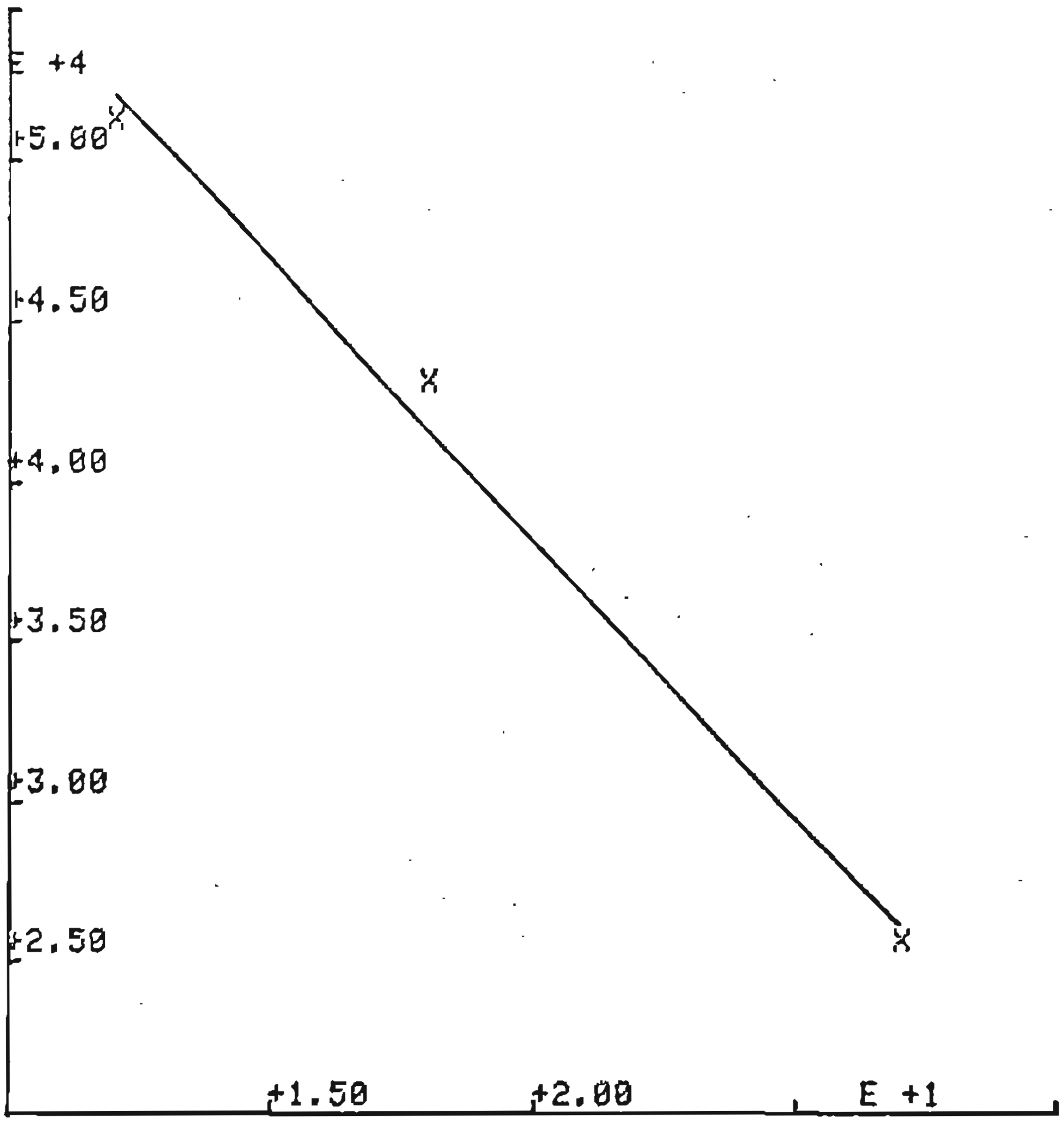


FIG. 9. YOUNG'S MODULUS OF FROZEN PEA-GRAVEL.

```
Y = A + B*X

A =
 390.223711699

B =
 -6.25522284123

R-SQUARE =
 0.33693655056

RES ERROR
 7371.49738858

MAX(ABS(RESIDUAL))
 90.3285167131



 ICE,Co
```

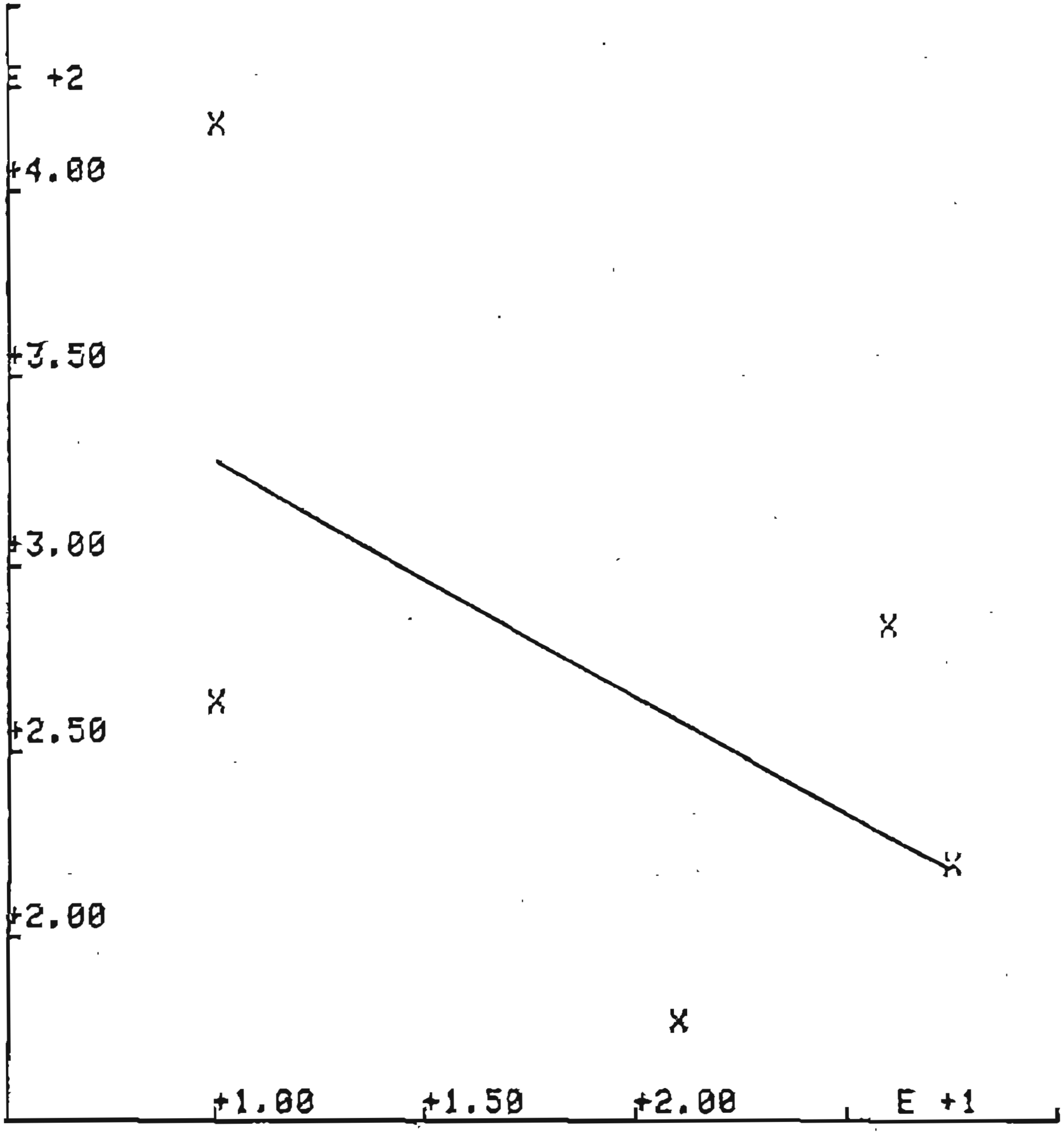


Fig. 10. Uniaxial strength of ice.

```
Y = A + B*X

A =
 93601.7235376

B =
 -2152.47214485


R-SQUARE =
 0.517606842531

RES ERROR
 4.133704149E+8

MAX(ABS(RESIDUAL))
 24022.9979109



 ICE,E
```

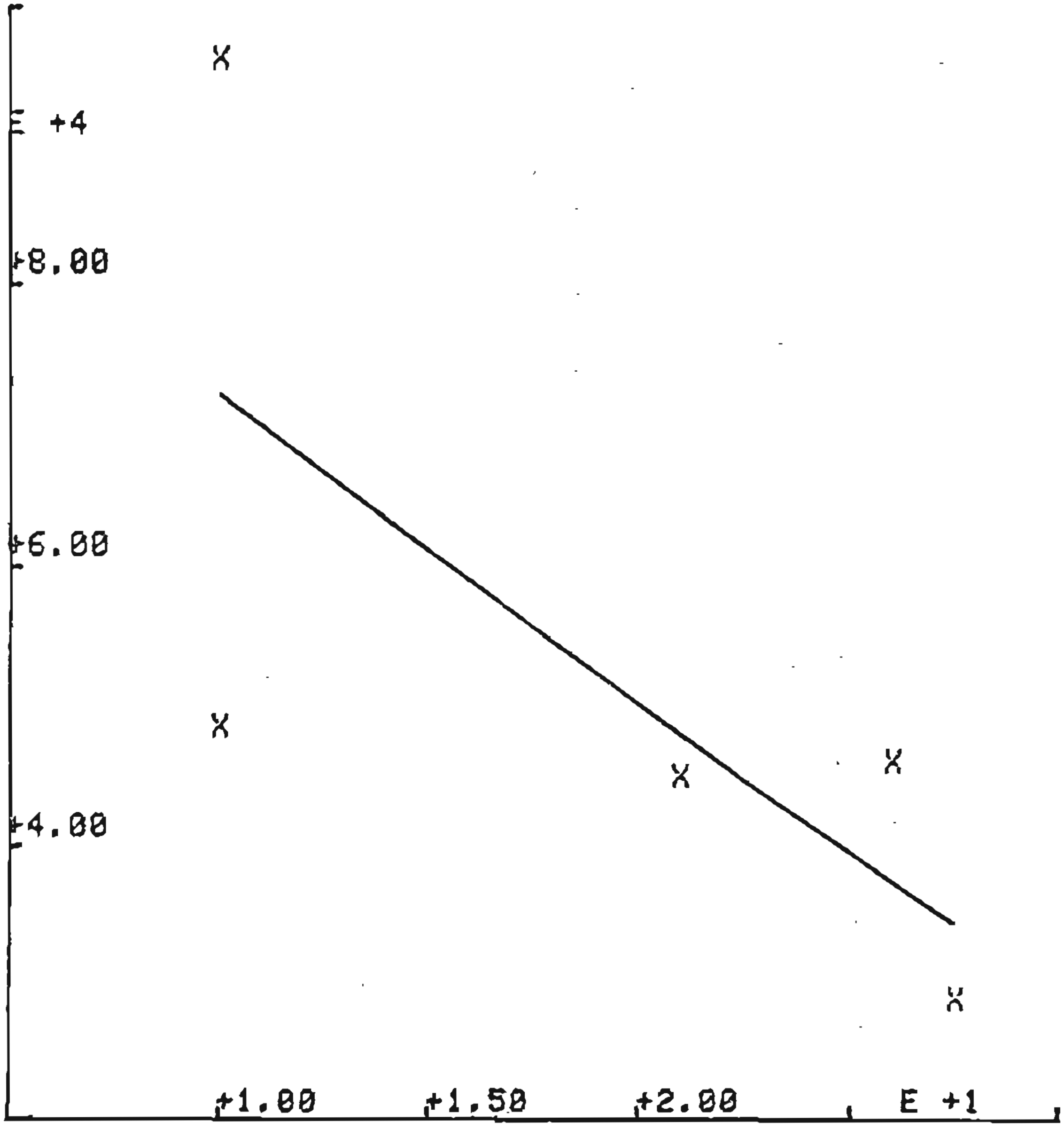


FIG. 11. YOUNG'S MODULUS OF ICE.

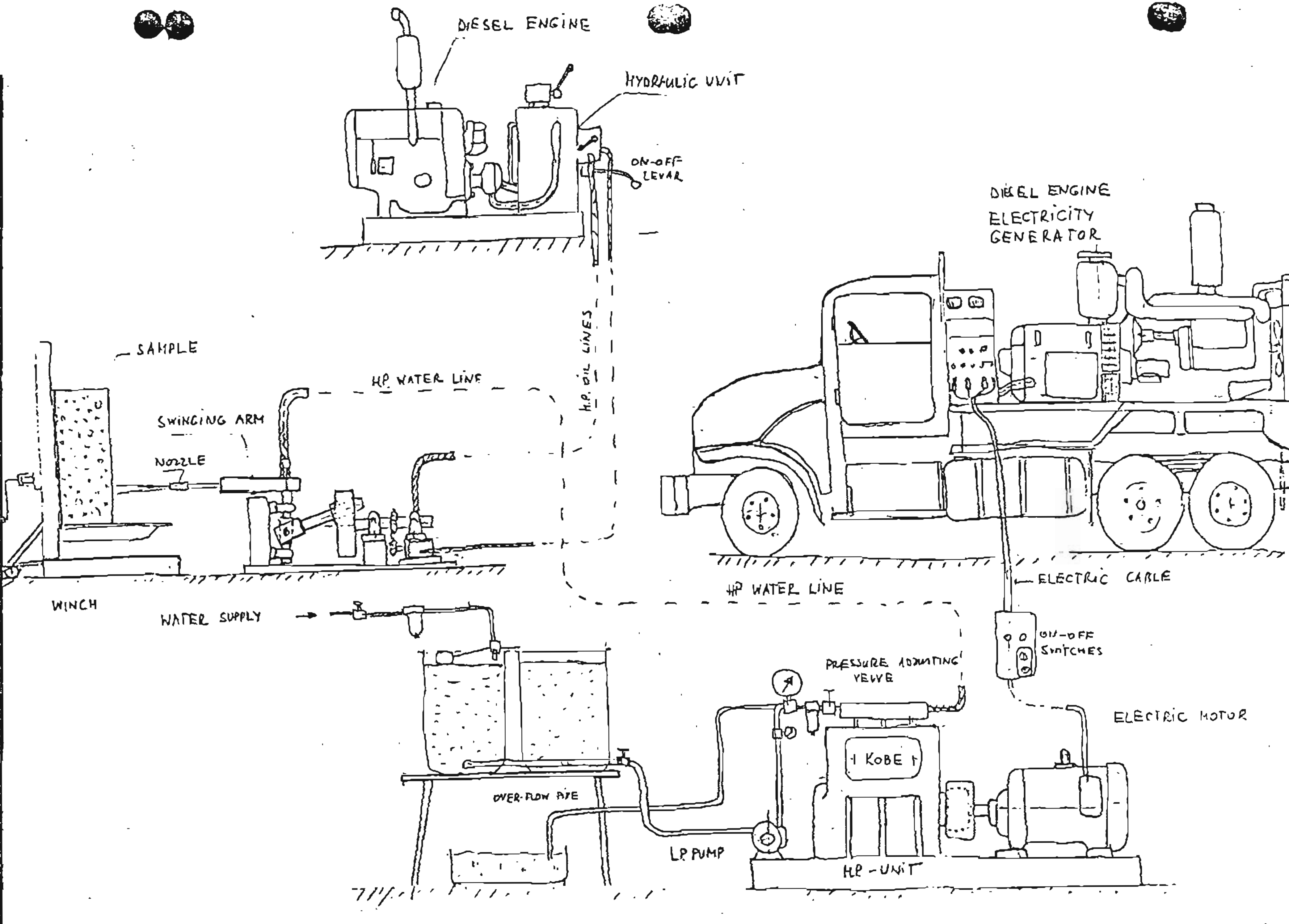


FIG. 12. GENERAL LAYOUT OF EQUIPMENT.

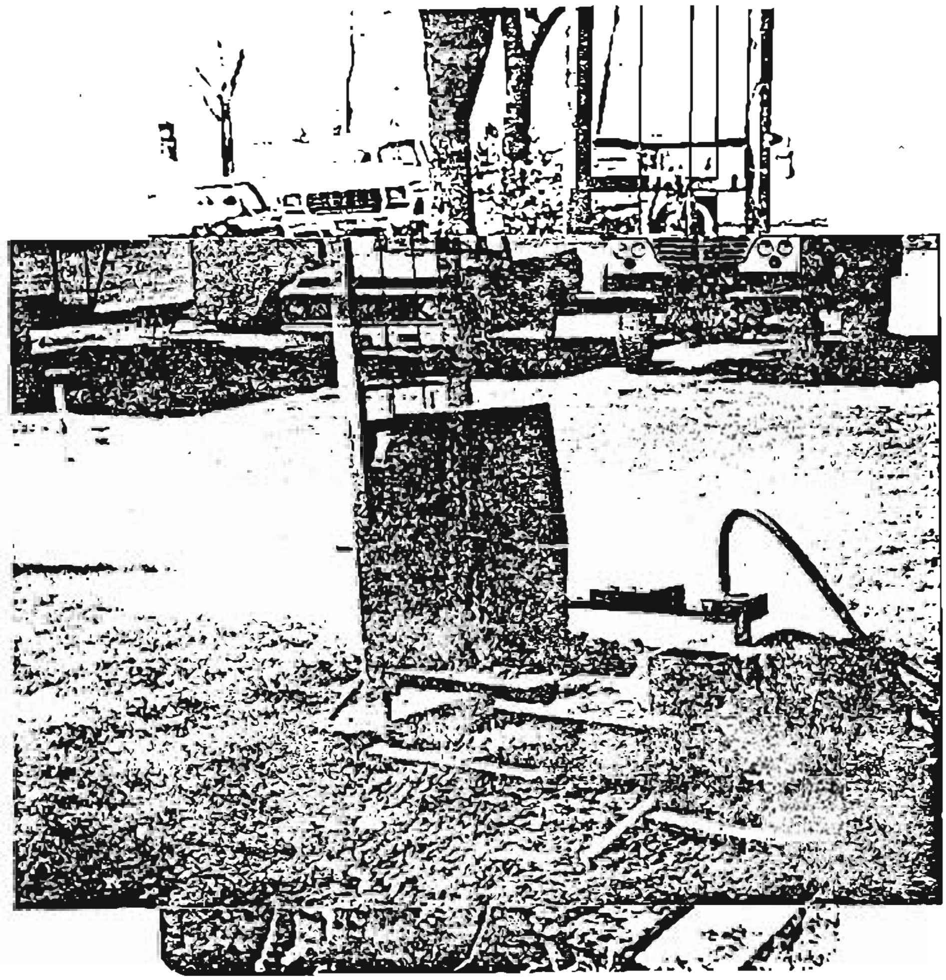


FIG. 13. MECHANISM USED TO OSCILLATE THE NOZZLE.

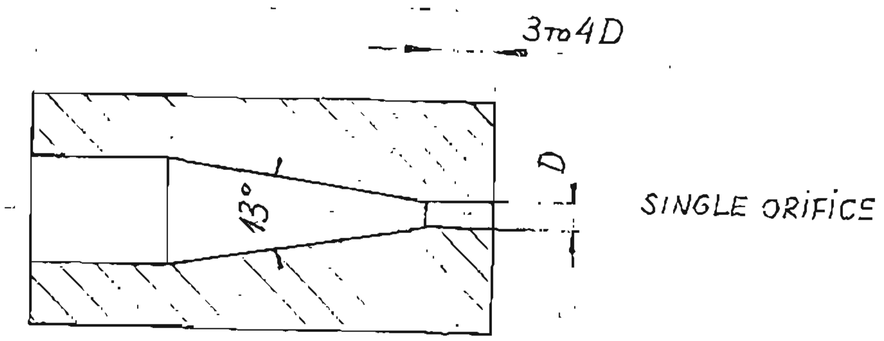


FIG. 14. SINGLE ORIFICE

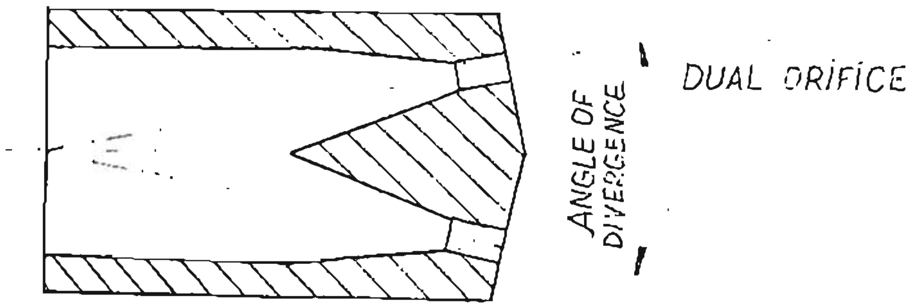
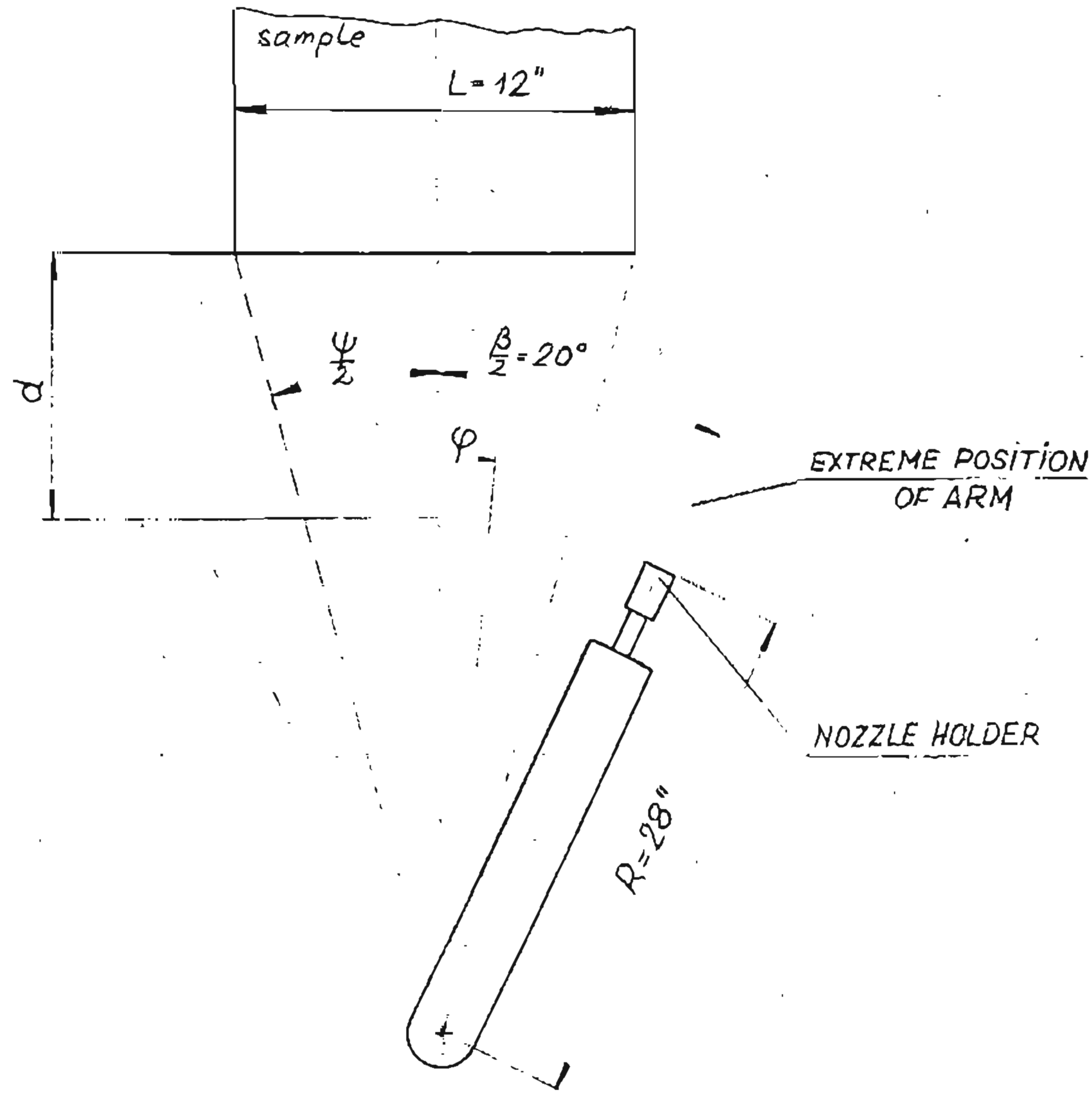


FIG. 15. DUAL ORIFICE



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

FIG. 16. POSITION OF SAMPLE WITH RESPECT TO THE OSCILLATING NOZZLE.

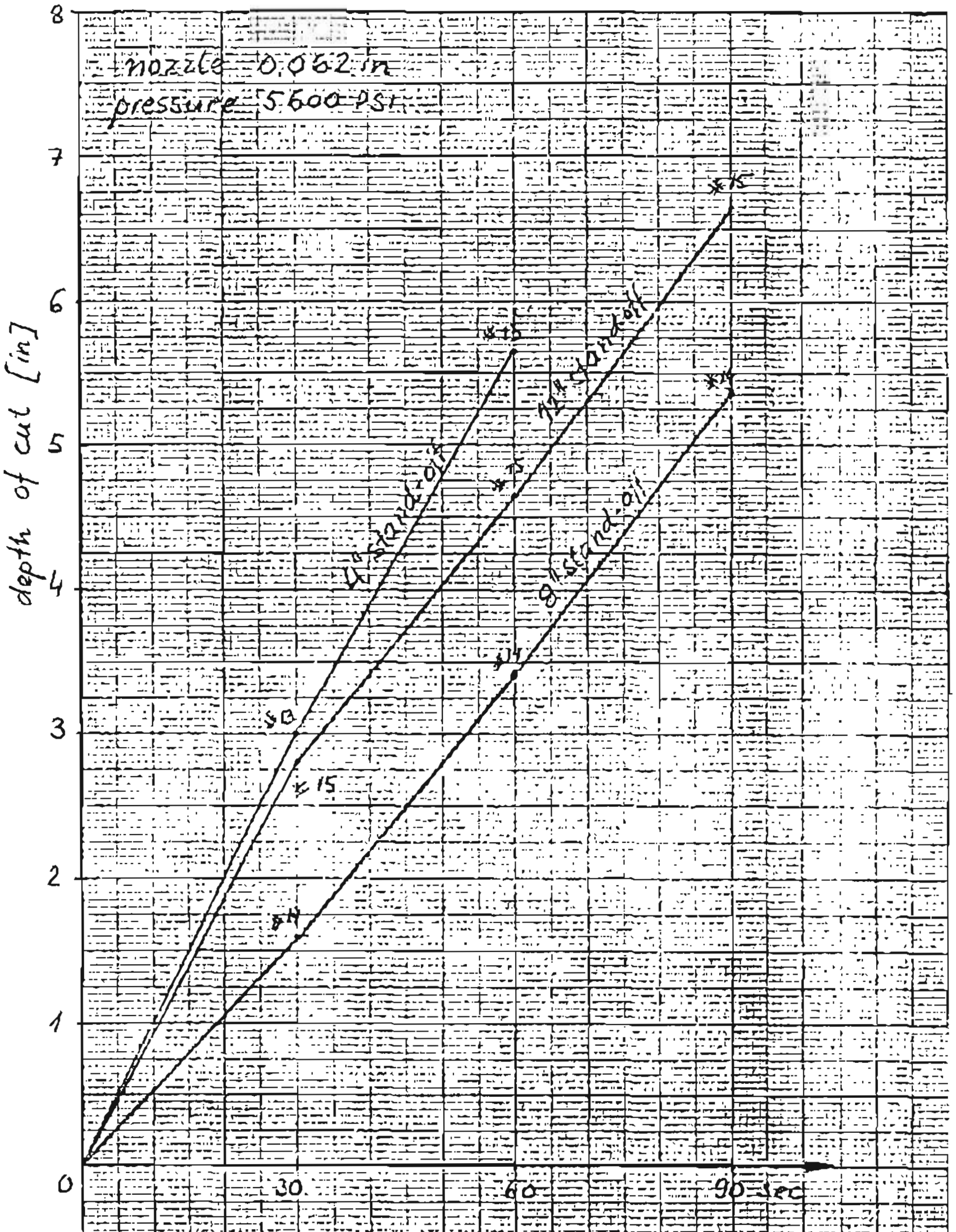


FIG.17. PENETRATION DEPTH FOR NOZZLE 370 AT 5600 PSI

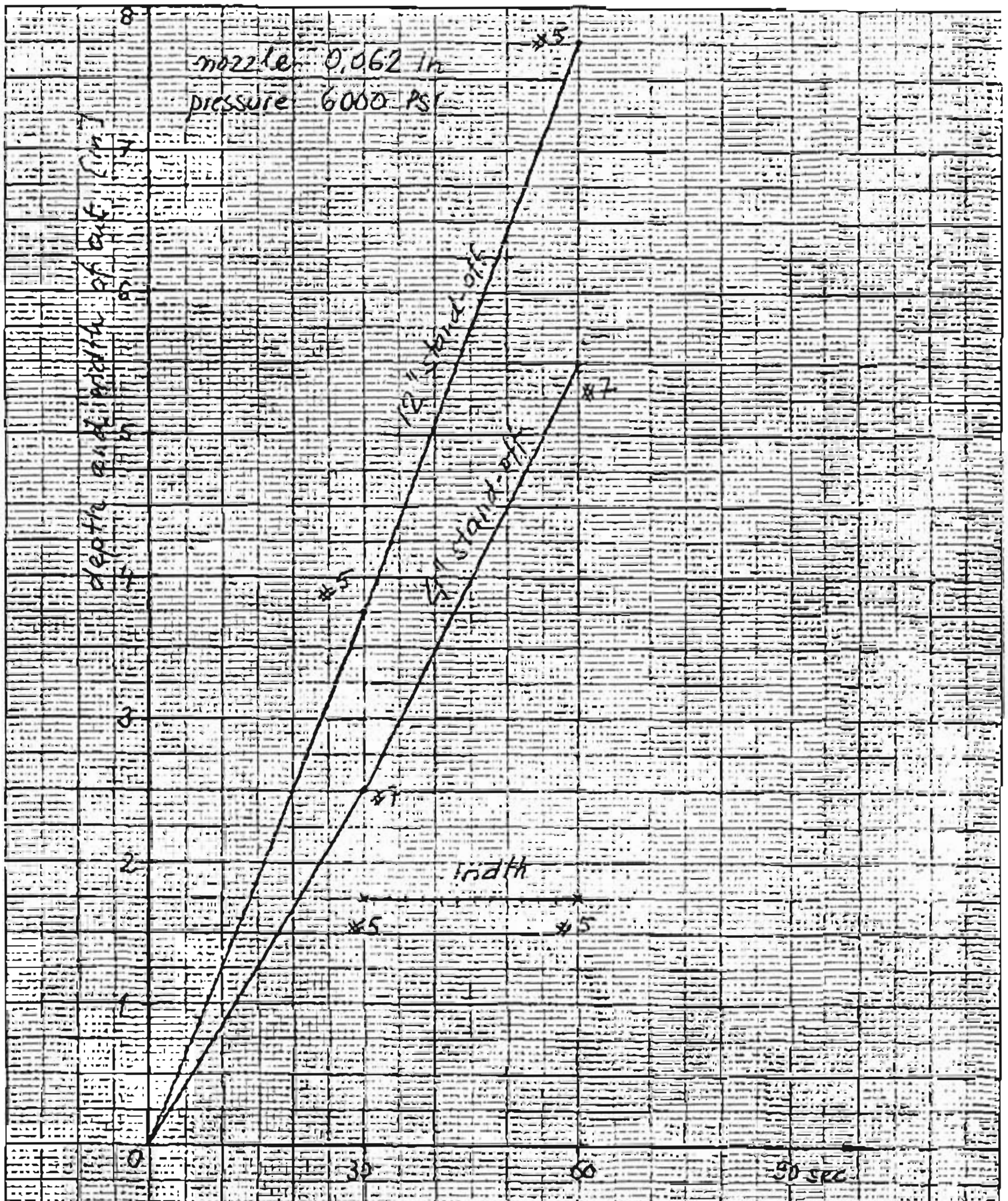


FIG. 18. PENETRATION DEPTH FOR NOZZLE 370 AT 6000 PSI.

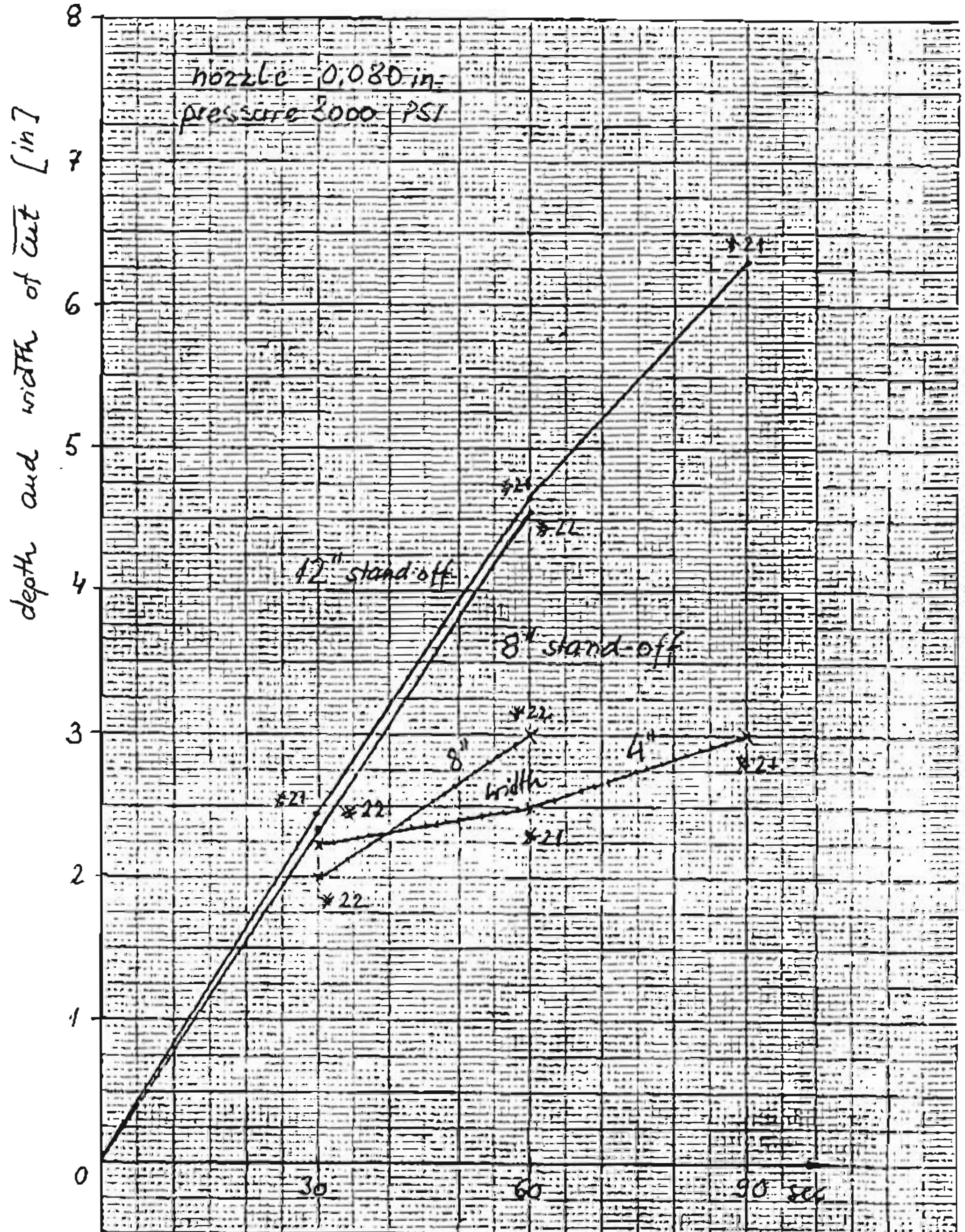


FIG 19. PENETRATION DEPTH FOR NOZZLE 430 AT 3000 PSI.

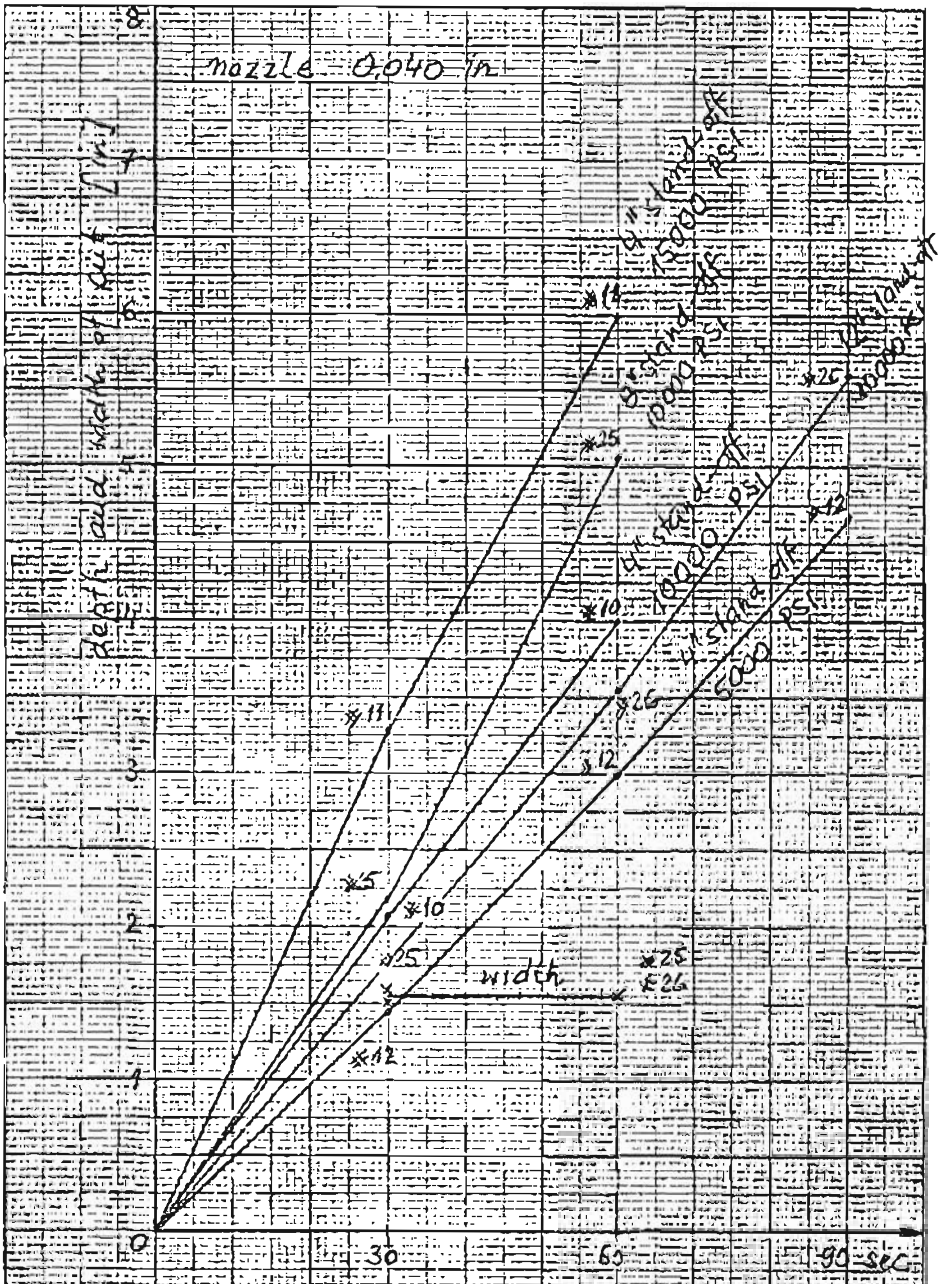


FIG 20. PENETRATION DEPTH FOR NOZZLE 400 AT 5000 10000 AND 15000 PSI.

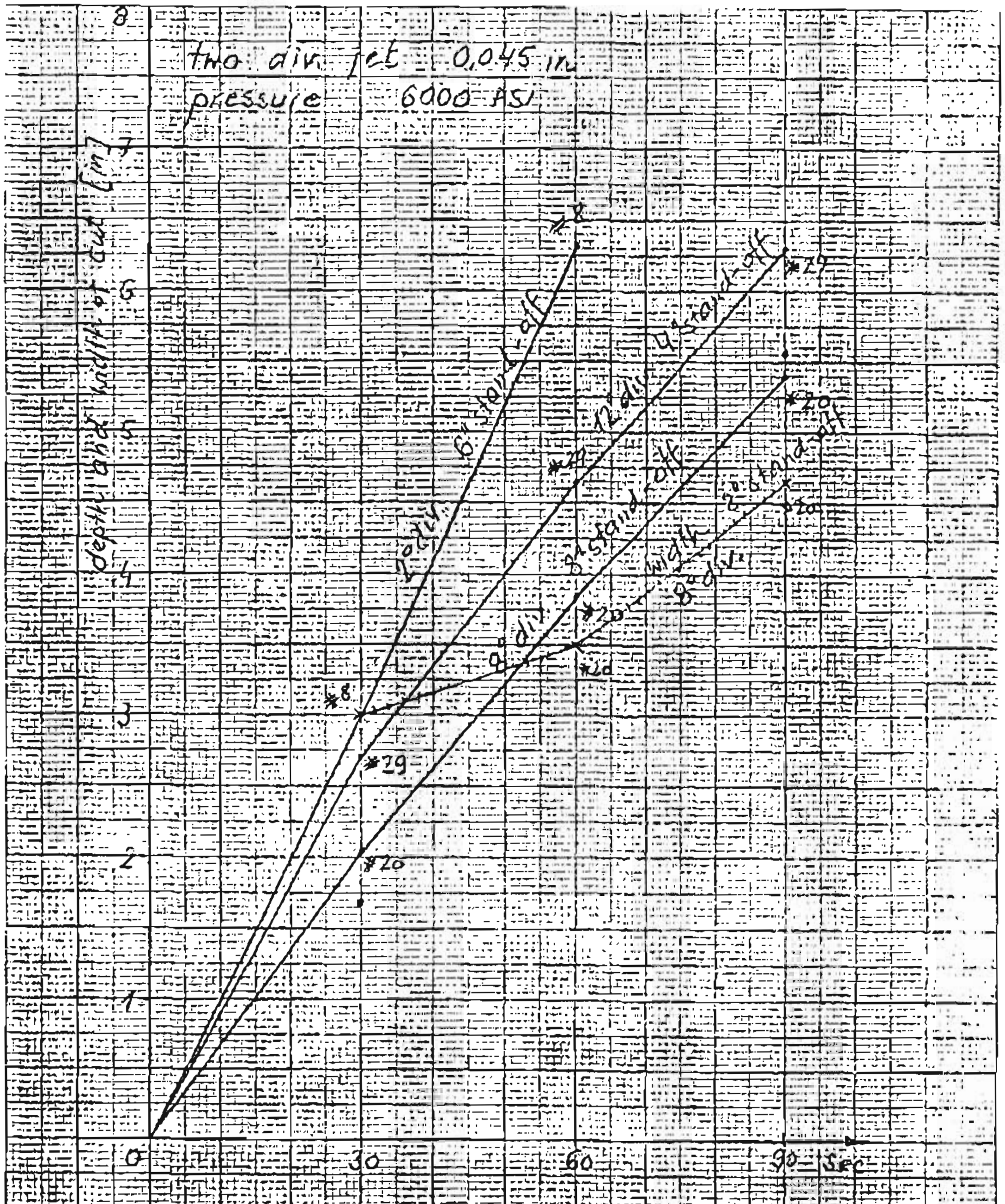


FIG. 21 PENETRATION DEPTH FOR DUAL ORIFICE NOZLE

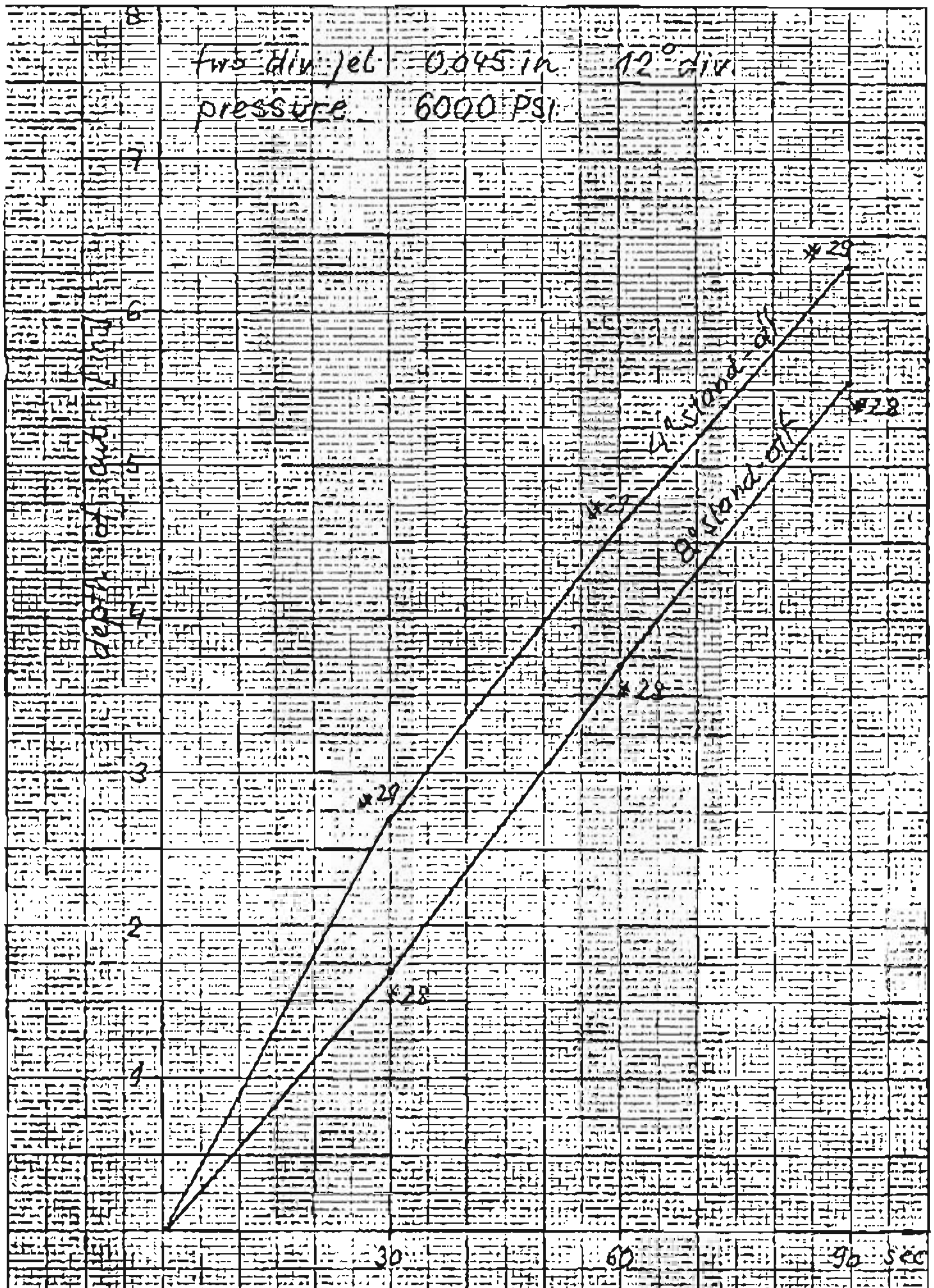


FIG. 22 PENETRATION DEPTH FOR 12° DIVERGING NOZZLE

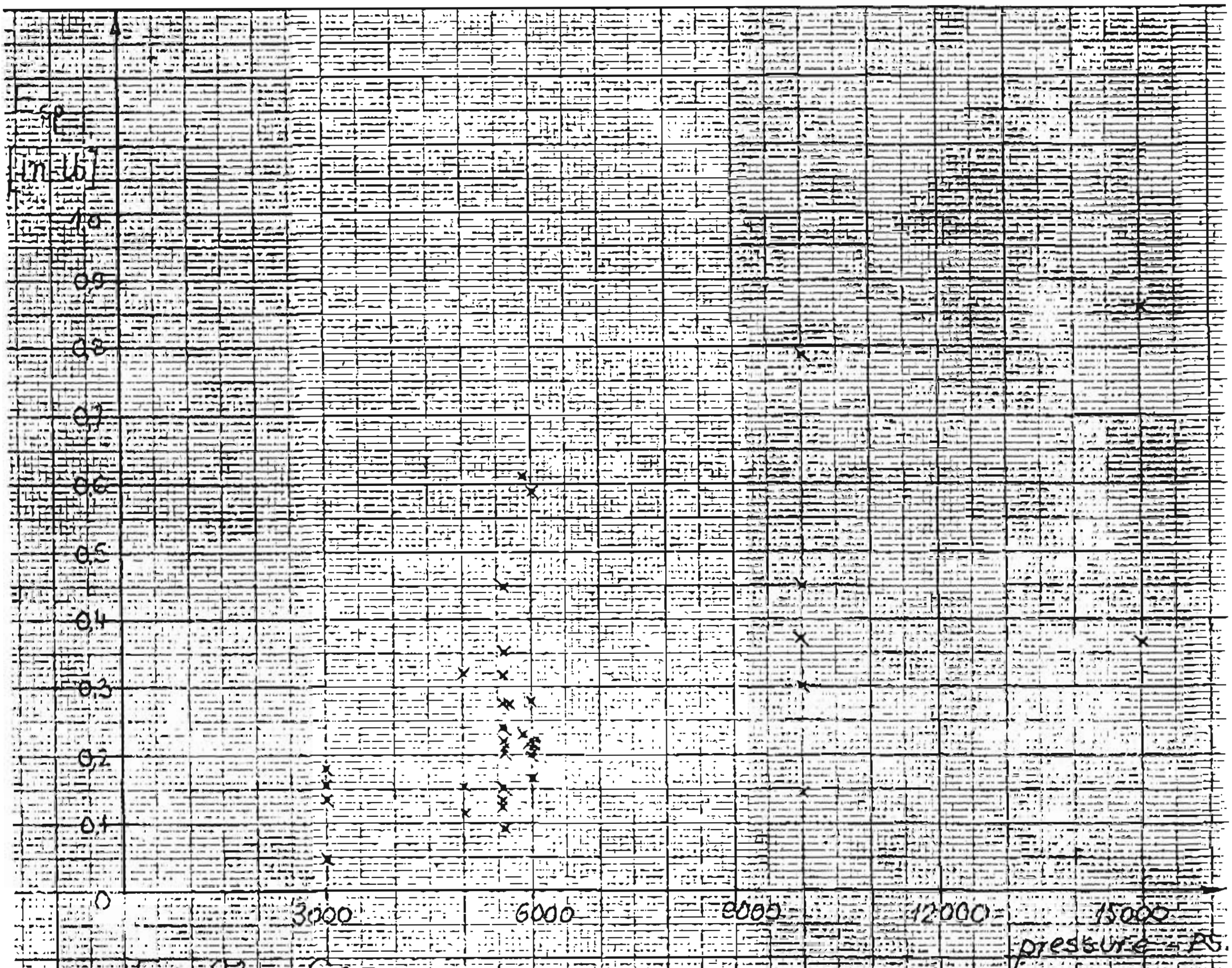
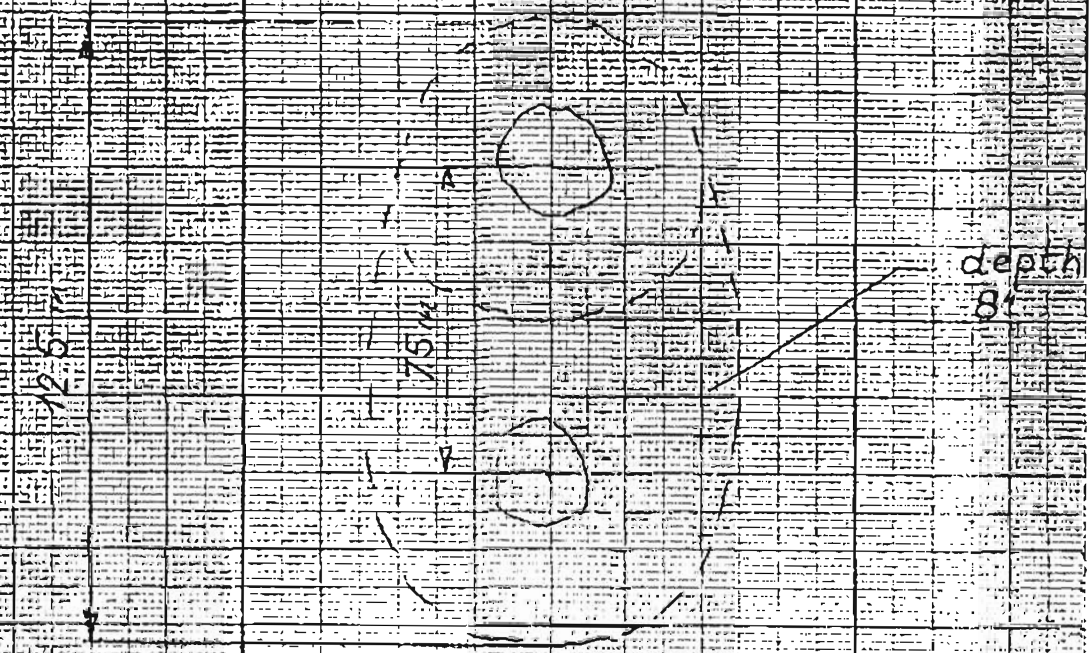


FIG. 23 SPECIFIC ENERGY VERSUS PRESSURE



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

FIG. 24. COMBINED EFFECT OF TWO CUTS

Table 3

Uniaxial Compressive Test

Sample Number	Material	Sample Size, in.	Temperature °F.	Uniaxial Compr. Strength C_o, psi	Young's Modulus E, psi	Noise Level	Remarks
1	gravel	14 1/2 x 8	16	736	137,200	some	
2	gravel	15 1/4 x 8	27	581	232,700	some	
3	gravel	15 1/4 x 8	26	422	125,600	no	
4	gravel	15 7/16 x 8	20	531	302,600	some	
5	gravel	16 7/16 x 8	9.5	740	314,000	much, after failure	
6	gravel	13 5/8 x 8	11	836	346,900	some	
7	gravel	14 3/8 x 8	17	800	376,100	very little	
8	gravel	13 5/8 x 8	28	416	126,200	no	
9	gravel	13 5/8 x 8	25	415	73,200	no	
10	gravel	14 1/8 x 8	27.5	327	40,300	no	
11	ice	13 5/8 x 8	10	418	96,100	lots	
12	pea gravel	14 1/8 x 8	12	702	51,300	some	*bottom not flat*
13	ice	13 3/8 x 8	27.5	219	28,900	some	
14	ice	13 5/8 x 8	26	283	46,000	very little	
15	pea gravel	15 x 8	27	323	25,600	-	
16	ice	14 1/2 x 8	10	263	48,600	much	
17	ice	13 3/4 x 8	21	177	45,000	much	
18	pea gravel	15 1/2 x 8	18	514	43,100	no	
19	ice	*sample fractured before testing*					
20	ice	*sample fractured before testing*					

Table 4

Statistical Results from Uniaxial Test

Material	Uniaxial Compressive Strength, C_o, (psi) average at 28°F	Uniaxial Compressive Strength, C_o, (psi) change psi/°F	Young's Modulus, E, (psi) average at 28°F	Young's Modulus, E, (psi) change psi/°F
Frozen Gravel	411	-23.2	116,800	-12,400
Frozen Pea-Gravel	288	-24.9	24,400	-1,730
Ice	215	-6.3	33,330	-2,150

WATER JET CUTTING DATA SUMMARY

Run #	(sec) Time	(psi) Pressure	Nozzle	(inch) Standoff	(inch) Penetration	(inch) Slot Width
3a	30	6000	370	6	4 to 5	1.75
3b	30	6000	370	6	8 (thru)	2.00
4	60	6000	370	6	6 to 8	1.75-2.50
5a	30	6000	370	12	3.5 to 4	
5b	30	6000	370	12	7.5 to 8	1.75
6	30	6000	370	6	Enlarged into Previous Slot #5	
7a	30	6000	370	6	1.5	1.75
7b	30	6000	370	6	4 to 6	1.75
8a	30	6000	300	6	0.5 to 4.75	1.75
8b	30	6000	300	6	5 to 8	1.75
9	very short	6000	370	6	Ice Sample Cracked Very Quickly	
10a	30	10000	400	4	1.25 to 2.75	1.5
10b	30	10000	400	4	3 to 6	1.75
11a	30	15000	400	4	2 to 3.75	1.75
11b	30	15000	400	4	5.25 to 6.5	2.0
12a	30	5000	400	4	0.75 to 2.25	1.75
12b	30	5000	400	4	2.5 to 3.75	1.75
12c	30	5000	400	4	3.5 to 6	2.00
13a	30	5600	370	4	1.75 to 4.25	1.75
13b	30	5600	370	4	4.25 to 7	2.00
14a	30	5600	370	8	0.25 to 2.25	1.75
14b	30	5600	370	8	3 to 4.5	1.75
14c	30	5600	370	8	3.5 to 6.5	2.0
15a	30	5600	370	12	1.75 to 5	1.75
15b	30	5600	370	12	3.75 to 6.25	1.75
15c	30	5600	370	12	5.74 to 8	2.0
16a	30	5600	370	12	2 to 7	1.75
16b	30	5600	370	12	5.5 to 9	2.0
17	30	5600	330	12	Slot #1 1.5 to 3.5	1.5
					Slot #2 1.75 to 3	1.5
18a	30	5600	330	4	1.75 to 6	1.75
18b	30	5600	330	4	4 to 6	1.75
18c	30	5600	330	4	5.5 to 8	2.0
19	40	5600	370	0	Drilled 8" Deep, 4 to 6" Dia Hole	
20a	30	5950	330	8	1.5 t0 3	3
20b	30	5950	330	8	3 to 4.5	3.5
20c	30	5950	330	8	4.5 to 6.5	4.5
21a	30	3000	430	4	2.5 to 3.5	2.25
21b	30	3000	430	4	4 to 6	2.5
21c	30	3000	430	4	5.25 to 7	3
22a	30	3000	430	8	2.75 to 3.5	2
22b	30	3000	430	8	4.0 to 6.5	3
23	60	3000	430	0	Drilled 8" Deep 5" Diameter	
24	25	3000	430	0	Drilled Into Cavity From Run 23	
25a	30	10000	400	8	1.25 to 3.5	1.75
25b	30	10000	400	8	4.5 to 5.5	1.75
25c	30	1000	400	12	1.5 to 2.5	2.0

Run #	(sec) Time	(psi) Pressure	Nozzle	(inch) Standoff	(inch) Penetration	(inch) Slot Width
26a	30	10000	400	12	1.5 to 2.5	1.5
26b	30	10000	400	12	2.75 to 4.25	1.5
26c	30	10000	400	12	5.25 to 6.25	1.5
27a	30	6000	350	12	Slot #1 0 to 2.5	1.5
					Slot #2 .75 to 2	1.5
27b	30	6000	350	12	Slot #1 2.75 to 4.25	1.5
					Slot #2 2.5 to 3.5	1.5
28a	30	6000	350	8	Slot #1 0.75 to 2.75	1.5
					Slot #2 0.75 to 3.5	1.5
28b	30	6000	350	8	Slot #1 2.5 to 4.25	2.0
					Slot #2 2.75 to 4.5	2.0
28c	30	6000	350	8	Slot #1 4 to 7	2.5
					Slot #2 4.25 to 7	2.5
29a	30	6000	350	4	2.25 to 3.5	2.5
29b	30	6000	350	4	4.25 to 5.25	3.5
29c	30	6000	350	4	5.74 to 7	4

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1. Mellor, M., "Jet Cutting in Frozen Ground," Paper G2, First International Symposium on Jet Cutting Technology, BHRA, (1972).
2. Chester, J. W., "Hydraulic fragmentation of frozen gravel," Report of Investigations, U. S. Bureau of Mines (in press).
3. Farmer, I. W. and Attewell, P. B., "Experiments with water as a dynamic pressure medium," Mine and Quarry Engineering, 29, pp. 524-530 (1963).
4. Foster-Miller Associates, Inc., "Fundamental concepts for the rapid disengagement of frozen soil," USACRREL Technical Reports 233 and 234, 237 and 190 pp. respectively, U. S. Army Cold Regions Research and Engineering Laboratory (1971).
5. Leach, S. J. and Walker, G. L., "Some aspects of rock cutting by high speed water jets," Phil. Trans. R. Soc. A260, pp. 295-308 (1966).
6. Mellor, M., "Some general relationships for idealized jet cutting," 1st Int. Symp. Jet Cutting Technol, Br. Hydromech. Res. Assoc. (1972).
7. Summers, D. A., "The water jet cutting of frozen gravel, 9 pp., 11 fig., for U. S. Army Cold Regions Research and Engineering Laboratory (Sept. 1971, unpub.).
8. Tousignant, T. L. and Swensen, R. A., "Liquid jet cutting of frozen soil," Tech. Note, 7 pp., 3 tables, 12 fig., U. S. Army Cold Regions Research and Engineering Laboratory (Oct. 1969, unpub.).