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High pressure water jet cutting of rock

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HIGH PRESSURE WATER JET CUTTING OF ROCK

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ABSTRACT

Three experiments are described that investigate the impingement of high pressure water jets on rock. The effect of jet pressure, stand-off distance, and time of impact on penetration and specific energy of rock removal are determined on Berea sandstone, Georgia marble, and Missouri granite. Pressures range from 5,000 psi to 25,000 psi, stand-off distances from 2.0 inches to 4.0 inches and time from 0.1 seconds to 5.0 seconds. The nozzle diameter used was 0.023 inches. The effect of nozzle speed and number of passes over the same area on depth of cut and specific energy are investigated on the above rock types and Indiana limestone using a continuous jet. The speed varied from 1.2 in/min to 561 ft/min and the number of passes from 1 to 16. The distance between adjacent cuts for complete rib removal by water jet action alone is determined for the 0.023 inch nozzle. The effect of nozzle diameter on penetration and specific energy is studied using both the continuous jet and the water cannon with pressures ranging up to 47,000 psi. The nozzle diameters vary from 0.023 inches to 1.0 inches.

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I. INTRODUCTION AND REVIEW OF LITERATURE

In recent years, there has been a growing interest in finding faster and more efficient ways of cutting rock. Novel excavation techniques have been considered (1) and the use of water under high pressure has shown to be one of the techniques considered most likely to succeed.

Water has been used for centuries in the extraction of minerals from the earth, but has been limited mainly to ore dressing or in flushing minerals, usually gold, from the country rock using very low pressure jets (3). This type of operation is still used for mining sand by Ontario Sand Company of Ontario, Illinois. In recent years, however, interest has turned to using high pressure water jets as a means of cutting and drilling rock in lieu of conventional methods.

The Russians were the first to realize the potential of water jets. In 1935, Dr. V. S. Muchnik of the Leningrad Mining Institute designed Russia's first complete hydraulic mining system (4). An experimental mine built in the Donets coal basin in 1939 produced 6,000 metric tons monthly.

Using water jets for mining was pioneered in this country by the American Gilsonite Company. Since 1948 this company has mined the solid hydrocarbon "Gilsonite" at Bonanza, Utah, by hydraulic mining. Water jet mining was used because Gilsonite is highly explosive in dust form and the naturally occurring spray from the water jets virtually eliminated the dust (5).

In 1959, the U.S. Bureau of Mines began to investigate the use of water jets in coal mines. A full scale experiment of hydraulic mining of anthracite was established in a Pennsylvania mine. A single jet monitor operating at a maximum pressure of 5,000 psi and 300 gal/min was used. The rate of production averaged 0.8 tons/min (6).

The success of these investigations led to more intensive research within the past decade. Farmer and Attewell (7, 8, 9) studied the mechanisms of rock fracture under single pulse jet impact and obtained a correlation between jet penetration rate and the rock static compressive strength.

Leach and Walker (10) examined water jets with high speed optical photography to determine the decay in jet velocity with distance from the nozzle. Nozzle designs were compared showing that nozzles having a contraction angle between 6 and 20 degrees followed by two to four nozzle diameters of straight section produced the most coherent jet. The jet pressure at the bottom of the hole was also investigated. For depths of ten nozzle diameters and greater, this pressure was one-tenth of the pump pressure. These results also indicated that there was a critical pressure below which penetration does not take place.

McClain and Cristy (11) at Oak Ridge National Laboratory studied the effect that nozzle traversing velocity had on the specific energy of cutting. For single traverse cuts in sandstone, specific energy as a function of water jet pressure, was found to decrease rapidly from an initially high value at the threshold cutting pressure to a minimum at approximately three times the threshold pressure, then gradually increase. When traverse cuts were made close enough together to produce interaction between adjacent slots, a specific energy value of about one-half of that obtained for cutting single slots was obtained.

Brook and Summers (12) investigated the jet parameters of pressure, nozzle stand-off distance, and time of impact on sandstone. They found penetration to be linear with jet pressure in the range 4,000 psi to 9,000 psi. A reduction in penetration occurred with an increase in stand-off distance from 0.3 inches to 2.0 inches. Most of the penetration was effected in the first few seconds of jet action. An addition of 100 ppm polyethylene oxide was shown to increase penetration by between 10 and 30%. Any method of operation that allowed some escape of the jet after impact was shown to improve penetration.

Cooley (13) using the specific energy of excavation as the major criterion of evaluation, determined that the optimum jet pressure, for minimum specific energy, was approximately equal to the rock compressive strength if the rock did not fail in shear or tension.

Brunton (14) studied the deformation at high strain rates of solids under impact of liquids using high speed photography, finding that the liquid behaved initially on impact in a compressible manner and that part of the deformation of the solid was due to this compressible behavior and part to the erosive shearing action of the liquid flowing at high speeds out across the surface.

Huck and Singh (15) investigated high speed pulsed water jets on six rock types. Single shots were conducted with jet pressures ranging up to 172,000 psi. The specific energy was found to decrease with specific pressure (jet pressure divided by compressive strength). Correlation of compressive strength and Schmidt hammer reading with the damage induced by the water jet were determined.

The oil industry has recently become interested in water jets as a method of drilling wells. Maurer and Heilhecker (16, 17) of Esso Production Research Company used a two inch diameter 830 HP erosion drill at pressures up to 13,500 psi to drill Carthage marble at an advance rate of 180 ft/hr, Indiana limestone at 280 ft/hr, and Berea sandstone at 300 ft/hr. Gulf Oil (18, 19) in field tests, drilled at speeds of 60 ft/hr using erosion drilling as compared to conventional rates of 20 ft/hr. Steel pellets were added to the jet stream.

The work described in this thesis was an extension of that previously reported by Summers (2). In his work, the upper limit of jet pressures investigated were 10,000 psi. The nozzle stand-off distances that he used were between 0.3 inches and 2.0 inches. This work continued where he left off, investigating pressures up to 30,000 psi for a continuous water jet pump and 47,000 psi for a single pulse cannon. The stand-off distances ranged from 2.0 inches to 4.0 inches. The time of jet impact used was 0.1 to 5.0 seconds.

In addition, the effect of speed of the nozzle traversing over the rock, the effect of the number of passes, and the effect of the nozzle diameter on penetration and specific energy of cutting, i.e., the kinetic energy of the water jet divided by the volume of rock removed, were studied.

Three experiments were devised. The first being a single pulse static experiment. The second used a continuous jet with the nozzle moving in relation to the rock surface. And, the third used the water cannon.

II. SINGLE PULSE STATIC EXPERIMENT

A. Introduction

The first experiment was designed to investigate the three jet parameters that were considered to be the most critical to water jet cutting of rock. These being the pressure of the water jet, the distance between the nozzle and the rock face or stand-off distance which influences the jet, and the length of time the jet was impinging on the rock, which controlled the total jet energy transmitted to the rock.

B. Description of Equipment

A Kobe triplex pump, four gal/min output, supplied water containing approximately 9% soluble oil by volume through a 0.023 inch titanium nozzle at pressures ranging up to 30,000 psi (Fig. 1). The soluble oil was added to the water for lubrication purposes. The pressure behind the jet was controlled by means of a bleed-off circuit which returned part of the water into the pump feed reservoir. Control of the flow through this circuit was by a bleed-off valve. By closing the valve, the jet pressure could be increased to a maximum value of 30,000 psi.

A steel bar was prepared as an interruptor mechanism for the continuous jet by slotting it lengthwise and connecting it between a pair of solenoids. The length of time that the jet struck the rock was measured using a digital electronic counter, connected to a photo electric cell (Fig. 2). An aluminum rod was attached to the steel bar in such a manner as to break the light beam during the time the jet was striking

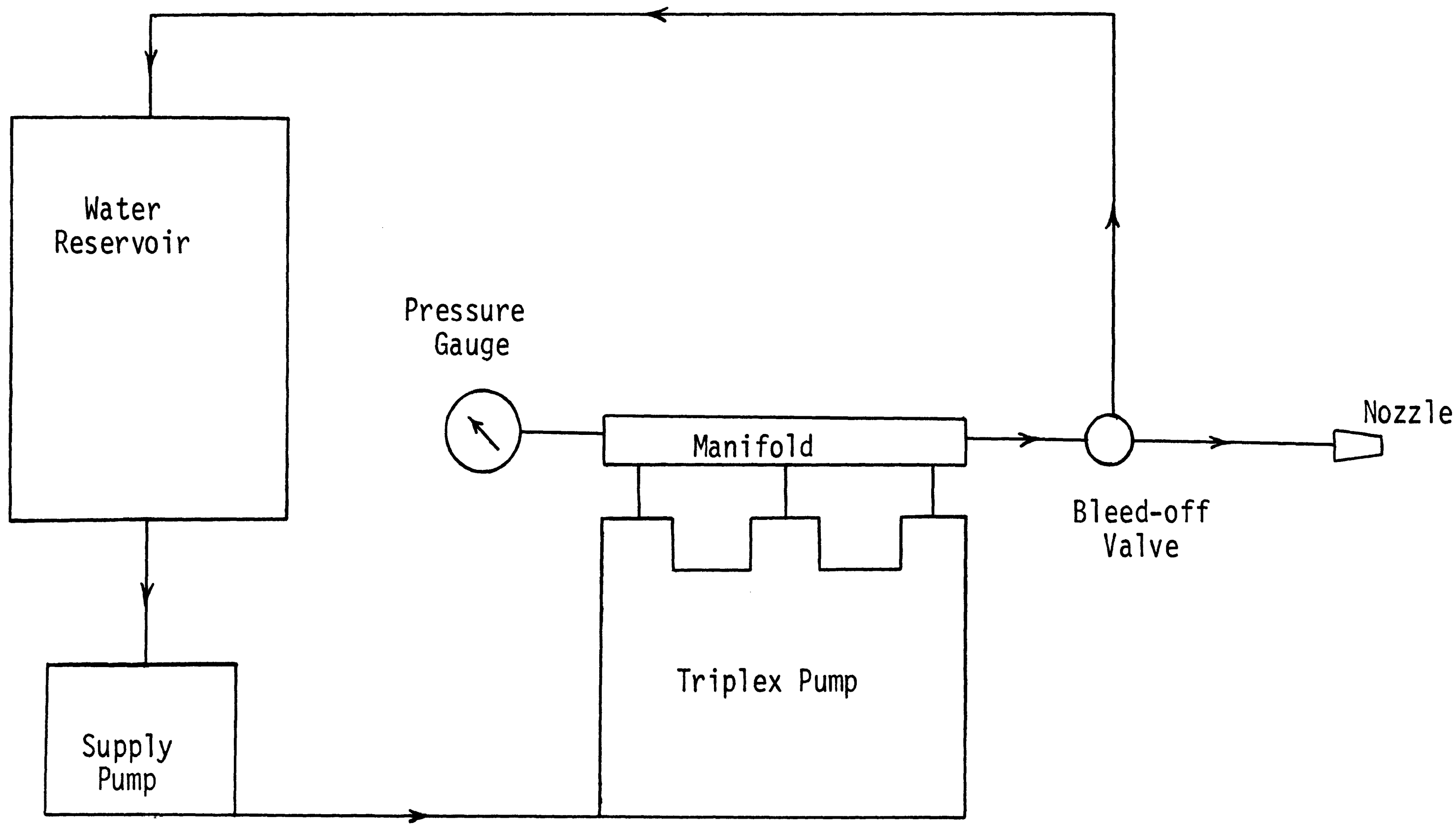


FIG. 1 SCHEMATIC DIAGRAM OF PUMP DELIVERY SYSTEM

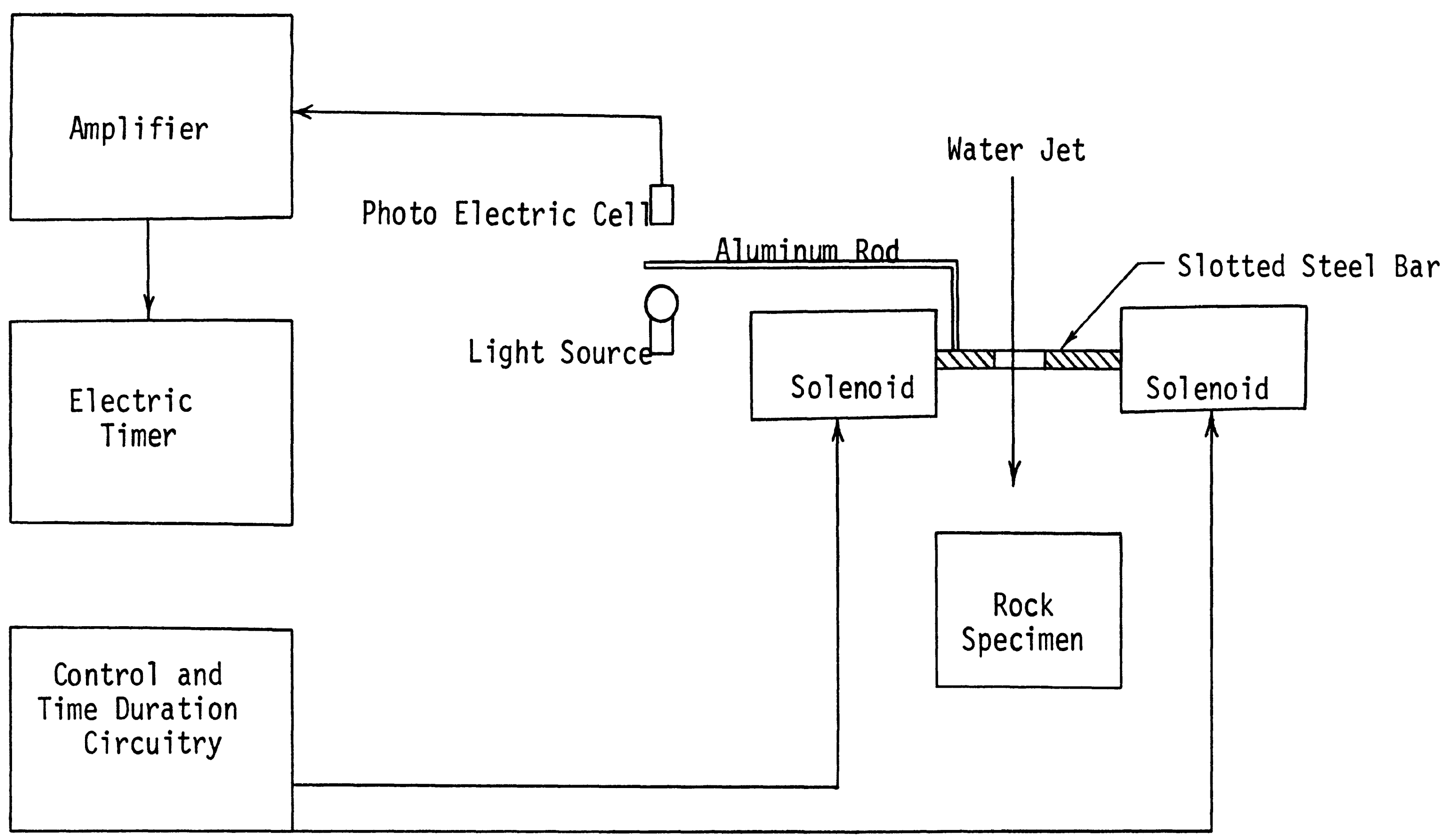


FIG. 2 SCHEMATIC DIAGRAM OF INTERRUPTOR SYSTEM

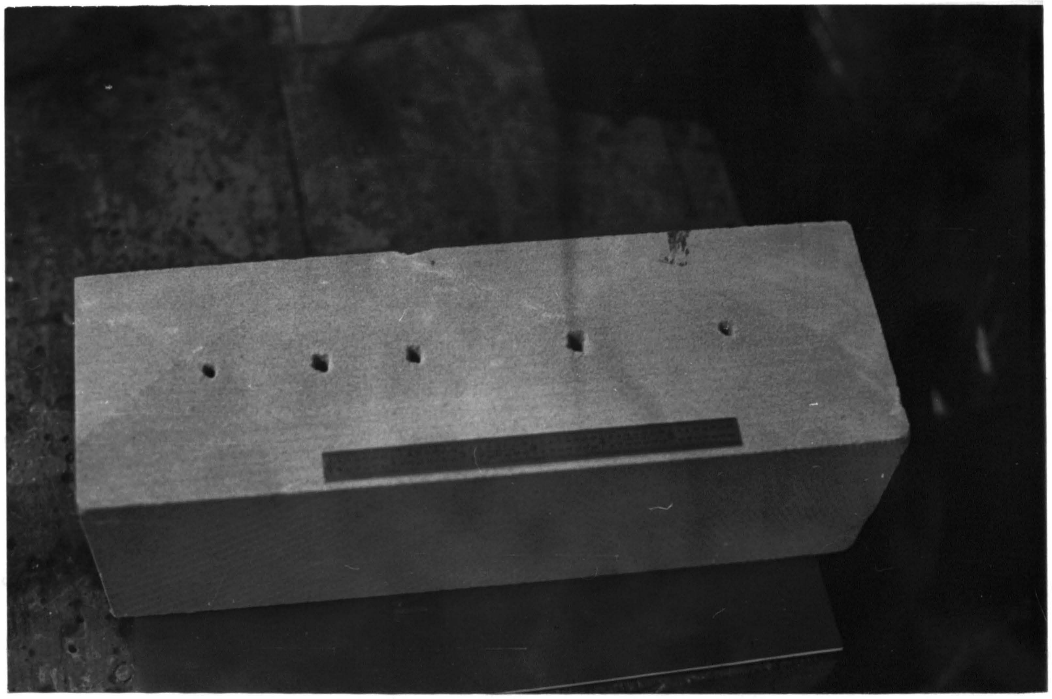
The target rock. With this system it was possible to let the water jet strike the rock for controlled periods of time at any desired pressure and to get time measurement with millisecond accuracy.

The rock was held in place by a steel clamp mounted on a lathe. The distance between the nozzle and the rock face was varied by inserting half-inch wood spacers underneath the target rock as required prior to tightening the clamp. A plexiglas cover three feet by two feet by two feet was placed over and around the working surface to contain the ejecta.

C. Experimental Procedure

The effect of change in three parameters as they affect the penetration of a water jet into rock were investigated: the pressure of the jet, the length of time the jet was striking the rock, and the distance of the nozzle from the rock surface. Five levels of each parameter were used in the experiment. The pressures used were 5,000 psi, 10,000 psi, 15,000 psi, 20,000 psi, and 25,000 psi. The time levels used were 0.1 seconds, 0.5 seconds, 1.0 seconds, 2.0 seconds, and 5.0 seconds. The nozzle stand-off distances used were 2.0 inches, 2.5 inches, 3.0 inches, 3.5 inches, and 4.0 inches.

The experiment was performed on samples of Berea sandstone, Georgia marble, and Missouri granite cut to dimensions 4" x 4" x 12". The experiment was designed factorially so that the five test levels of each parameter were used once in each combination (20). For reasons of economy five tests were performed on each block at two inch intervals (Fig. 3). Since each of the three parameters had five test levels, 125 tests were run on each rock type. The test pattern was arranged to



a. Berea Sandstone

b. Missouri Granite

FIG. 3 TYPICAL SPECIMENS-INTERRUPTED JET minimize end effects or errors which might occur due to specimen inhomogeneity.

The blocks were tested according to a random distribution of the sample population of seventy-five where numbers one to twenty-five represented sandstone blocks, twenty-six to fifty represented marble blocks, and fifty-one to seventy-five represented granite blocks. The five tests on each block was carried out consecutively.

For each test, the pressure, stand-off distance, and actual time were recorded. The pressure was read directly from a pressure gage, having an accuracy of ±1,000 psi, attached to the manifold of the triplex pump. The stand-off distance was measured with a ruler and the accuracy was ±1/16 inches. The time, as already mentioned, was recorded on a digital counter with millisecond accuracy. The depth of penetration was measured using a modified vernier caliper. The end of the slider had been tapered with a grinding wheel to allow insertion into the hole made by the water jet. The volume of rock removed was measured using dry sand. A graduated cylinder was filled with sand, tapped lightly, and a measurement taken. Sand from the cylinder was then poured into the hole made by the water jet until the sand was level with the top of the rock and a second reading taken. The difference in the two measurements was recorded as the hole volume.

D. Results and Discussion

The results were averaged (Tables XI, XII, XIII) and penetration was plotted versus pressure, time, and stand-off distance for each rock type tested (Figs. 4, 5, 6).

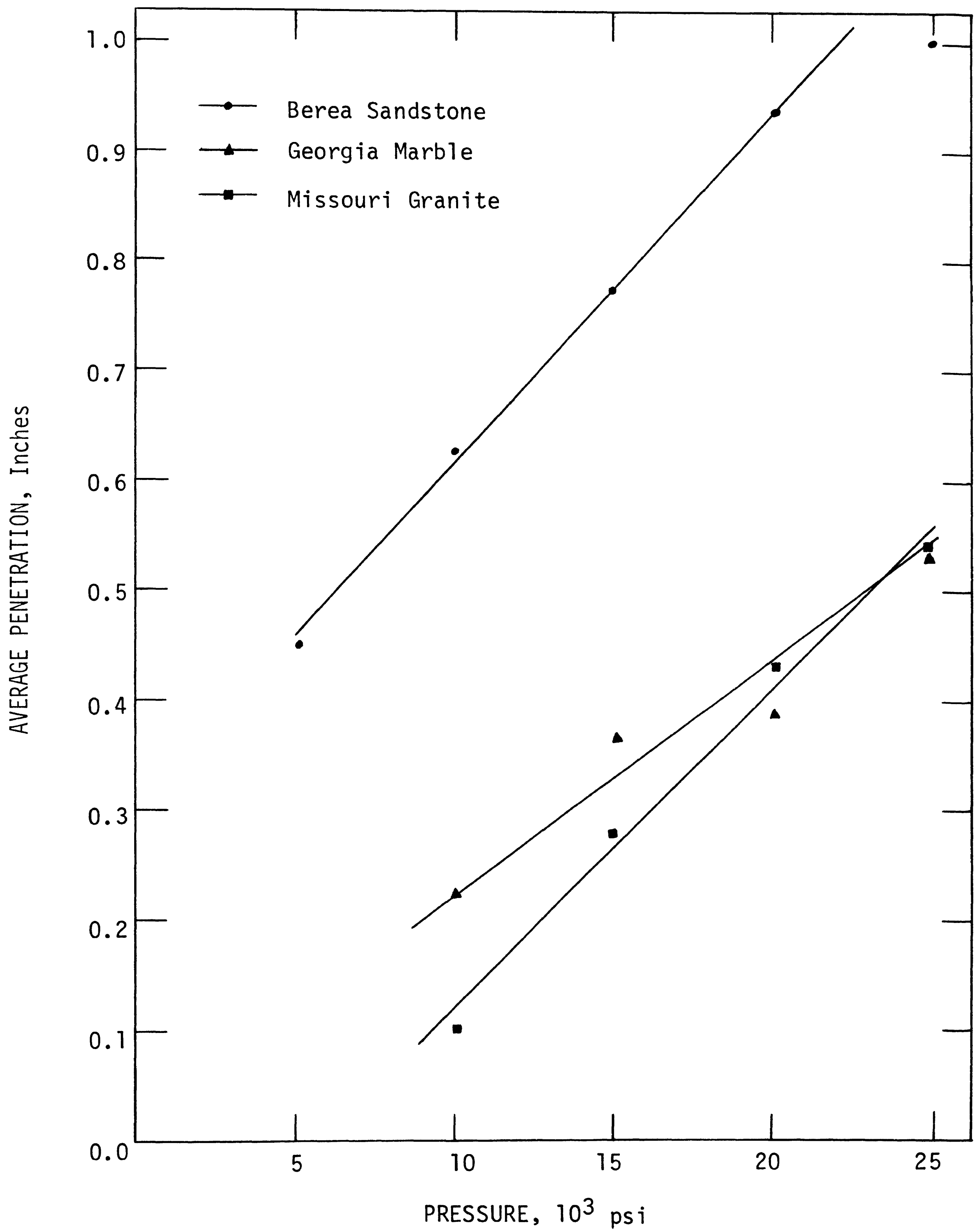


FIG. 4 PENETRATION VS. PRESSURE FOR BEREA SANDSTONE, GEORGIA MARBLE, AND MISSOURI GRANITE

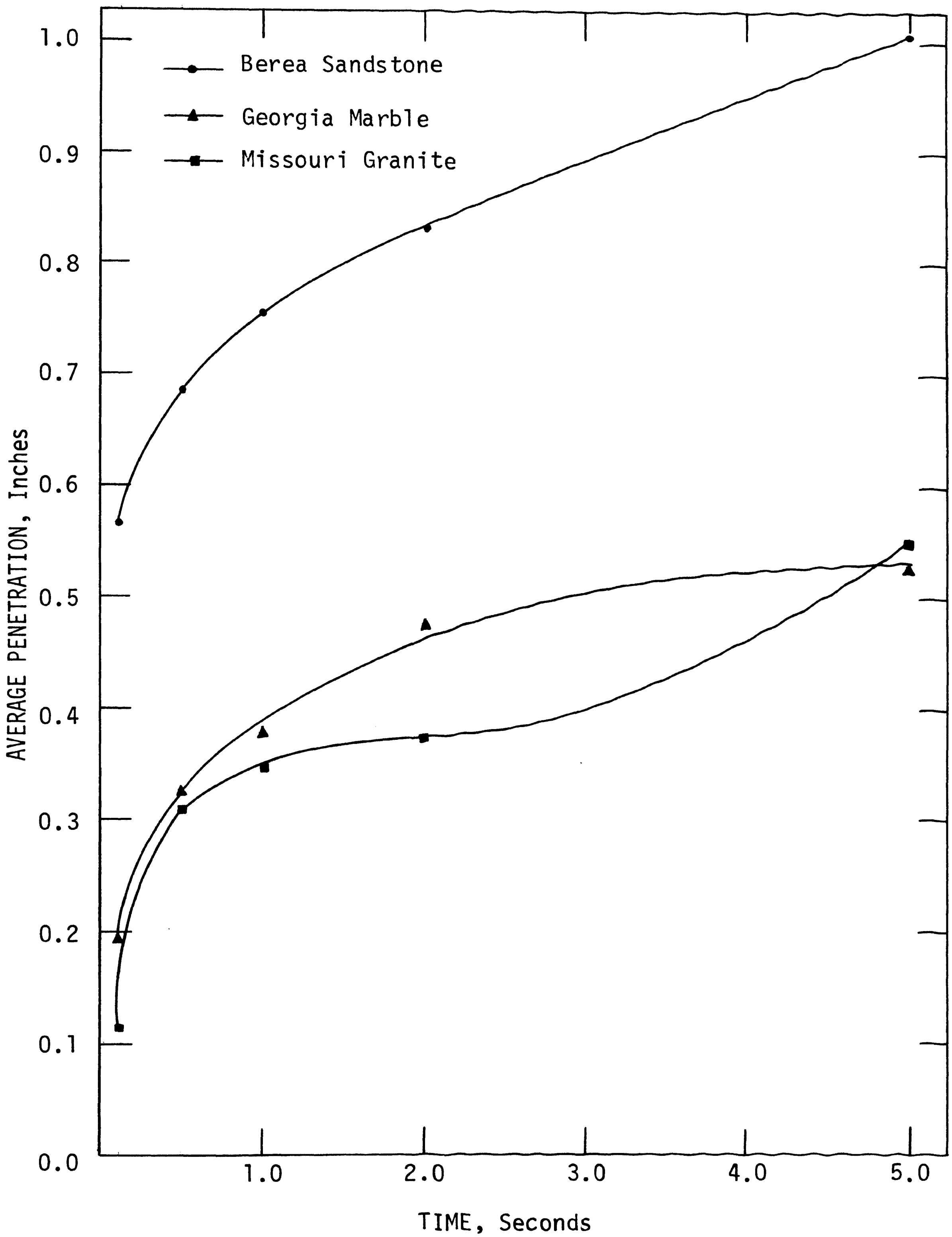


FIG. 5 PENETRATION VS. TIME FOR BEREA SANDSTONE, GEORGIA MARBLE, AND MISSOURI GRANITE

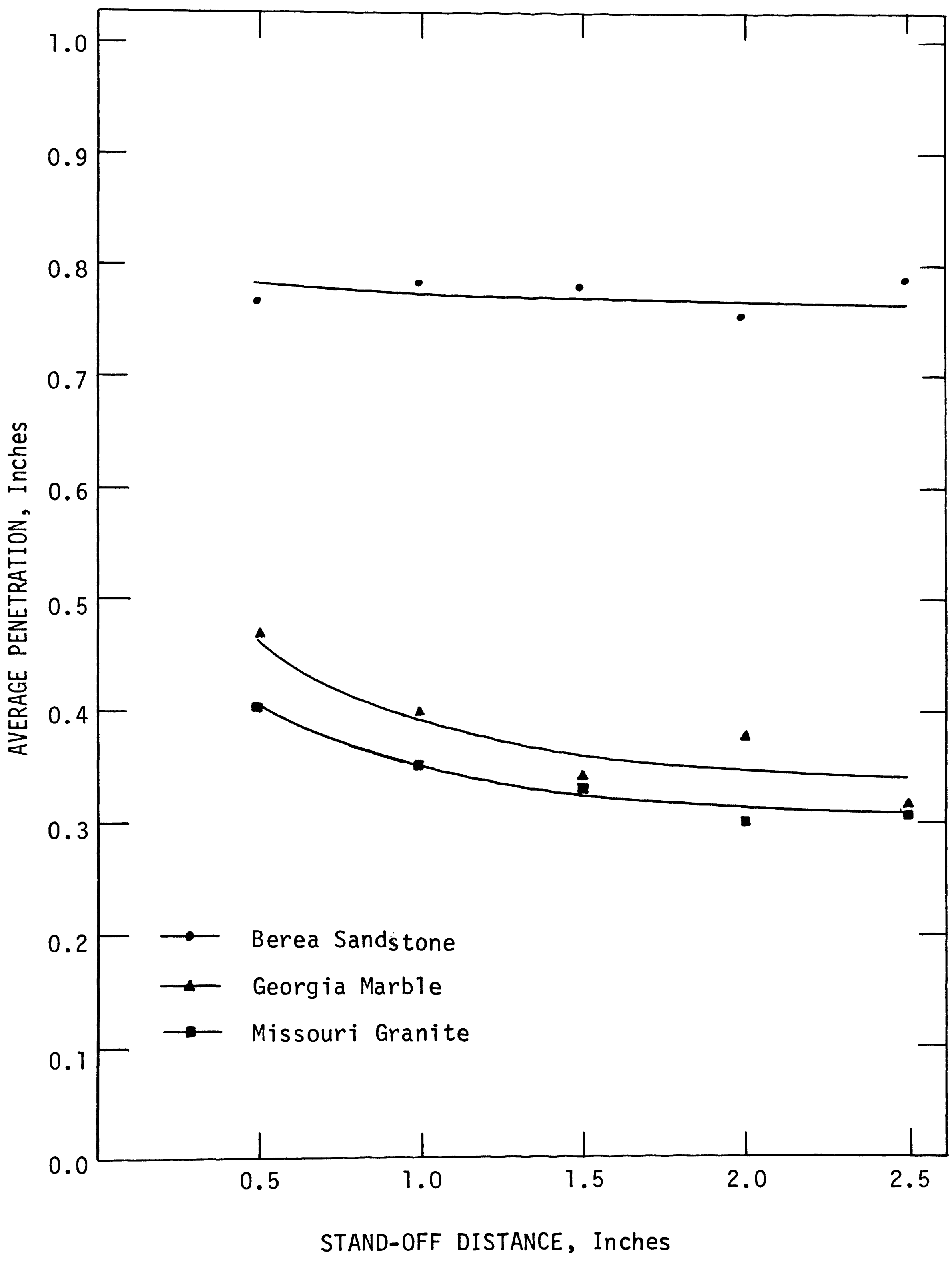


FIG. 6 PENETRATION VS. STAND-OFF DISTANCE FOR BEREA SANDSTONE, GEORGIA MARBLE, AND MISSOURI GRANITE

Of the three parameters examined, pressure seemed to be the most dominate. Of the three rocks tested the jet penetrated the sandstone to the greatest depth for all the jet pressures. The two crystalline rocks, Georgia marble and Missouri Granite, had no penetration at the 5,000 psi pressure level and over the shorter time intervals. Penetration was found to vary linearly with pressure (Fig. 4).

The curves of stand-off distance versus average penetration showed that, over the range tested for the sandstone, the distance between the nozzle and the working surface did not affect the penetration. In the marble and granite, penetration decreased as stand-off distance increased, but most of this decline occurred between 2.0 and 2.5 inches (Fig. 6).

The time-average penetration curves indicated that the water jet did 55% of its cutting within the first tenth of a second. For the crystalline rocks, 60% of the cutting was achieved within the first half second (Fig. 5). After initial impact, the jet encounters the rebounding water from the bottom of the hole. This returning flow causes a loss of energy in the impacting jet, resulting in slower penetration. As the hole becomes deeper, more and more energy is lost resulting in a critical depth being approached at which time the rate of penetration will be zero. This has been demonstrated by Leach and Walker (10).

Specific energy of cutting was calculated so that the jet parameters investigated could be compared on the basis of relative efficiencies of the water jet cutting rock. The procedure of calculation was as follows:

$$P.E.=K.E.=\frac{1}{2}mv^2=mgh$$

$$v=\sqrt{2gh}$$

$$p=\rho gh/144*14.7 \quad atm$$

$$v=\sqrt{2*144*14.7gP/\rho g} = \sqrt{2*144*14.7*32.2P/62.4}$$

$$v=46\sqrt{P} \quad ft/sec$$

$$v=14.2\sqrt{P} \quad m/sec$$

Based on previous work (21), the relationship has, however, been experimentally determined as

$$v=12.5\sqrt{P}$$

where v is the jet velocity in meters per second and P is the jet pressure in atmospheres, suggesting a discharge coefficient of 0.88.

The specific energy of cutting was calculated by dividing the kinetic energy of the jet by the volume of rock removed. For Berea sandstone, the jet was most effective under the given test conditions at a pressure of 5,000 psi and at an impact time of 0.1 seconds, the lowest tested, with a specific energy of cutting of as low as 805 joules per cubic centimeter (Table VIII). Averaging the Berea sandstone specific energy values over the range of this experiment showed that specific energy values increased with jet pressure for this rock (Table XI).

For Georgia marble and Missouri granite, the lowest specific energies were 267 joules/cc occurring at 15,000 psi and 304 joules/cc at 25,000 psi respectively (Tables IX, X). The average specific energies were lowest at 10,000 psi for the Georgia marble and 20,000 psi for the Missouri granite. These values were 36,227 joules/cc and 16,236 joules/cc respectively (Table XI). Comparing the average specific energies at the 15,000 psi, 20,000 psi, and 25,000 psi pressure levels, the granite had lower values than the sandstone. Thus, at the higher jet pressures, the water jet was more efficient in the granite.

This may be due to the difference in the way the water jet acts on the rock. In crystalline rocks, such as granite and marble, the jet, after gaining initial entry, takes advantage of planes of weakness in the rock which usually lie along the large crystal boundaries. Spallation occurs due to the intergrowth of the crystals and the stress applied by the water along these planes of weakness. The area of influence of the jet, therefore, is not limited to that area directly impacted by the water. In a granular rock, on the other hand, the process is by direct impaction and shearing action of the jet, making the surface area of the hole and the volume removed smaller than in crystalline rocks. It is interesting to note that in the granite, spallation consistently occurred when penetration was greater than one-third of an inch. Below this depth, spallation hardly ever occurred.

Comparing stand-off distance with specific energies (Table XII) found that the efficiency was best, i.e., lowest specific energy of cutting, at the two-inch stand-off distance except for the sandstone where the value was not statistically significant. The efficiency was the best at the shortest time of impact, 0.1 second, in all three rocks (Table XIII).

TABLE I. KINETIC ENERGY IN WATER JET

Nozzle Diameter = 0.023 in.

$$\text{Area} = \pi r^2 = \pi(.0115)^2 = 4.15\text{x}10^{-4}\ \text{in}^2 = 26.8\text{x}10^{-4}\ \text{cm}^2$$

P		$\sqrt{P}$	$v=12.5\sqrt{P}$	
5,000 psi	340 atm	18.4	230 m/sec	23,000 cm/sec
10,000	680	26.1	326	32,600
15,000	1,020	31.9	399	39,900
20,000	1,360	36.9	461	46,100
25,000	1,700	41.2	515	51,500
30,000	2,040	45.2	565	56,500

m=vA	K.E. = $\frac{1}{2}mv^2$
61.6	1,629 joules/sec
87.4	4,644
106.9	8,509
123.5	13,123
138.0	18,300
151.4	48,330

TABLE II. BERGA SANDSTONE HOLE DEPTHS

Time, seconds	Depths in Inches Pressure, 10^3 psi					Stand-off Inches
	5	10	15	20	25	
0.1	0.318	0.466	0.571	0.736	0.818	2.0
0.5	0.400	0.499	0.601	0.920	0.866	
1	0.473	0.643	0.604	0.988	1.140	
2	0.433	0.750	0.812	1.025	1.160	
5	0.660	0.794	1.029	1.223	1.242	
0.1	0.335	0.433	0.536	0.750	0.866	2.5
0.5	0.394	0.588	0.674	0.900	1.050	
1	0.416	0.580	0.710	0.849	1.018	
2	0.489	0.742	0.842	1.008	1.295	
5	0.534	0.798	1.063	1.273	1.389	
0.1	0.283	0.474	0.560	0.747	0.782	3.0
0.5	0.410	0.582	0.680	0.841	0.924	
1	0.463	0.685	0.814	0.847	1.168	
2	0.413	0.731	0.825	0.988	1.142	
5	0.617	0.763	0.852	1.172	1.621	
0.1	0.322	0.398	0.550	0.638	0.635	3.5
0.5	0.481	0.525	0.721	0.798	0.939	
1	0.425	0.630	0.757	0.875	0.940	
2	0.565	0.729	0.928	0.954	1.078	
5	0.591	0.788	1.077	1.105	1.307	
0.1	0.316	0.429	0.584	0.695	0.929	4.0
0.5	0.384	0.559	0.694	0.795	0.942	
1	0.540	0.611	0.755	0.959	0.986	
2	0.474	0.433	0.919	1.030	1.068	
5	0.510	0.872	1.083	1.341	1.543	

TABLE III. BEREA SANDSTONE HOLE VOLUMES

Time, seconds	Volumes in cm^3 Pressure, 10^3psi					Stand-off inches
	5	10	15	20	25	
0.1	0.10	0.10	0.10	0.30	0.30	2.0
0.5	0.20	0.20	0.30	0.70	0.90	
1	0.10	0.30	0.70	0.50	1.00	
2	0.20	0.60	0.30	0.70	0.80	
5	0.40	0.50	0.70	0.80	1.00	
0.1	0.20	0.20	0.20	0.40	0.40	2.5
0.5	0.40	0.25	0.20	0.50	0.80	
1	0.15	0.30	0.40	0.50	0.90	
2	0.20	0.40	0.60	0.60	0.80	
5	0.20	0.40	0.60	1.10	0.90	
0.1	0.05	0.10	0.30	0.40	0.40	3.0
0.5	0.20	0.20	0.30	0.50	0.50	
1	0.20	0.50	0.30	0.40	0.80	
2	0.20	0.40	0.40	0.60	0.80	
5	0.20	0.30	0.60	0.80	1.40	
0.1	0.05	0.20	0.20	0.30	0.20	3.5
0.5	0.20	0.10	0.30	0.45	0.80	
1	0.20	0.20	0.40	0.40	0.70	
2	0.20	0.30	0.50	0.50	0.60	
5	0.30	0.40	0.60	0.80	1.00	
0.1	0.20	0.10	0.20	0.50	1.40	4.0
0.5	0.20	0.20	0.40	0.50	0.70	
1	0.20	0.20	0.30	0.60	0.50	
2	0.20	0.30	0.50	0.60	0.70	
5	0.30	0.50	0.60	0.70	1.40	

TABLE IV. GEORGIA MARBLE HOLE DEPTHS

Depths in inches

Time, sec.	Pressure, 10^3psi: 5	10	15	20	25	Stand-off, inches
0.1	0.037	0.049	0.165	0.362	0.308	2.0
0.5	0.055	0.300	0.329	0.684	0.731	
1	0.075	0.266	0.317	0.443	0.380	
2	-	0.375	0.494	0.575	0.612	
5	0.025	0.393	0.314	0.525	1.715	
0.1	-	0.046	0.318	0.315	0.245	2.5
0.5	0.035	0.172	0.252	0.404	0.418	
1	0.018	0.356	0.499	0.372	0.615	
2	0.075	0.330	0.840	0.497	0.356	
5	0.175	0.614	0.347	0.430	0.561	
0.1	0.027	0.060	0.105	0.283	0.332	3.0
0.5	0.047	0.088	0.284	0.361	0.318	
1	0.034	0.259	0.258	0.348	0.529	
2	0.061	0.160	0.575	0.675	0.457	
5	0.072	0.225	0.429	0.353	0.594	
0.1	-	0.063	0.156	0.171	0.282	3.5
0.5	0.027	0.129	0.284	0.368	0.514	
1	-	0.394	0.437	0.261	0.370	
2	0.022	0.180	0.273	0.429	0.600	
5	0.102	0.469	0.520	0.430	1.133	
0.1	-	0.011	0.183	0.164	0.321	4.0
0.5	-	0.074	0.220	0.234	0.291	
1	0.052	0.135	0.247	0.320	0.657	
2	0.065	0.228	1.016	0.365	0.413	
5	0.058	0.323	0.276	0.324	0.505	

TABLE V. GEORGIA MARBLE HOLE VOLUMES

	Volumes in cm^3					Stand-off, inches
Time, sec.	5	10	15	20	25	
0.1	0.02	0.07	0.10	2.30	0.40	2.0
0.5	0.05	2.50	1.00	5.60	4.10	
1	0.10	0.10	0.30	0.60	0.30	
2	-	4.20	1.90	5.40	1.80	
5	0.02	1.70	0.30	1.00	3.60	
0.1	-	0.07	0.40	0.10	0.20	2.5
0.5	0.07	0.15	0.10	0.30	1.10	
1	-	1.00	2.10	0.20	1.00	
2	0.02	7.80	1.10	0.50	0.20	
5	0.30	10.80	0.20	0.20	1.60	
0.1	0.01	0.10	0.10	0.20	1.00	3.0
0.5	0.04	0.10	0.20	0.60	0.20	
1	0.02	0.30	0.20	0.30	0.60	
2	0.10	0.10	2.40	5.00	0.20	
5	0.05	0.07	2.00	0.30	1.30	
0.1	-	0.07	0.10	0.10	0.20	3.5
0.5	-	0.20	0.40	0.40	3.60	
1	-	1.30	4.00	0.20	0.30	
2	0.01	0.07	0.20	2.40	1.40	
5	0.10	1.30	0.70	0.20	38.30	
0.1	-	0.05	0.20	0.20	0.30	4.2
0.5	-	0.10	0.20	0.10	0.15	
1	-	0.10	0.20	0.20	3.40	
2	0.07	0.20	68.00	0.90	0.20	
5	0.05	0.40	0.20	0.20	0.90	

TABLE VI. MISSOURI GRANITE HOLE DEPTHS

Depths in Inches

Time, sec.	Pressure, 10^3psi 5	10	15	20	25	Stand-off, inches
0.1	-	0.010	0.058	0.154	0.260	2.0
0.5	-	0.115	0.221	0.440	0.838	
1	0.013	0.112	0.407	0.683	0.832	
2	0.005	0.154	0.479	0.703	0.389	
5	0.009	0.115	0.390	0.644	1.034	
0.1	-	0.058	0.075	0.217	0.282	2.5
0.5	-	0.063	0.265	0.361	0.343	
1	0.016	0.069	0.244	0.262	0.697	
2	-	0.091	0.323	0.519	0.467	
5	0.072	0.265	0.580	0.490	1.243	
0.1	0.055	0.010	0.070	0.175	0.169	3.0
0.5	-	0.079	0.375	0.317	0.477	
1	-	0.120	0.288	0.250	0.770	
2	-	0.189	0.272	0.486	0.314	
5	0.032	0.151	0.548	0.430	1.088	
0.1	0.012	0.010	0.057	0.119	0.233	3.5
0.5	-	0.090	0.025	0.410	0.595	
1	0.015	0.084	0.203	0.353	0.250	
2	0.079	0.077	0.356	0.540	0.595	
5	0.020	0.255	0.680	0.783	0.338	
0.1	-	0.023	0.069	0.080	0.116	4.0
0.5	-	0.143	0.105	0.429	0.496	
1	-	0.075	0.243	0.478	0.480	
2	0.009	0.072	0.319	0.491	0.582	
5	0.032	0.094	0.268	1.010	0.583	

TABLE VII. MISSOURI GRANITE HOLE VOLUMES

Volumes in cm^3

Time, sec.	Pressure, 10^3psi: 5	10	15	20	25	Stand-off, inches
0.1	-	0.01	0.10	0.10	0.40	2.0
0.5	-	0.20	0.40	2.50	12.80	
1	-	0.20	1.30	24.20	2.40	
2	-	0.20	9.20	26.00	0.90	
5	0.01	0.15	1.70	7.20	10.20	
0.1	-	0.07	0.10	0.40	1.20	2.5
0.5	-	0.05	0.80	4.30	0.50	
1	0.05	0.05	0.30	0.20	12.30	
2	-	0.20	1.70	4.50	0.20	
5	0.07	0.90	5.20	1.40	60.10	
0.1	0.07	0.05	0.20	0.20	0.50	3.0
0.5	-	0.15	2.50	0.60	29.60	
1	-	0.20	0.80	0.30	22.00	
2	-	0.20	0.30	2.20	0.50	
5	-	0.20	5.20	1.00	12.20	
0.1	-	0.05	0.07	0.10	0.40	3.5
0.5	-	0.10	0.10	1.20	13.00	
1	0.01	0.30	0.35	0.60	0.15	
2	0.10	0.10	2.20	4.30	13.40	
5	-	1.00	9.00	1.50	0.40	
0.1	-	0.05	0.10	0.20	0.05	4.0
0.5	-	0.50	0.02	2.00	12.10	
1	-	0.10	0.20	1.30	2.60	
2	-	0.10	2.20	1.90	5.20	
5	0.07	0.10	0.30	54.00	1.10	

TABLE VIII. SPECIFIC ENERGIES-BEREA SANDSTONE

Specific Energies in joules/cc

	Pressure, 10^3psi					Stand-off, inches
Time, sec.	5	10	15	20	25	
0.1	1,610	4,553	8,365	4,293	6,000	2.0
0.5	4,025	11,383	13,941	9,199	9,999	
1	16,098	15,178	11,950	25,758	17,998	
2	16,098	15,178	55,767	36,797	44,997	
5	20,123	45,534	59,751	80,493	89,994	
0.1	805	2,277	4,183	3,220	4,500	2.5
0.5	2,012	9,107	20,912	12,879	11,249	
1	10,732	15,178	20,912	25,748	19,998	
2	16,098	22,767	27,883	42,930	44,997	
5	40,246	56,917	69,709	58,541	99,994	
0.1	3,220	4,553	2,788	3,220	4,500	3.0
0.5	4,025	11,383	13,941	12,879	17,998	
1	8,049	9,107	27,883	32,197	22,498	
2	16,098	22,767	41,825	42,930	44,997	
5	40,246	75,890	69,709	80,493	64,282	
0.1	3,220	2,277	4,183	4,293	8,999	3.5
0.5	4,025	22,767	13,941	14,310	11,249	
1	8,049	22,767	20,912	32,197	25,712	
2	16,098	30,356	33,460	51,516	59,996	
5	26,831	56,917	69,709	80,493	89,994	
0.1	805	4,553	4,183	2,576	1,286	4.0
0.5	4,025	11,383	10,456	12,879	12,856	
1	8,049	22,767	27,883	21,465	35,997	
2	16,098	30,356	33,460	42,930	51,425	
5	26,831	45,534	69,709	91,993	64,282	

TABLE IX. SPECIFIC ENERGIES-GEORGIA MARBLE

Specific Energies in joules/cc

	Pressure, 10^3psi				Stand-off, inches
Time, sec.	10	15	20	25	
0.1	6,505	8,365	560	4,500	2.0
0.5	911	4,183	1,150	2,195	
1	45,534	27,883	21,465	59,996	
2	2,168	8,805	4,770	19,998	
5	13,392	139,410	64,395	24,998	
0.1	6,505	2,091	12,879	8,999	2.5
0.5	15,178	41,825	21,465	8,181	
1	4,553	3,983	64,395	17,998	
2	1,168	15,209	51,516	179,980	
5	2,108	209,120	321,970	56,246	
0.1	4,553	8,365	6,440	1,800	3.0
0.5	22,767	20,912	10,732	44,997	
1	15,178	41,825	42,930	29,998	
2	91,068	6,971	5,152	179,980	
5	325,240	20,912	214,650	69,226	
0.1	6,505	8,365	12,879	8,999	3.5
0.5	11,383	10,456	16,098	2,500	
1	3,503	2,091	64,395	59,996	
2	130,090	83,651	10,732	25,712	
5	17,513	59,751	321,970	2,350	
0.1	9,107	4,183	6,440	6,000	4.0
0.5	22,767	20,912	64,395	59,996	
1	45,534	41,825	64,395	5,294	
2	45,534	246	28,620	179,980	
5	56,917	209,120	321,970	99,994	

TABLE X. SPECIFIC ENERGIES-MISSOURI GRANITE

Specific Energies in joules/cc

Time, sec.	Pressure, 10^3psi: 10	15	20	25	Stand-off, inches
0.1	45,534	8,365	12,879	4,500	2.0
0.5	11,383	10,456	2,576	703	
1	22,767	6,435	532	7,500	
2	45,534	1,819	991	39,997	
5	151,780	24,603	8,944	8,823	
0.1	6,505	8,365	3,220	1,550	2.5
0.5	45,534	5,228	1,498	17,998	
1	91,068	27,883	64,395	1,463	
2	45,534	9,841	5,724	179,980	
5	25,296	8,043	45,996	1,497	
0.1	9,107	4,183	6,440	3,600	3.0
0.5	15,178	1,673	10,732	304	
1	22,767	10,456	42,930	818	
2	45,534	55,767	11,708	71,995	
5	113,830	8,043	64,395	7,377	
0.1	9,107	11,950	12,879	4,500	3.5
0.5	22,767	41,825	5,366	692	
1	15,178	23,900	21,465	119,990	
2	91,068	7,605	5,990	2,686	
5	22,767	4,647	42,930	224,980	
0.1	9,107	8,365	6,440	35,997	4.0
0.5	4,553	209,120	3,220	744	
1	45,534	41,825	9,907	6,923	
2	91,068	7,605	13,556	6,923	
5	227,670	139,410	1,193	81,813	

TABLE XI. AVERAGE DEPTH, VOLUME, & SPECIFIC ENERGY VS. PRESSURE

Pressure, psi	Depth, ins.	Volume, cc	Specific Energy, j/cc
	Berea Sandstone		
5,000	0.452	0.202	12,540
10,000	0.620	0.290	22,858
15,000	0.770	0.400	29,497
20,000	0.938	0.566	33,049
25,000	1.074	0.788	34,632
	Georgia Marble		
10,000	0.228	1.314	36,227
15,000	0.366	3.464	40,019
20,000	0.388	1.100	70,255
25,000	0.530	2.654	46,398
	Missouri Granite		
10,000	0.101	0.209	49,447
15,000	0.277	1.774	27,497
20,000	0.433	5.688	16,236
25,000	0.539	8.568	33,333

TABLE XII. AVERAGE DEPTH, VOLUME, & SPECIFIC ENERGY VS. DISTANCE

Berea Sandstone

Distance, in.	Depth, in.	Volume, cc.	Specific Energy, j./cc.
2.0	0.767	0.472	25,003
2.5	0.781	0.464	25,752
3.0	0.775	0.434	27,099
3.5	0.750	0.396	28,571
4.0	0.780	0.480	26,151

Georgia Marble

Distance, in.	Depth, in.	Volume, cc.	Specific Energy, j./cc.
2.0	0.467	1.863	23,059
2.5	0.399	1.456	52,269
3.0	0.335	0.763	58,185
3.5	0.373	2.772	42,947
4.0	0.315	3.810	64,662

Missouri Granite

Distance, in.	Depth, in.	Volume, cc.	Specific Energy, j./cc.
2.0	0.402	5.008	20,806
2.5	0.346	4.723	29,829
3.0	0.329	3.945	25,342
3.5	0.303	2.416	34,615
4.0	0.308	4.206	47,549

TABLE XIII. AVERAGE DEPTH, VOLUME, & SPECIFIC ENERGY VS. TIME

Berea Sandstone

Time, sec.	Depth, in.	Volume, cc.	Specific Energy, j./cc.
0.1	0.567	0.276	3,778
0.5	0.687	0.400	11,313
1.0	0.755	0.430	20,204
2.0	0.833	0.480	34,313
5.0	1.012	0.660	62,969

Georgia Marble

Time, sec.	Depth, in.	Volume, cc.	Specific Energy, j./cc.
0.1	0.197	0.313	6,702
0.5	0.323	1.055	20,150
1.0	0.373	0.835	33,138
2.0	0.472	5.198	53,569
5.0	0.524	3.263	127,560

Missouri Granite

Time, sec.	Depth, in.	Volume, cc.	Specific Energy, j./cc.
0.1	0.112	0.217	10,627
0.5	0.309	4.171	20,578
1.0	0.345	3.492	29,187
2.0	0.371	3.795	37,046
5.0	0.549	8.642	60,703

III. CONTINUOUS JET CUTTING

A. Introduction

In an attempt to keep energy from being lost in overcoming the spent water from the bottom of the hole, to improve jet performance, and to more closely model a possible rock cutting situation the jet nozzle was set in motion. A three part experiment was designed. In the first part, the jet was traversed laterally across the rock. This part had a three-fold objective: a) to see if the traversing depths were equivalent to those obtained by the single pulse; b) to find how close two consecutive traverses could be run before interaction occurred; and c) to investigate the efficiency of cutting at fairly slow traversing speeds.

The second part of the experiment was to rotate the rock in the chuck of the lathe while the water jet traversed across it. Three parameters were investigated: the pressure of the water jet, the rate at which the jet moved relative to the rock, and the number of passes the jet made over the same area.

The third part of the experiment was to investigate the effect of nozzle diameter on jet cutting performance.

B. Traversing Experiment on Berea Sandstone, Georgia Marble, Missouri Granite, and Indiana Limestone

1. Experimental Procedure

Specimens of Berea sandstone, Georgia marble, and Missouri red granite were prepared as 6" x 4" x 4" blocks. Each block was mounted in turn on a lathe and traversed under the water jet (Fig. 7). Five passes

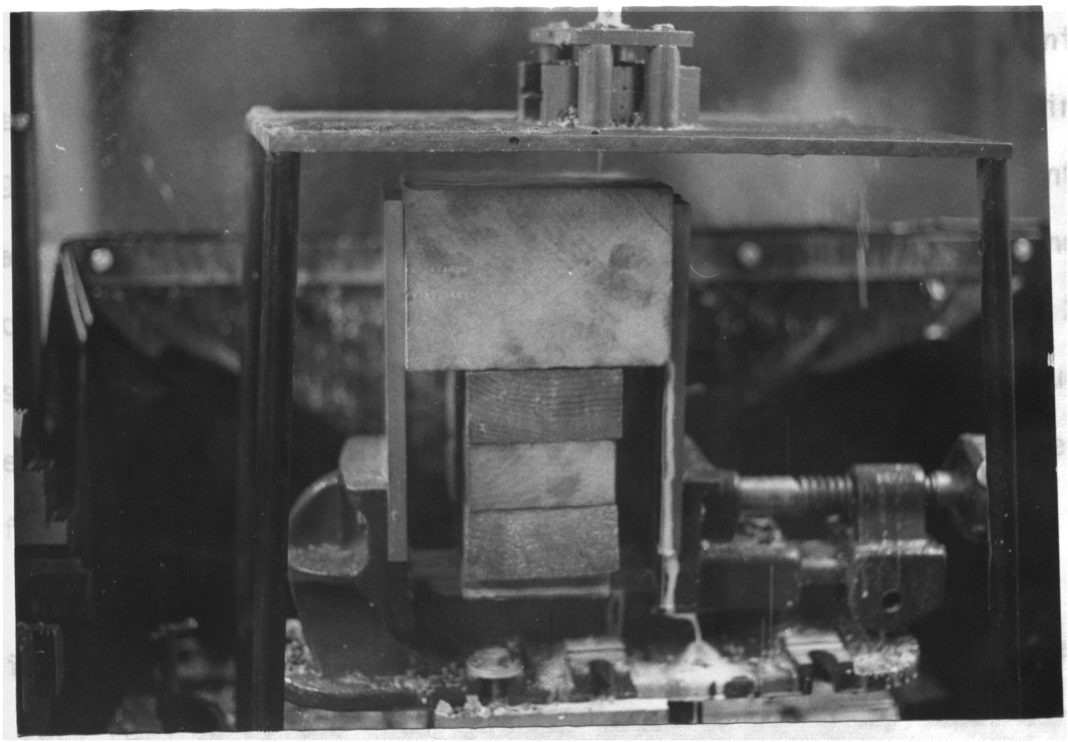


FIG. 7 JET CUTTING IN TRAVERSE

were made across each specimen; each pass being indexed closer to the previous cut by half the previous distance beginning with one inch, i.e., the second cut was one inch from the first and the third one-half inch from the second, so that the last pass was one-eighth inch from the previous one (Fig. 8).

The water jet pressures were standardized at 10,000 psi for the sandstone, 20,000 psi for the marble, and 25,000 psi for the granite. The traversing speeds were 62.18 in/min, 11.83 in/min, 5.98 in/min, 2.99 in/min, and 1.197 in/min. These rates are roughly equivalent to stationary impact times of 0.1 sec, 0.5 sec, 1.0 sec, 2.0 sec, and 5.0 seconds respectively (Table XIV). An assumed water jet width of 2.5 mm was used to calculate these rates. The lathe was unable to produce the speeds required for an accurate correlation, the values chosen represent a first approximation.

On each test block, the depth of the cut was measured every inch using a vernier caliper and an average depth was calculated. The volume of rock removed by the water jet was measured using dry sand, as described in Chapter II.

Traverse tests were also set up on Indiana limestone in the manner described above. Since static tests were not performed on this rock type, three pressures were used: 10,000 psi, 20,000 psi, and 30,000 psi. Four traversing speeds were used: 0.455 in/min, 1.82 in/min, 3.64 in/min, and 14.56 in/min.

2. Results and Discussion

The first objective of this experiment was to compare the depths while the water jet was traversing, hereafter referred to as traversing

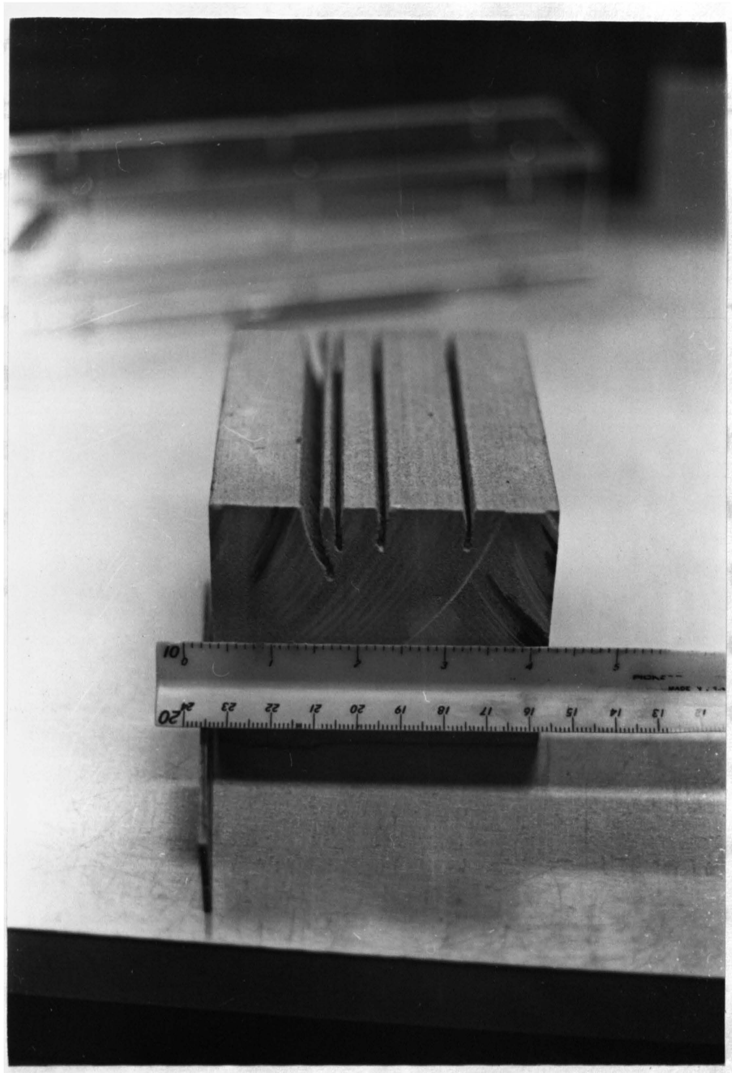


FIG. 8 TYPICAL SPECIMEN AFTER TRAVERSE CUTTING

depths, with those obtained where the nozzle was held fixed (static depths). In the Berea sandstone, the depths were equivalent, but in the two crystalline rocks, the traversing depths were substantially less than the static depths (Table XXIII). In some static tests, the crystalline rocks spalled relatively large volumes of rock on the surface because, after initial penetration, the water trying to get out of the hole was forced by oncoming jet into the micro-cracks and crevices along the grain boundaries around the hole. Due to the rock structure and the stress applied by the water along these micro-cracks, spalling and an increase in depth resulted. In the traversing experiment, after initial penetration, the water could flow through the cut it had already made. It did not have to seek an escape route, as one was already available. In granular rocks, the two methods give equivalent depth results because the cutting is more localized.

The second purpose of this experiment was to find out how close two successive passes of the water jet had to be before the intervening rib was removed by the action of the water jet alone. In Berea sandstone and Indiana limestone, this distance was found to be one-eighth of an inch (Tables XV, XXIV). Not only was the rib removed, but the depth was increased by about a third.

The third objective of this experiment was to investigate the efficiency of cutting at slow traversing speeds. In the Berea sandstone and Indiana limestone, for each pressure tested, the specific energy of cutting was found to be lowest at the fastest speed of traverse (Tables XXIII, XXVI).

TABLE XIV. CALCULATION OF TRAVERSE RATES

A. Desired Traversing Speeds

v_1 = 2.5 mm/0.1 sec = 25 mm/sec(60 sec/min)(1 inch/2.54 cm) = 60 in/min

v_2 = 2.5/0.5 = 5 = 12 in/min

v_3 = 2.5/1.0 = 2.5 = 6 in/min

v_4 = 2.5/2.0 = 1.25 = 3 in/min

v_5 = 2.5/5.0 = 0.5 = 1.2 in/min

B. Traversing Speeds Used

v_1 = .116 in/rev (536 rev/min) = 62.18 in/min

v_2 = .087 (136) = 11.83 in/min

v_3 = .044 (136) = 5.98 in/min

v_4 = .022 (136) = 2.99 in/min

v_5 = .0035 (342) = 1.197 in/min

TABLE XV. TRAVERSING DEPTHS-BEREA SANDSTONE

Pressure = 10,000 psi, Depths in inches,
Rates, in/min

Traverse	62.18	11.83	5.98	2.99	1.197
A	0.417	0.578	0.592	0.599	0.818
B	0.421	0.553	0.613	0.628	0.963
C	0.417	0.649	0.654	0.771	1.040
D	0.432	0.936	0.807	0.889	1.268
E	0.491				

TABLE XVI. TRAVERSING VOLUMES-BEREA SANDSTONE

Pressure = 10,000 psi, Volume in cm^3
Rates, in/min

Traverse	62.18	11.83	5.98	2.99	1.197
A	3.0	3.2	4.2	4.5	6.0
B	3.3	3.6	4.2	4.4	6.6
C	3.0	3.6	4.7	5.6	7.4
D-E	8.9	9.9	14.6	14.4	20.6
Length, in.	5.346	4.509	6.409	5.339	5.338
Time, sec.	5.2	22.9	64.3	107.1	267.6

TABLE XVII. TRAVERSING DEPTHS-GEORGIA MARBLE

Pressure = 20,000 psi, Depths in inches
Rates, in/min

Traverse	62.18	11.83	5.98	2.99	1.197
A	0.012	0.015	0.054	0.124	0.108
B	0.012	0.020	0.050	0.152	0.075
C	0.017	0.017	0.045	0.407	0.225
D	0.011	0.020	0.104		
E	0.006	0.030			

TABLE XVIII. TRAVERSING VOLUMES-GEORGIA MARBLE

Pressure = 20,000 psi, Volumes in cm^3
Rates, in/min

Traverse	62.18	11.83	5.98	2.99	1.197
A	0.2	0.3	0.8	5.3	2.3
B	0.2	0.2	0.9	44.8	3.6
C	0.3	0.3	4.1		16.9
D-E	0.4	0.7			
Lenth, in.	6.280	6.311	6.252	6.304	6.271
Time, sec.	6.1	32.0	62.7	126.5	314.3

TABLE XIX. TRAVERSING DEPTHS-MISSOURI GRANITE

Pressure = 25,000 psi, Depths in inches
Rates, in/min

Traverse	62.18	11.83	5.98	2.99	1.197
A		0.014		0.036	0.075
B		0.014		0.037	0.070
C		0.012		0.034	0.095
D		0.010		0.052	0.169
E		0.015			

TABLE XX. TRAVERSING VOLUMES-MISSOURI GRANITE

Pressure = 25,000 psi, Volumes in cm^3
Rates, in/min

Traverse	62.18	11.83	5.98	2.99	1.197
A		0.2		0.4	1.8
B		0.2		0.6	1.2
C		0.2		0.8	8.7
D-E		0.4		2.6	
Length, in		5.659		5.632	6.102
Time, sec.		28.7		113.0	305.9

TABLE XXI. TRAVERSING DEPTHS-INDIANA LIMESTONE

Pressure = 10,000 psi, Depths in inches
Rates, in/min

Traverse	14.56	3.64	1.82	0.455
A	0.058	0.067	0.079	0.171
B	0.058	0.094	0.136	0.175
C	0.062	0.078	0.169	0.129
D	0.092	0.113	0.193	0.173
E		0.155	0.252	

Pressure = 20,000 psi
Rates, in/min

Traverse	14.56	3.64	1.82	0.455
A	0.155	0.212	0.616	0.709
B	0.120	0.219	0.581	0.732
C	0.153	0.279	0.622	1.253
D-E	0.226	0.426	1.021	

Pressure = 30,000 psi
Rates, in/min

Traverse	14.56	3.64	1.82	0.455
A	0.295	0.346		1.173
B	0.374	0.613		1.132
C	0.169	0.551		0.932
D-E	0.542	0.758		1.075

TABLE XXII. TRAVERSING VOLUMES-INDIANA LIMESTONE

Pressure = 10,000 psi, Volumes in cm^3
Rates, in/min

Traverse	14.56	3.64	1.82	0.455
A	0.8	0.6	1.0	1.1
B	0.6	0.5	1.1	1.5
C	0.6	0.4	1.2	1.3
D-E	1.6	2.6	4.4	3.8
Length, in.	5.414	5.308	5.306	5.161
Time, sec.	22.3	87.5	174.9	680.5

Pressure = 20,000 psi
Rates, in/min

Traverse	14.56	3.64	1.82	0.455
A	1.9	1.8	3.0	5.4
B	1.4	2.4	4.0	5.5
C	5.1	3.0	4.3	22.6
D-E		9.4	12.8	
Length, in.	5.212	5.909	5.336	5.261
Time, sec.	21.5	97.4	175.9	693.8

Pressure = 30,000 psi
Rates, in/min

Traverse	14.56	3.64	1.82	0.455
A	2.4	3.3		9.0
B	2.8	5.8		8.4
C	2.2	5.7		7.0
D-E	9.1	11.3		11.2 (1.5 traverses)
Length, in.	5.126	5.264		5.300
Time, sec.	21.1	86.8		698.9

TABLE XXIII. AVERAGE DEPTH, VOLUME, & SPECIFIC ENERGY VS. SPEED (TIME)

Berea Sandstone
Pressure = 10,000 psi

Speed in/min	Depth, in. traverse	static	Volume cc	Specific Energy j/cc
62.18	0.418	.440	3.1	7,790
11.83	0.593	.551	3.5	30,385
5.98	0.620	.630	4.4	67,866
2.99	0.666	.677	4.8	103,619
1.197	0.940	.783	6.7	185,483

Georgia Marble
Pressure = 20,000 psi

Speed in/min	Depth, in. traverse	static	Volume cc	Specific Energy j/cc
62.18	0.012	.259	0.2	400,251
11.83	0.020	.410	0.3	1,399,787
5.98	0.050	.349	0.9	914,236
2.99	0.138	.508	5.3	313,219
1.197	0.092	.412	3.0	1,374,853

Missouri Granite
Pressure = 25,000 psi

Speed in/min	Depth, in. traverse	static	Volume cc	Specific Energy j/cc
11.83	0.013	.550	0.2	2,626,050
2.99	0.036	.469	0.6	3,446,500
1.197	0.080	.857	1.5	3,731,980

TABLE XXIV. AVERAGE TRAVERSING DEPTHS-INDIANA LIMESTONE

Depths in inches
Speed, in/min

Pressure, psi	14.56	3.64	1.82	0.455
10,000	0.059	0.080	0.128	0.162
20,000	0.143	0.237	0.606	0.720
30,000	0.279	0.503	-	1.079

TABLE XXV. AVERAGE TRAVERSING VOLUME-INDIANA LIMESTONE

Volumes in cm^3
Speed, in/min

Pressure, psi	14.56	3.64	1.82	0.455
10,000	0.7	0.5	1.1	1.3
20,000	1.6	2.4	3.8	5.4
30,000	2.5	4.9	-	8.1

TABLE XXVI. SPECIFIC ENERGIES-INDIANA LIMESTONE

Specific Energies in joules/cc
Speed, in/min

Pressure, psi	14.56	3.64	1.82	0.455
10,000	147,945	812,700	738,396	2,430,955
20,000	176,340	532,575	607,457	1,686,062
30,000	407,905	856,131	-	4,170,103

C. Rotational Experiment on Indiana Limestone

1. Experimental Procedure

It has been shown in Section A that the specific energy of cutting decreases with an increase in nozzle traverse speed. An investigation at faster speeds than could be obtained by linear movement of the rock specimen on the lathe was therefore desirable. An experiment was designed in which each rock specimen was rotated concentrically in the chuck of the lathe while the water jet was traversed horizontally across it (Fig. 9).

Initially, the parameters investigated were water jet pressure, the relative speed of the jet to the target rock, and the number of passes the jet makes over the same area. Subsequently, a preliminary investigation was made on the effect that different nozzle sizes had on rock removal rate and specific energy of cutting.

Indiana limestone samples were prepared in blocks measuring 6" x 4" x 4". These blocks were clamped in the chuck of a lathe with the 4" x 4" surface facing the water jet supply nozzle and rotated at four different velocities: 58 rpm, 136 rpm, 342 rpm, and 536 rpm. The water jet nozzle was traversed linearly across the rock face at four increments of rotational speed: 0.020 in/rev, 0.040 in/rev, 0.080 in/rev, and 0.160 in/rev. A spiral cut was thus excavated in each limestone block.

Four pressures were used: 10,000 psi, 15,000 psi, 20,000 psi, and 25,000 psi. Sixty-four specimens were prepared using the factorial design (Appendix A) with a random distribution to determine the order in which the tests were run.

FIG. 9 JET CUTTING IN ROTATION

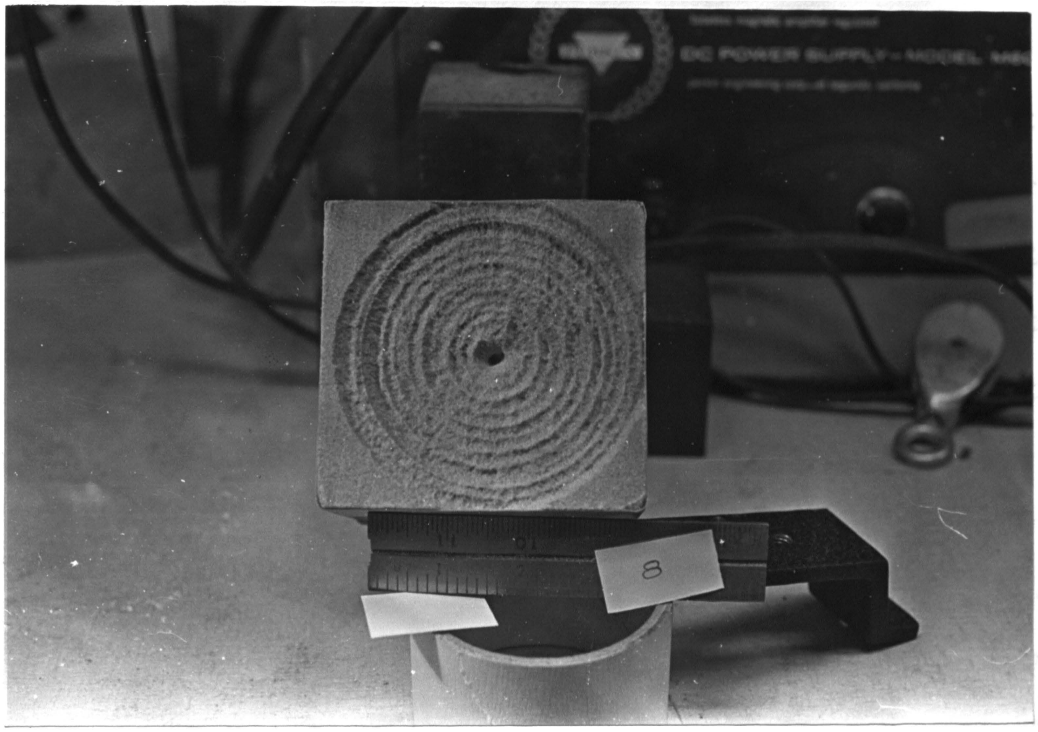


FIG. 10 TYPICAL SPECIMEN AFTER ROTATIONAL CUTTING

A steel guard having a slot 3.5 inches wide cut in it, was placed between the nozzle and the rotating rock. This kept the water jet from impinging the rock while the pressure was being raised to the desired level, and was used to obtain a fairly constant diameter of about 3.8 inches in each test making the calculation of relative speeds somewhat less tedious. The nozzle was kept approximately two inches from the rock face during the tests.

The typical procedure followed in these tests was to clamp the rock specimen in the chuck of the lathe making sure it was centered properly. The steel guard was clamped into place and the nozzle traversed to the far left hand side so that the water jet would initially strike the steel guard. The rotational speed of the chuck and the lateral traversing speed of the nozzle were set and the lathe turned on with the clutch disengaged. The door of the plexiglas cover was closed and the supply pump turned on. The main pump was then turned on and the pressure raised by closing the bleed-off valve. When the desired pressure was reached, the clutch of the lathe was engaged causing the chuck to rotate and the nozzle to traverse across the rock face. When the nozzle came to the far right hand side, the jet again encountered the steel guard, which increased the noise level, indicating that the test was over. The pressure was reduced, the clutch disengaged, the pumps turned off, and the test rock removed from the lathe. The procedure was repeated for each test.

Measurements were taken of the diameter of the cut, the volume of rock removed, and the depth of slot at ½ inch increments along the diagonals of the block. The lateral speed of the jet relative to the rock face decreased as the jet approached the center of each test. Since measurements were taken at 0.5, 1.0, 1.5, and 1.9 inches from the center and since four rotational speeds were used, sixteen jet speeds relative to the rock were obtained (Table XXVII).

The four linear nozzle traverse rates were used as a means of varying the number of passes over the same area. From the previous experiment, it had been determined that if two passes were within 0.125 inches of each other, the jet had effectively passed over the same area twice. Thus, for the 0.160 in/rev nozzle traverse rate, the pass number would be one, for 0.080 in/rev, two, etc. Since the linear nozzle traverse passed through the center of station, the number of passes was doubled. Thus, the numbers of passes used in this experiment were 2, 4, 8, and 16.

A preliminary investigation was made using two larger nozzle diameters, one 0.030 inches and the other 0.040 inches in diameter. Pressures of 18,000 psi and 8,000 psi were used respectively. These pressures were the maximum obtainable on the Kobe pump for each nozzle. The speeds were the same as above. The number of passes used were two.

2. Results and Discussion

Penetration was found to be linear with pressure for the Indiana limestone (Fig. 11), as it had been for the other rocks tested. Penetration varied inversely with speed (Fig. 12). It increased with an increase in number of passes, but the rate of penetration, i.e., slope of the curve, decreased (Fig. 13), indicating that the first pass provides deeper penetration than do subsequent passes.

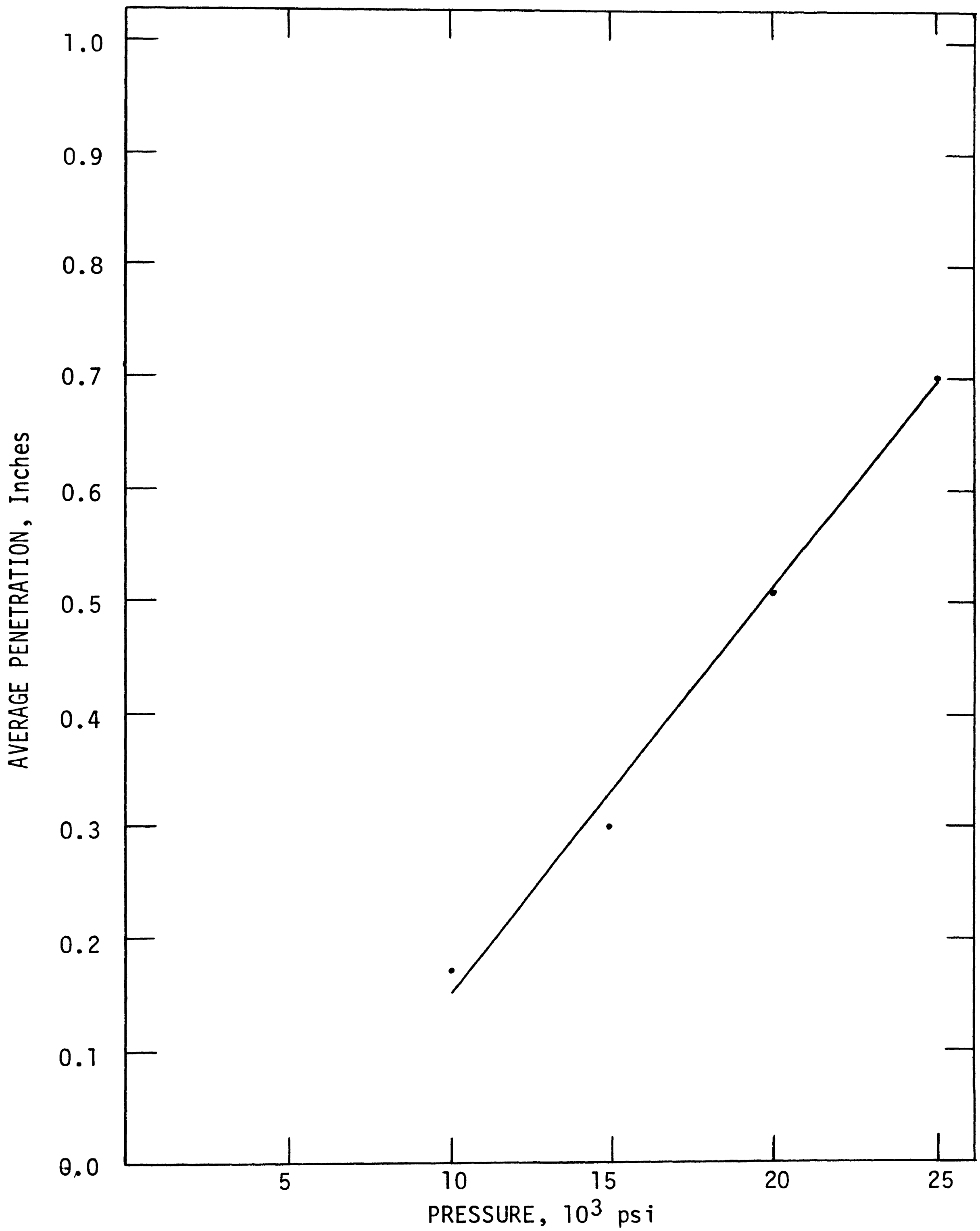


FIG. 11 PENETRATION VS. PRESSURE FOR INDIANA LIMESTONE

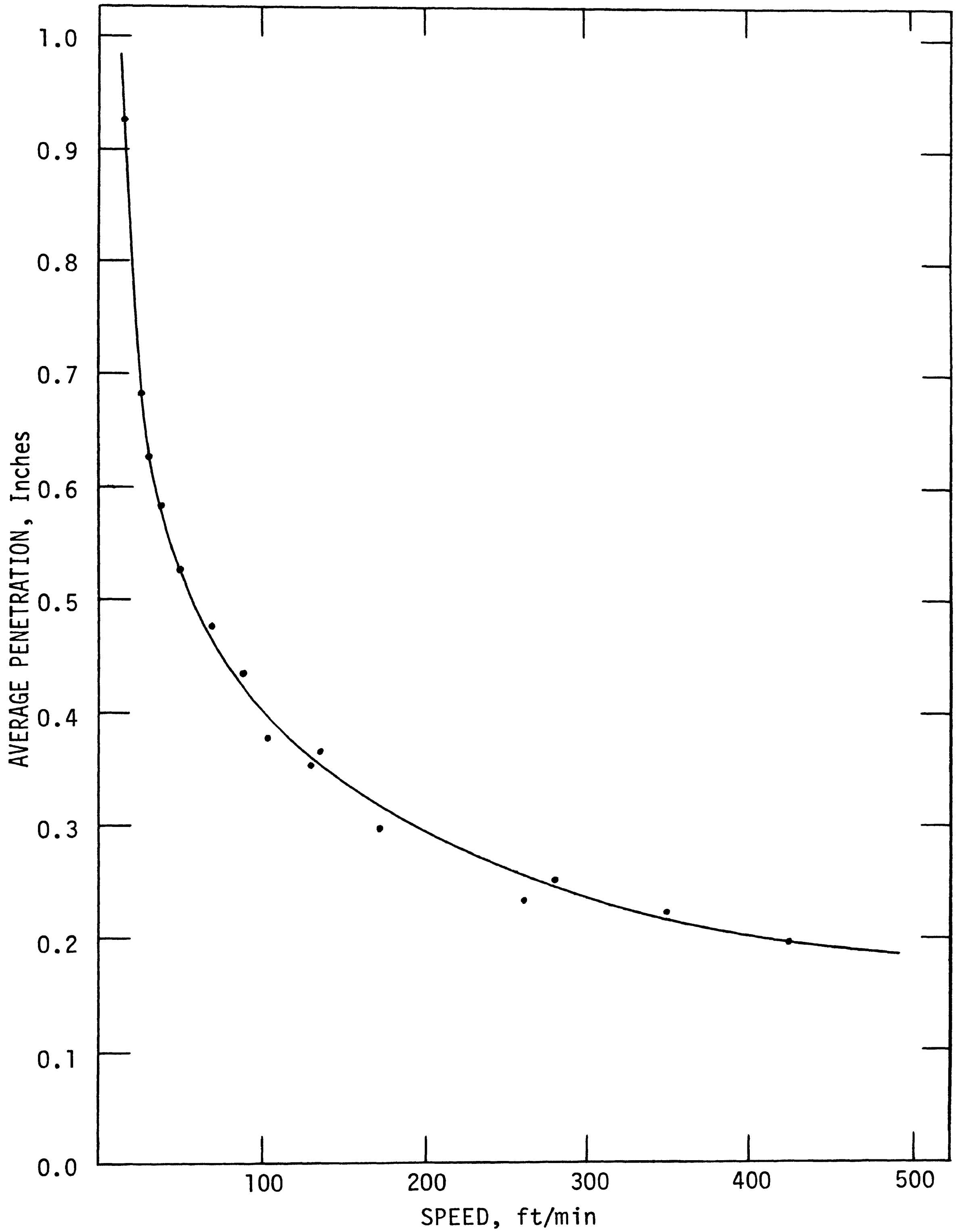


FIG. 12 PENETRATION VS. SPEED FOR INDIANA LIMESTONE

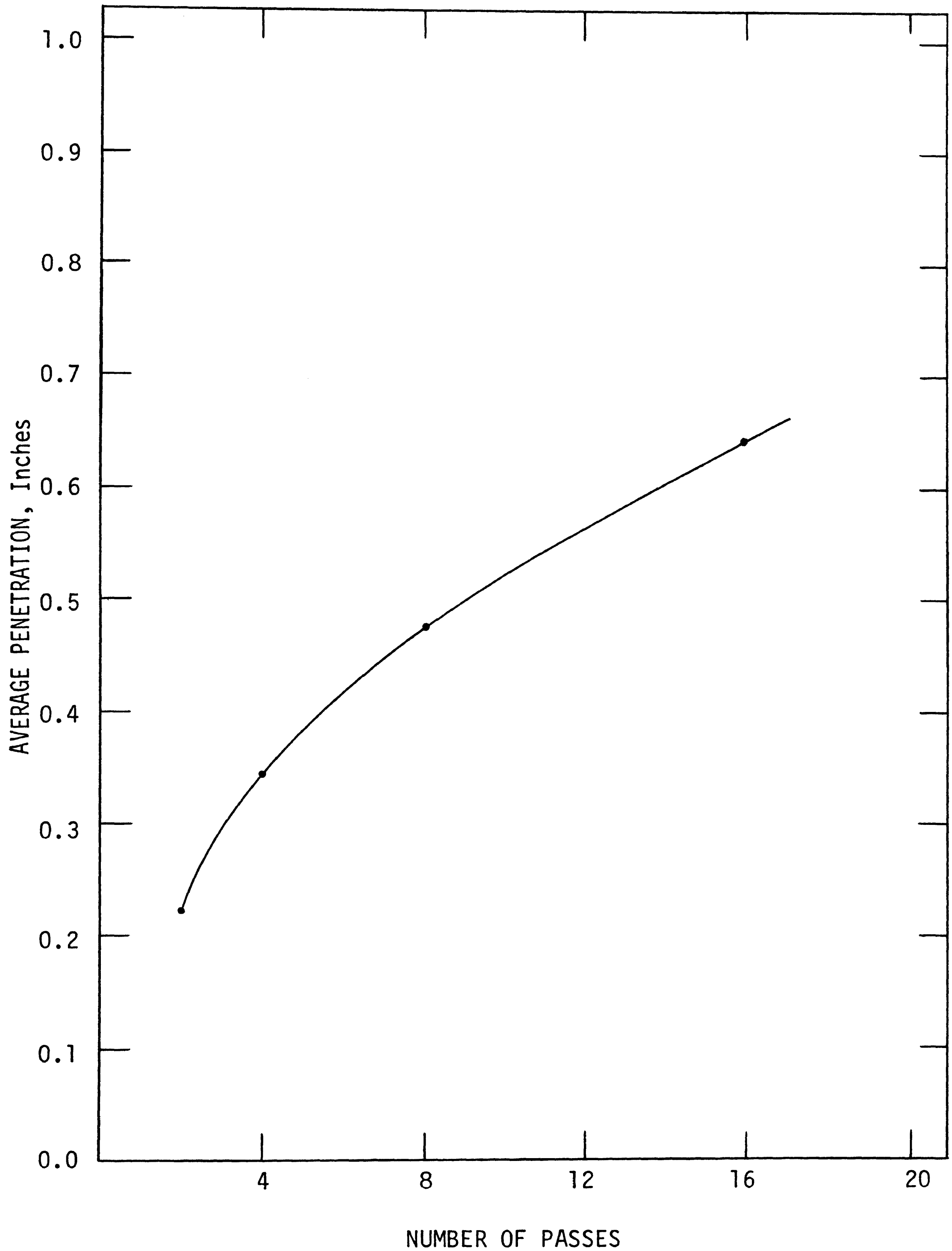


FIG. 13 PENETRATION VS. PASS NUMBER FOR INDIANA LIMESTONE

Specific energy decreased as pressure increased (Fig. 14). This is in contrast to what was observed in the traversing tests on Berea sandstone, where specific energy increased with an increase in pressure. Speed greatly affected specific energy over the range tested. An inverse relationship was observed, with specific energy decreasing with an increase in speed (Fig. 15). Specific energy per pass increased linearly with an increase in number of passes (Fig. 16), indicating that the most effective jet cutting occurred for a single pass.

Comparing the depths obtained by the three nozzle sizes used (Table XXVIII), the increase in nozzle diameter seemed to result in an increase in depth. The 0.030 inch nozzle, at 18,000 psi and two passes produced deeper penetration than did the 0.023 inch nozzle at 20,000 psi and two passes. The 0.040 inch nozzle, at 8,000 psi and two passes, produced penetrations deeper than the 0.023 inch nozzle at 10,000 psi and two passes.

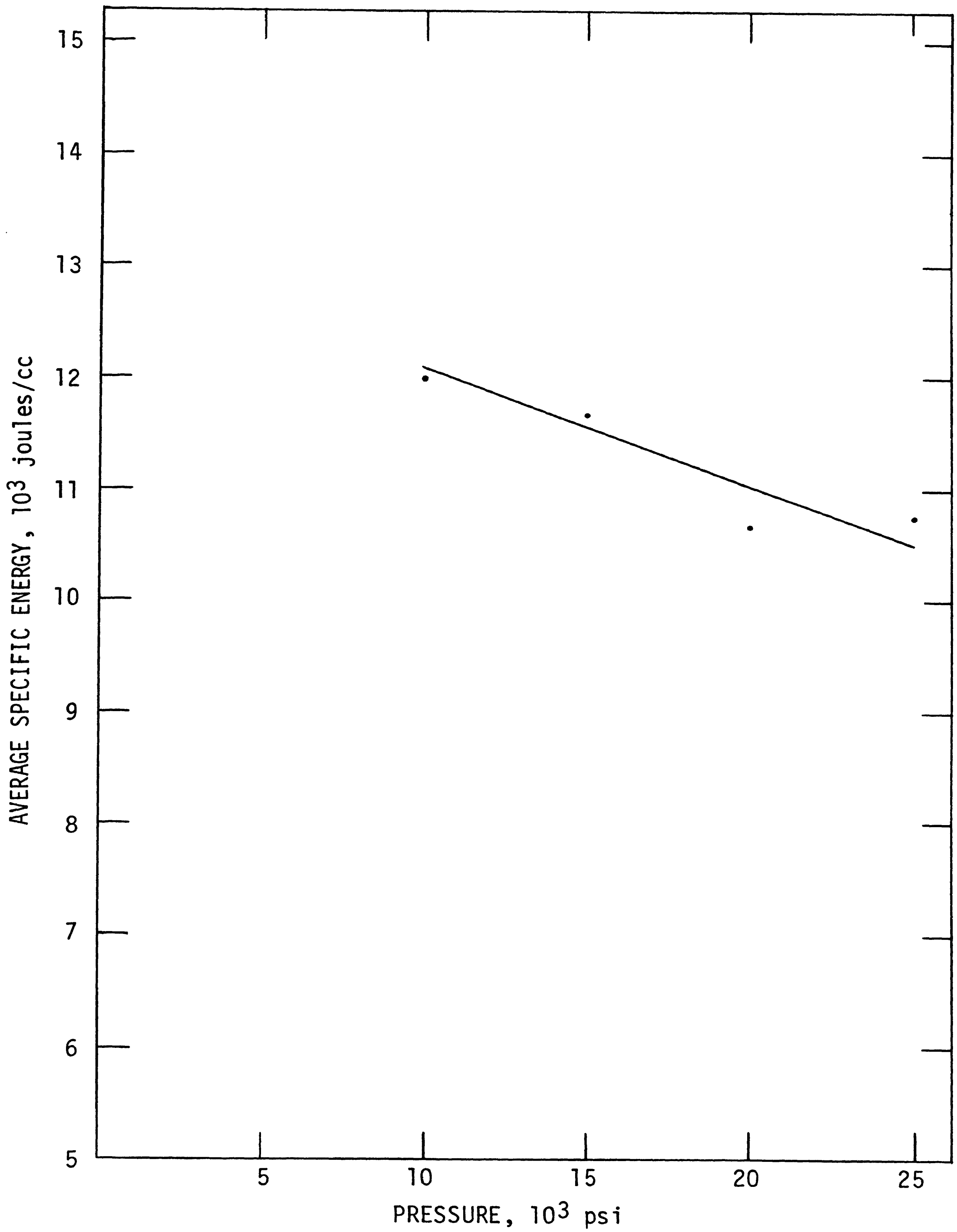


FIG. 14 SPECIFIC ENERGY VS. PRESSURE FOR INDIANA LIMESTONE

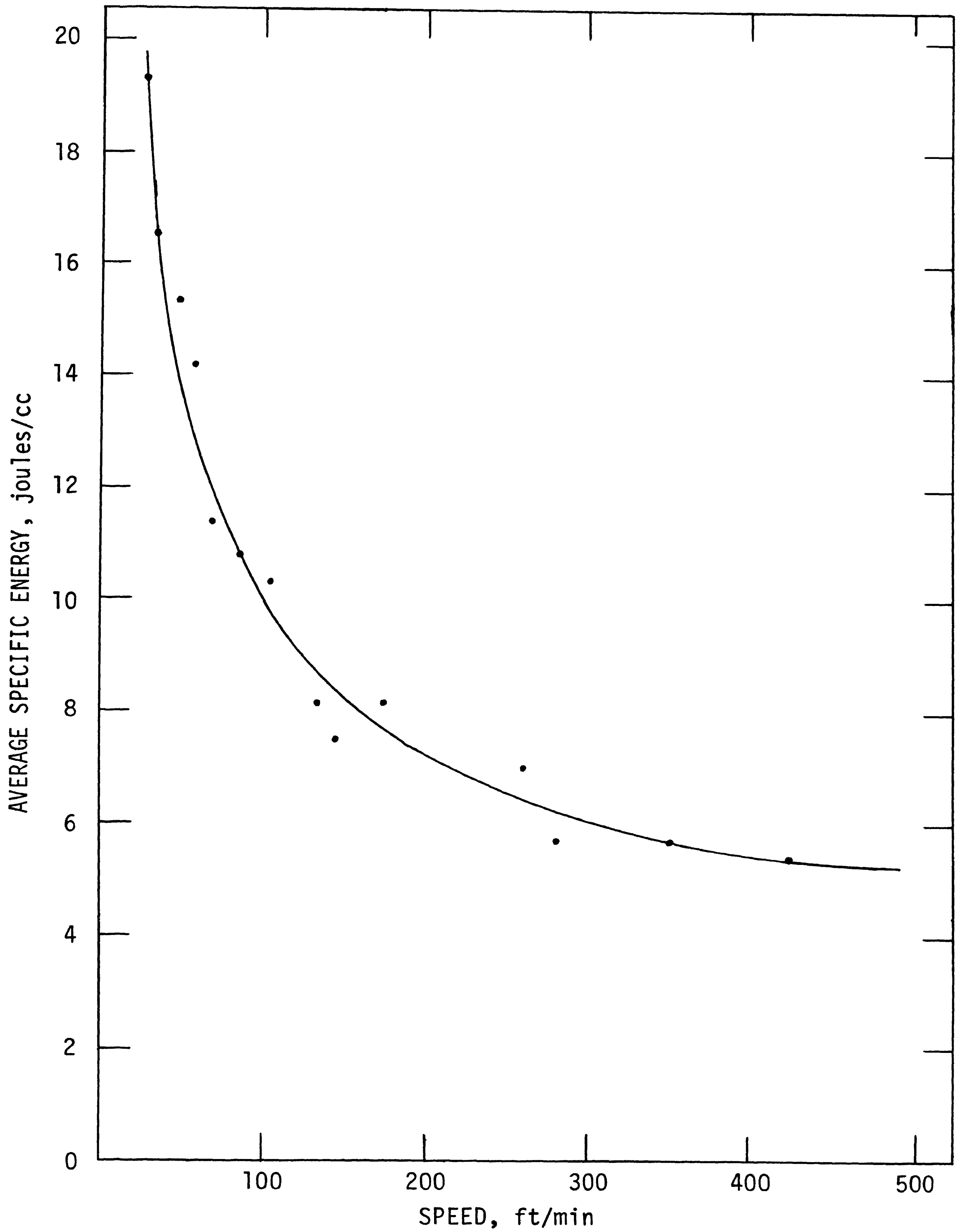


FIG. 15 SPECIFIC ENERGY VS. SPEED FOR INDIANA LIMESTONE

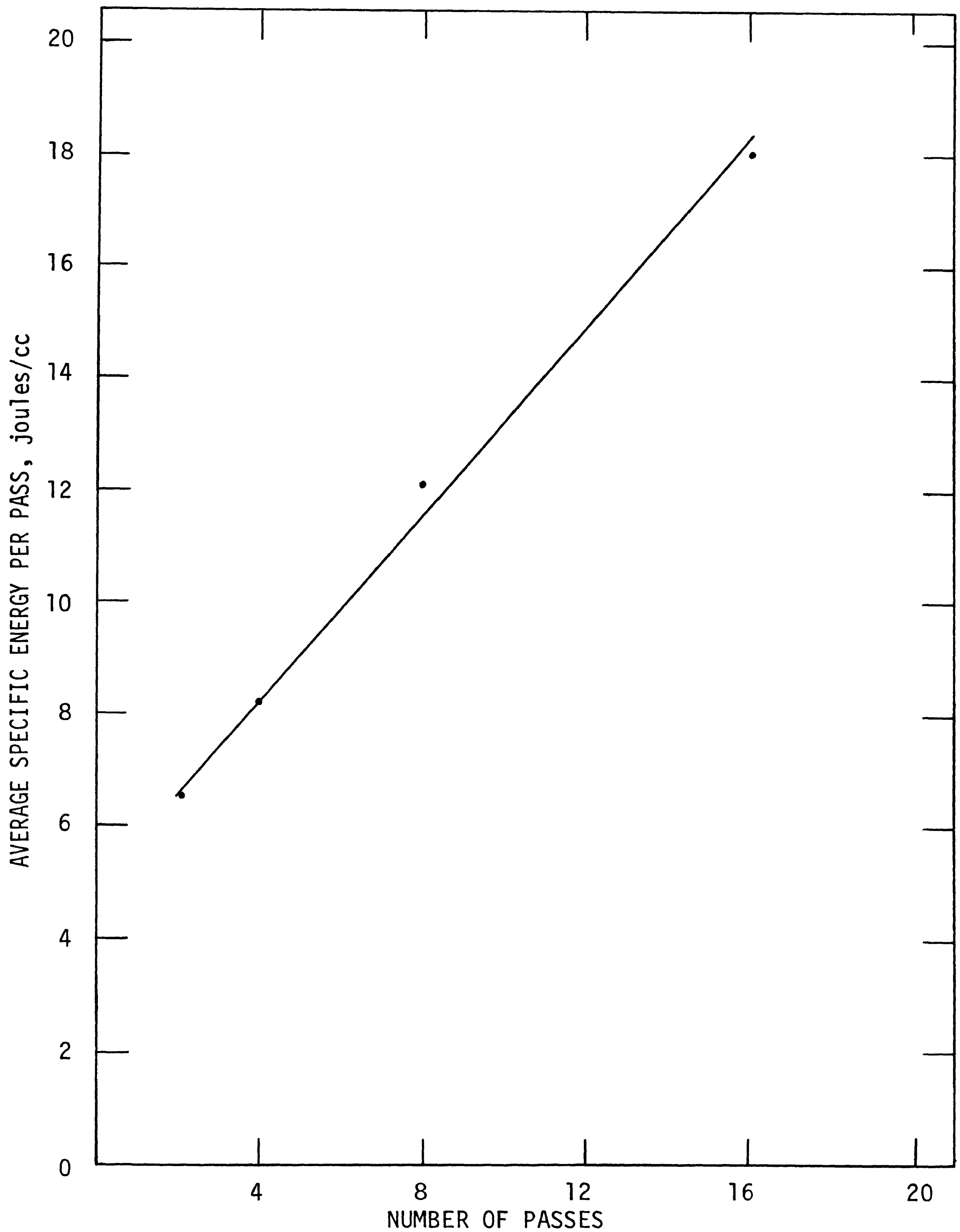


FIG. 16 SPECIFIC ENERGY PER PASS VS. PASS NUMBER FOR INDIANA LIMESTONE

TABLE XXVII. SPEED OF JET NOZZLE RELATIVE TO ROCK FACE

Average diameter of rotational tests = 3.826 inches

Circumference of cut every 0.5 inches from center:

$$C_1 = \pi d = \pi(1) = 3.14 \text{ inches}$$

$$C_2 = \pi(2) = 6.28$$

$$C_3 = \pi(3) = 9.42$$

$$C_4 = \pi(3.826) = 12.02$$

Speed = rotational rate x circumference

	@ 58 rpm	@ 136 rpm	@ 342 rpm	@ 536 rpm
S_1	15.2 ft/min	35.6	89.6	140.4
S_2	30.3	71.2	179.1	280.7
S_3	45.5	106.8	268.7	421.1
S_4	58.1	142.4	358.2	561.5

TABLE XXVIII. ROTATIONAL DEPTHS-INDIANA LIMESTONE

Pressure = 10,000 psi, Nozzle Diameter = 0.023 inches
Depths in inches
Rates, ft/min

No. of Passes	15.2	30.3	35.6	45.5	58.1	71.2	89.6	106.8
2	0.205	0.110	0.109	0.123	0.084	0.097	0.079	0.091
4	0.582	0.367	0.156	0.284	0.246	0.119	0.149	0.069
8	0.378	0.268	0.280	0.185	0.148	0.250	0.124	0.180
16	0.408	0.342	0.536	0.332	0.220	0.338	0.174	0.278
	136.2	140.4	179.1	268.7	280.7	242.6	421.1	536.9
2	0.084	0.056	0.048	0.043	0.028	0.060	0.028	0.052
4	0.104	0.195	0.068	0.059	0.109	0.074	0.070	0.090
8	0.166	0.262	0.091	0.062	0.152	0.066	0.112	0.096
16	0.256	0.344	0.113	0.081	0.249	0.104	0.174	0.114

Pressure = 15,000 psi, Nozzle Diameter = 0.023 inches
Depths in inches
Rates, ft/min

No. of Passes	15.2	30.3	35.6	45.5	58.1	71.2	89.6	106.8
2	0.339	0.178	0.243	0.168	0.214	0.146	0.202	0.117
4	0.655	0.516	0.518	0.364	0.272	0.348	0.229	0.304
8	0.686	0.612	0.540	0.470	0.352	0.420	0.343	0.370
16	0.984	0.689	0.590	0.636	0.574	0.494	0.522	0.369
	136.2	140.4	179.1	268.7	280.7	342.6	421.1	536.9
2	0.148	0.109	0.091	0.082	0.072	0.144	0.061	0.068
4	0.246	0.164	0.124	0.104	0.152	0.124	0.043	0.088
8	0.332	0.231	0.225	0.197	0.138	0.116	0.096	0.108
16	0.322	0.448	0.475	0.349	0.298	0.264	0.178	0.170

TABLE XXVIII. ROTATIONAL DEPTHS-INDIANA LIMESTONE - CONTINUED

Pressure = 20,000 psi, Nozzle Diameter = 0.023 inches
Depths in inches
Rates, ft/min

No. of Passes	15.2	30.3	35.6	45.5	58.1	71.2	87.6	106.8
2	0.823	0.492	0.416	0.379	0.524	0.284	0.260	0.208
4	1.032	0.701	0.537	0.422	0.480	0.415	0.518	0.148
8	1.413	1.089	0.767	0.951	0.756	0.598	0.651	0.519
16	1.388	1.054	1.384	0.882	0.746	1.111	0.755	0.725
	136.2	140.4	179.1	268.7	280.7	342.6	421.1	536.9
2	0.240	0.201	0.188	0.207	0.118	0.138	0.129	0.122
4	0.236	0.224	0.380	0.291	0.132	0.306	0.095	0.112
8	0.614	0.550	0.400	0.262	0.392	0.188	0.343	0.228
16	0.622	0.719	0.604	0.390	0.513	0.420	0.431	0.300

Pressure = 25,000 psi, Nozzle Diameter = 0.023 inches
Depths in inches
Rates, ft/min

No. of Passes	15.2	30.3	35.6	45.5	58.1	71.2	89.6	106.8
2	0.922	0.584	0.572	0.463	0.424	0.347	0.315	0.328
4	1.412	1.206	0.874	1.021	0.848	0.556	0.533	0.384
8	1.687	1.300	0.908	1.280	1.300	0.799	0.904	0.768
16	1.924	1.497	1.603	1.327	1.206	1.311	1.166	1.120
	136.2	140.4	179.1	268.7	280.7	342.6	421.1	536.9
2	0.370	0.364	0.178	0.144	0.160	0.138	0.143	0.190
4	0.314	0.404	0.388	0.319	0.246	0.202	0.198	0.112
8	0.610	0.558	0.538	0.424	0.420	0.742	0.353	0.230
16	1.006	1.073	0.810	0.638	0.824	0.484	0.662	0.802

TABLE XXVIII. ROTATIONAL DEPTHS-INDIANA LIMESTONE - CONTINUED

Pressure = 18,000 psi, Nozzle Diameter = 0.30 inches
Depths in inches
Rates, ft/min

No. of Passes	15.2	30.3	35.6	45.5	58.1	71.2	89.6	106.8
2	0.950	0.568	0.534	0.432	0.408	0.434	0.426	0.318
	136.2	140.4	179.1	268.7	280.7	342.6	421.1	536.9
2	0.340	0.343	0.229	0.190	0.151	0.174	0.125	0.128

Pressure = 8,000 psi, Nozzle Diameter = 0.40 inches
Depths in inches
Rates, ft/min

No. of Passes	15.2	30.3	35.6	45.5	58.1	71.2	89.6	106.8
2	0.303	0.198	0.196	0.144	0.138	0.137	0.125	0.090
	136.2	140.4	179.1	268.7	280.7	342.6	421.1	536.9
2	0.090	0.084	0.070	0.049	0.062	0.068	0.037	0.072

TABLE XXIX. ROTATIONAL VOLUMES-INDIANA LIMESTONE

Nozzle Diameter = 0.023 inches

Volumes in cu. cm

Ave. Rate, ft/min

Pressure, psi	No. of Passes	30.3	71.2	179.1	280.7
10,000	2	16.0	13.8	6.7	5.3
	4	45.5	21.0	9.8	17.5
	8	42.5	35.8	15.0	17.0
	16	53.0	51.0	23.2	28.0
15,000	2	22.1	17.7	17.5	8.6
	4	59.0	53.0	20.5	16.7
	8	75.5	58.6	37.0	23.8
	16	121.5	70.5	60.0	47.0
20,000	2	58.5	30.0	30.0	17.0
	4	109.5	69.0	55.0	21.5
	8	165.0	94.5	60.5	63.5
	16	153.0	146.0	85.0	73.5
25,000	2	60.0	53.5	15.5	31.0
	4	172.0	74.5	55.5	38.5
	8	219.0	119.0	99.0	65.0
	16	232.0	202.5	114.0	124.0

Nozzle Diameter = 0.030 inches
Ave. Rates, ft/min

Pressure, psi	No. of Passes	30.3	71.2	179.1	280.7
18,000	2	69.0	52.5	24.5	18.4

Nozzle Diameter = 0.040 inches
Ave. Rates, ft/min

Pressure, psi	No. of Passes	30.3	71.2	179.1	280.7
8,000	2	23.0	15.4	7.9	6.4

TABLE XXX. AVERAGE DEPTH, VOLUME, & SPECIFIC ENERGY VS. PRESSURE
INDIANA LIMESTONE

Pressure, psi	Depth, in.	Volume, cc/sec	Specific Energy j/cc
10,000	0.171	0.653	11,973
15,000	0.301	1.080	11,611
20,000	0.508	1.880	10,654
25,000	0.702	2.488	10,708

TABLE XXXI. AVERAGE DEPTH, VOLUME, & SPECIFIC ENERGY VS. SPEED
INDIANA LIMESTONE

Speed, ft/min	Depth, in.	Volume, cc/sec	Specific Energy j/cc
15.2	0.927	0.515	28,633
30.3	0.688	0.718	19,360
35.6	0.627	0.738	16,447
45.5	0.580	0.883	15,370
58.1	0.524	1.078	14,114
71.2	0.477	1.055	11,434
89.6	0.432	1.268	10,792
106.8	0.373	1.237	10,315
136.2	0.354	1.603	8,102
140.4	0.369	1.610	7,532
179.1	0.295	1.633	8,180
268.7	0.228	2.027	7,092
280.7	0.250	1.998	5,783
342.6	0.223	2.562	5,731
421.1	0.194	2.407	5,363
536.9	0.179	3.069	4,374

TABLE XXXII. AVERAGE DEPTH, VOLUME, & SPECIFIC ENERGY VS. PASS NUMBER
INDIANA LIMESTONE

No. of Passes	Depth, in.	Volume, cc/sec	Specific Energy j/cc
2	0.220	2.291	6,553
4	0.344	1.614	8,269
8	0.478	1.258	12,140
16	0.640	0.937	17,984

D. Rotational Experiment on Berea Sandstone

The effect of nozzle size on jet cutting was investigated in Berea sandstone. Three nozzle sizes were used: 0.023 inches, 0.030 inches, and 0.040 inches in diameter. Four rotational speeds were used and depth measurements were taken every ½ inch on the diagonals, giving 16 speeds of the water jet relative to the rock face, as before. The number of passes was held at two, one either side of center.

The pressures used were 5,000 psi and 8,000 psi for the 0.040 inch nozzle; 5,000 psi, 8,000 psi, 15,000 psi, and 18,000 psi for the 0.030 inch nozzle; and 8,000 psi and 18,000 psi for the 0.023 inch nozzle. The sandstone blocks used measured six inches on a side. These were mounted in the chuck of the lathe and the operational procedure in Section B was followed.

A comparison of results for the three nozzles (Table XXXIV) at equivalent pressures shows that the penetration increased with nozzle diameter. At a pressure of 8,000 psi, the penetration increased from 0.420 inches to 0.724 inches to 0.953 inches indicating that larger nozzle sizes are more effective. The specific energy at this pressure decreased from 963 joules/cc for the 0.023 inch nozzle to 727 joules/cc for the 0.030 inch nozzle, then went up to 738 joules/cc for the 0.040 inch nozzle. This may indicate that an optimum nozzle diameter exists for a given pressure when using specific energy as the criterion. More work could be done in this area.

TABLE XXXIII. ROTATIONAL DEPTHS-BEREA SANDSTONE

Depths in inches, No. of Passes = 2
Rates, ft/min

Nozzle Dia.	Pressure psi	15.2	30.3	35.6	45.5	58.1	71.2	87.6	106.8
0.040	5,000	1.893	1.489	0.731	1.247	0.886	0.480	0.772	0.360
	8,000	2.130	1.826	1.458	1.498	1.358	1.148	0.941	0.852
0.030	5,000	0.938	0.609	0.645	0.486	0.502	0.391	0.503	0.318
	8,000	1.389	1.156	1.117	0.998	0.962	0.811	0.780	0.616
	15,000	3.600	2.987	2.851	2.485	2.458	1.947	1.267	1.593
	18,000	4.653	3.920	3.139	3.187	3.162	2.297	2.066	1.911
0.027	8,000	0.854	0.646	0.641	0.524	0.502	0.482	0.465	0.387
	18,000	2.721	1.825	1.973	1.494	1.760	1.408	1.307	1.233

Nozzle Dia.	Pressure psi	136.2	140.4	179.1	268.7	280.7	342.6	421.1	536.9
0.040	5,000	0.216	0.773	0.500	0.391	0.484	0.258	0.302	0.170
	8,000	0.622	0.733	0.672	0.524	0.502	0.344	0.387	0.258
0.030	5,000	0.352	0.395	0.301	0.263	0.219	0.278	0.145	0.184
	8,000	0.584	0.664	0.513	0.419	0.411	0.468	0.346	0.344
	15,000	1.630	1.340	0.683	0.601	0.994	0.550	0.722	0.662
	18,000	1.764	1.836	1.572	1.202	1.217	0.988	0.987	0.800
0.023	8,000	0.348	0.460	0.270	0.225	0.244	0.240	0.204	0.232
	18,000	1.062	0.889	0.938	0.713	0.687	0.680	0.475	0.438

TABLE XXXIV. EFFECT OF NOZZLE DIAMETER ON PENETRATION, VOLUME, & SPECIFIC ENERGY IN BEREA SANDSTONE

Nozzle Diameter in.	Pressure psi	Depth in.	Volume cc/sec.	Specific Energy j/cc
0.023	8,000	0.420	4.756	963
	18,000	1.225	12.816	1108
0.030	5,000	0.408	5.825	640
	8,000	0.724	10.555	727
	15,000	1.648	21.091	840
	18,000	2.169	29.270	814
0.040	5,000	0.684	11.524	564
	8,000	0.953	15.910	738

IV. WATER CANNON EXPERIMENT ON INDIANA LIMESTONE

A. Introduction

The Kobe triplex pump had a maximum output of four gallons per minute, limiting the range of pressures and nozzle diameters that could be used for continuous water jet testing. In order to increase the range of investigation, tests were carried out using a 90 mm field cannon adapted to fire six gallons of water at pressures up to 50,000 psi through nozzles ranging in diameter from 0.1 to 1.0 inches. Previous experiments have shown that correlation can be made between penetration of a single water jet pulse, such as the cannon produces, and that achieved by a continuous jet, where the rock penetrated is granular.

B. Description of Equipment

A 90 mm gun tube was modified by removing the blast deflector and threading a one inch diameter nozzle in its place (Fig. 19). The nozzle was constructed so that additional, smaller nozzles could be added as required to the end of the barrel without detaching the primary nozzle. This was done by attaching a circular clamping ring to the front of the nozzle with four bolts such that any secondary nozzles could be inserted therein and held in correct alignment against the face of the primary nozzle.

The cannon was mounted on a platform modified from an inspection module obtained from McDonnell Douglas and the NASA Gemini program and inverted so that the nozzle was pointing downward at an angle of approximately 50 degrees with the horizontal (Fig. 17). Two ports were tapped in the side of the cannon, one near the breach and the other near the

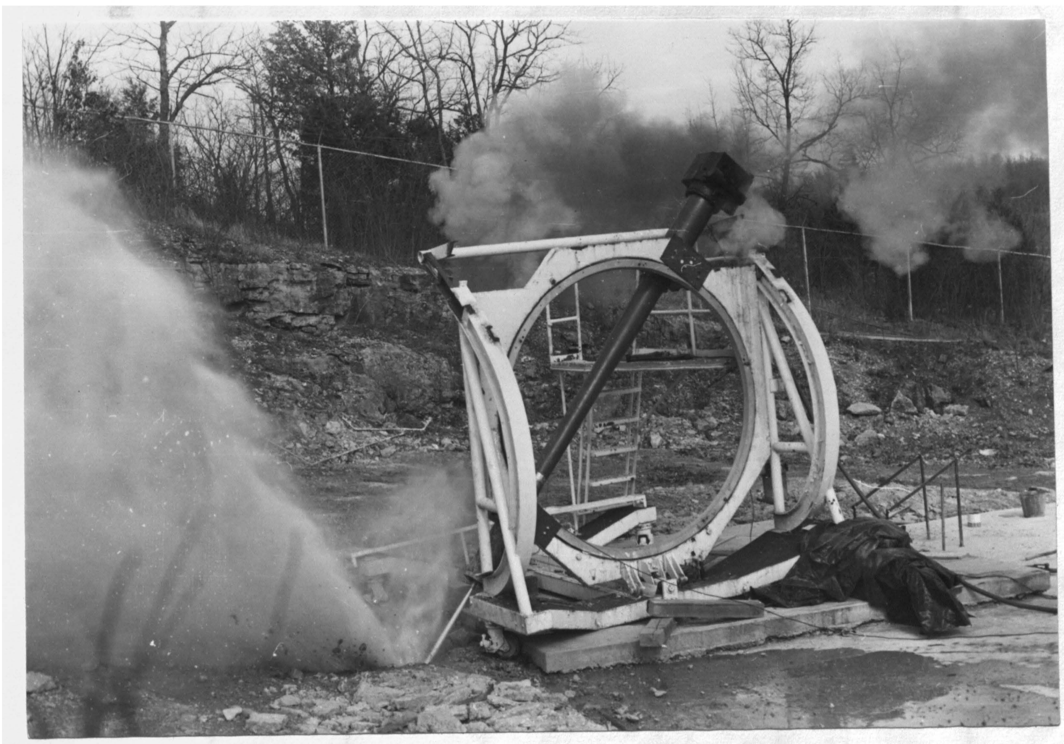
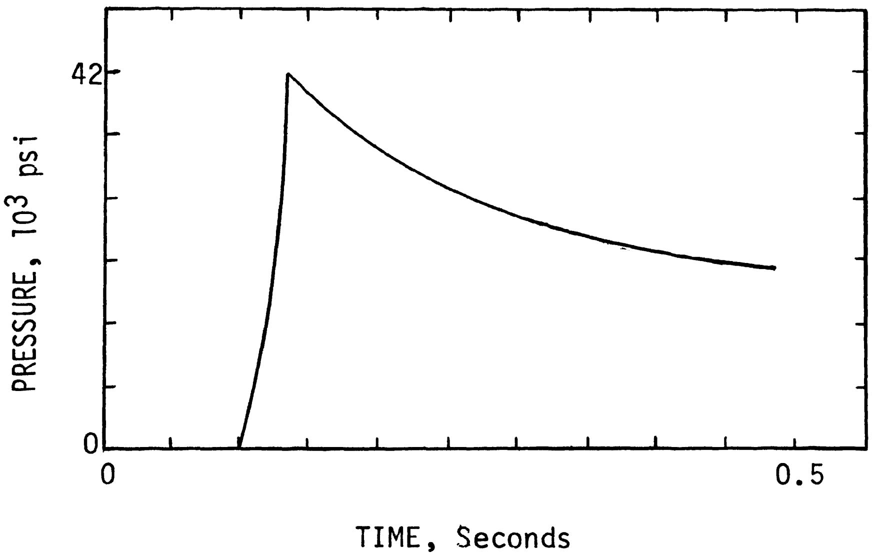
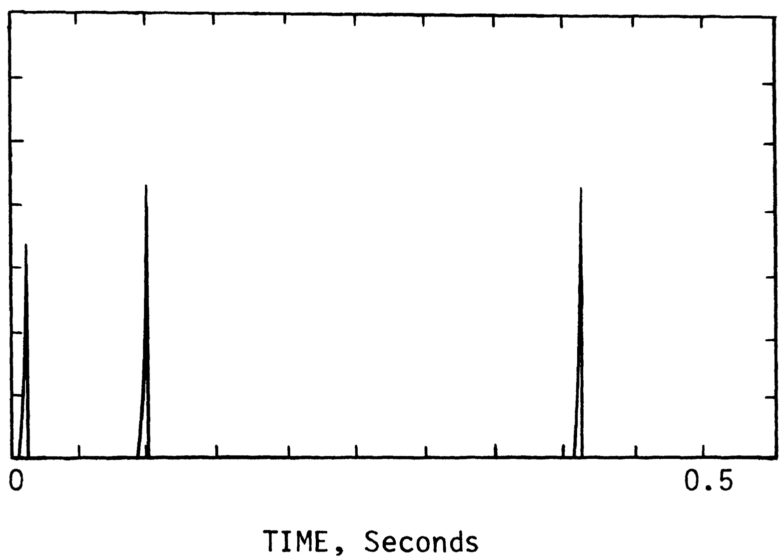


FIG. 17 WATER CANNON



a. Pressure-Time Profile



b. Contact Switch Traces Showing When First Three Switches Are Impacted

FIG. 18 OSCILLOSCOPE TRACES FOR TYPICAL CANNON SHOT

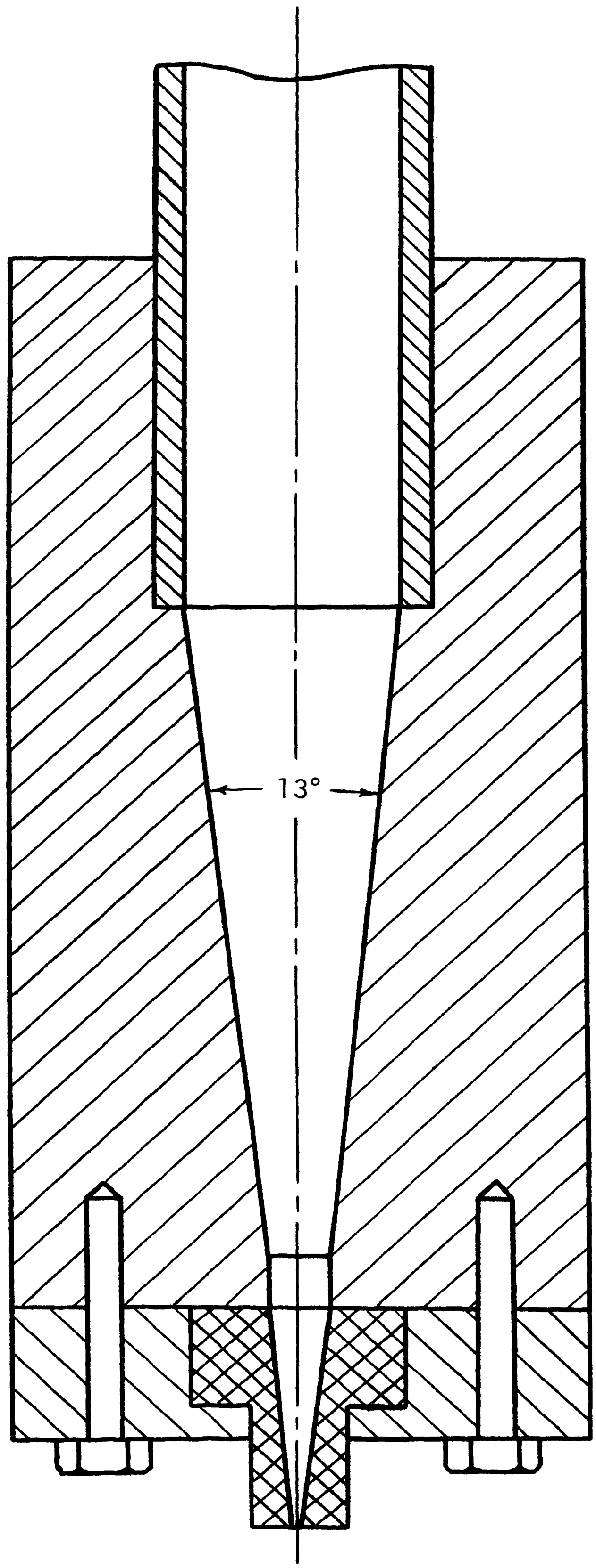


FIG. 19 CANNON NOZZLE

nozzle. Pressure transducers were located at these points and connected to an oscilloscope to give a pressure vs. time curve. The pressure was generated by igniting charges of smokeless powder in standard 90 mm cartridges supplied by the U. S. Army.

C. Experimental Procedure

Indiana limestone was cut into 6" x 6" x 12" blocks. Holes were drilled every two inches down the side of each block. These holes were ¼ inch in diameter, 3½ inches deep, and centered along the projected axis of jet penetration.

Electrical switches were prepared from coaxial cable by stripping the insulation and bending the inner wire back over the outer wire, but held separate by small strips of insulating tape (Fig. 20). These were inserted into soda straws to give some rigidity and protection. These, in turn, were inserted into the limestone blocks (Fig. 21). Also, one switch was taped on top of each test specimen to trigger the system. As the water jet impacted each soda straw switch, it closed the contact causing a blip to occur on the oscilloscope. Thus, the amount of time it took for the water jet to drill through each two inches of limestone was measured.

A 50 msec/cm sweep rate was used on the oscilloscope to obtain a picture of both pressure and cutting time (Fig. 18). While the pressure was still measurable beyond this time, the contact switches indicated that penetration ceased in less than half second of sweep for small nozzle diameters and all the water was expended in this time for the larger nozzles.

FIG. 20 SODA STRAW SWITCH

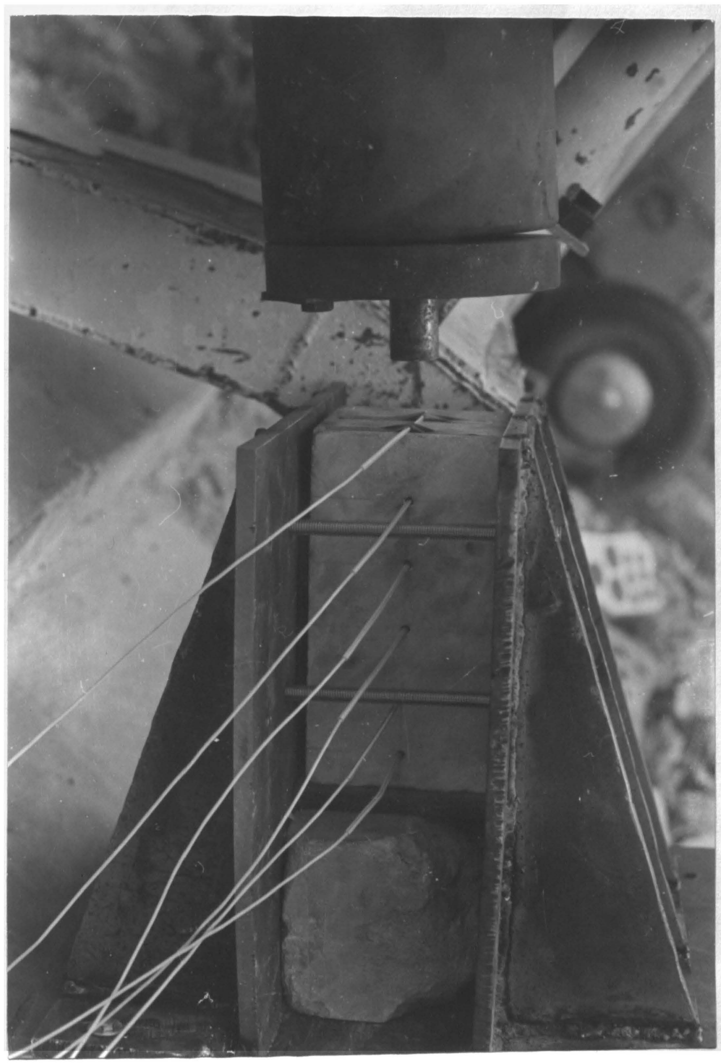


FIG. 21 TEST BLOCK WITH SWITCHES ATTACHED

FIG. 22 TEST BLOCK AFTER CANNON SHOT

The limestone specimens were held in place by a steel clamp. The distance between the rock surface and the nozzle varied between two and three inches. The stand-off distance was not considered critical, because previous experiments had shown that penetration did not decrease significantly with an increase in stand-off distance in the 2.0 to 4.0 inch range.

Nine tests were run, using four different nozzle sizes and four different charge sizes. The nozzles used were 1.0, 0.5, 0.2, and 0.1 inches in diameter. The charges used were 1.0, 1.5, 2.0, and 2.25 kilograms of smokeless powder. Because of the large reaction force on the cannon when using the one inch nozzle, only one shot was fired at this diameter. Only two shots were carried out using the 0.1 inch nozzle since it did not prove possible to obtain two inches of penetration at this diameter below a pressure of 25,000 psi.

D. Results and Discussion

Data was evaluated over the first five centimeters of penetration only, although the full shot data are given (Table XXXV). It has been shown (Chapter III) that at the same pressure and at equivalent jet impact times, a single water jet pulse fired into a fixed granular target will penetrate the rock to a depth equivalent to that obtained when a water jet traverses over the rock. Therefore, the results obtained from the water cannon could be directly related to the results of the continuous pump.

To correlate between the results obtained by the 0.023 inch nozzle used on the continuous pump and the data from the nozzle sizes used on the water cannon, graphical extrapolation and interpolation of data was used. The relationships used were that depth of cut varies linearly with jet pressure and that the specific energy of cutting is inversely related to traverse speed, as shown previously.

Specific energy was calculated as before, using the velocity term $v = 12.5 \sqrt{P}$ and a calculated volume based on a effective jet cutting width of 3.5 times the nozzle diameter.

Examination of the data obtained from the water cannon testing (Tables XXXV and XXXVI) indicates no value for specific energies below 16,195 joules/cc where at the same pressure the 0.023 inch nozzle has a cutting effectiveness of 5,456 joules/cc indicating that smaller nozzles may be more efficient. However, a comparison of equivalent depths indicated that the larger nozzle sizes produced a marked increase in depth.

The use of large nozzle sizes presented a problem outside the area of jet cutting. The water cannon frame had to be held in place by rock bolts and on occasion these were pulled out by the large reaction force applied to the cannon by the jet. The smaller nozzle diameters, on the other hand, have the advantage of a low reaction force and a 0.023 inch nozzle assembly operating at 25,000 psi can be operated by hand.

TABLE XXXV. WATER CANNON DATA

Charge (kg)	Nozzle Diameter (in)	Maximum Pressure (psi)	Average[(1)] Pressure (psi)	Penetration (Time[(2)] (millisec)	Total Depth (in)	Hole Volume (cm^3)	Specific[(1)] Energy (joules/cm^3)
1.0	0.2	12,500	8,300	440	2.031	16.0	28,934
1.5	0.1	32,500	25,500	410	2.795	12.5	146,670
1.5	0.2	31,000	27,800	62	4.213	44.5	25,221
1.5	0.5	28,000	23,200	47	2.008	(3)	116,195
1.5	1.0	12,300	-	-	0.110	2.5	-
2.0	0.1	45,000	39,500	68	3.528	15.0	46,957
2.0	0.2	45,000	36,700	93	7.000	76.0	57,397
2.0	0.5	36,500	29,700	44	3.937	(4)	21,965
2.25	0.2	47,000	42,500	42			32,090

NOTES

(1) Calculated over the first 5 cms of penetration
(2) Time for penetration of the first 5 cms
(3) After penetrating the first 5 cms of the jet deflected on the switch and broke to the side of the specimen
(4) The top 10 cms of the block were completely removed
(5) The jet split the rock in two pieces after penetrating 10 cms

TABLE XXXVI. COMPARATIVE RESULTS FROM PUMP & CANNON TESTING

Pressure (psi)	Speed (ft/min)	Nozzle Diameter (in.)		Equivalent Depth (cm)		Specific Energy (joules/cm^3)	
		Cannon	Pump	Cannon	Pump	Cannon	Pump
42,500	83.0	0.2	.023	2.0	.638	32,133	2,628
15,000	7.5	0.2	.023	2.0	.299	74,549	14,224
82,500	7.9	0.2	.023	2.0	.079	28,849	20,422
82,500	7.9		.040		.075		14,967
25,000	4.3	0.1	.023	2.0	.701	146,670	23,679
37,500	25.6	0.1	.023	2.0	.689	46,975	7,883
36,700	37.7	0.2	.023	2.0	.378	57,154	8,512
23,300	186.0	0.4	.023	2.0	.079	16,195	5,456
27,800	56.1	0.2	.023	2.0	.268	25,221	4,856
29,700	199.1	0.4	.023	2.0	.150	21,965	4,199

V. CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

Depth of penetration was found to vary linearly with water jet' pressure. Stand-off distance, in the range investigated, seemed to have little effect on penetration. Time of impact greatly affected the rate of penetration, with most of the rock cutting being done in the first tenth of a second.

When the water jet is traversed across a granular rock, the depth of penetration was equivalent to that of a singular water jet pulse fired into a static rock target for the same pressures and at equivalent impact times. Interaction between two passes of the water jet occurred at 0.125 inches for the 0.023 inch nozzle.

Penetration was found to vary inversely with the speed of traverse. The rate of penetration was found to decrease as the number of passes increased. Pressure had only a small effect on specific energy when the rock was rotated, but the relative speed was found to have a great effect. Specific energy varied inversely with speed and directly with the pass number.

Penetration increased with an increase in nozzle diameter. There appears to be an optimum nozzle diameter when using specific energy as the criterion. More work needs to be done in this area.

Jet parameters, jet stability, nozzle design, cutting rates, and energy efficiencies have been studied in the laboratory and the field. However, more basic work needs to be done on the breaking mechanisms of water jets, that is, the method of failure that occurs in the rock under high pressure water jet impact. Correlation of jet performance with surface energy of rocks needs to be done. Application of current knowledge could result in a reliable and efficient hydraulic mining machine.

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VITA

Richard Lee Henry was born on May 26, 1948, in Edinburg, Texas. He received his primary and secondary education in Carl Junction, Missouri. He received his college education from Missouri Southern College in Joplin, Missouri, and the University of Missouri-Rolla, in Rolla, Missouri. He received a Bachelor of Science degree in Petroleum Engineering from the University of Missouri-Rolla, in Rolla, Missouri, in May 1970.

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APPENDIX A

DESIGN OF FACTORIAL EXPERIMENT

In a factorial experiment each parameter level is used only once in relation to the other parameter levels (20). For example, in the single pulse static experiment, five pressures, five stand-off distances, and five time levels were used. The total number of tests were then 5 x 5 x 5 or 125 for each rock type. For reasons of economy five tests were performed on each test block at two inch intervals making a total of 25 test blocks. The tests were arranged to minimize end effects or errors which might occur due to specimen inhomogeneity.

Table XXXVII shows the position and test levels of each block. The underlined numbers in the table are the rock specimen number. Each vertical set of numbers represents one test. For example, the end test on specimen number 3 was at pressure level 3 (15,000 psi), time level 4 (2.0 seconds), and stand-off distance level 3 (3.0 inches).

In the rotational experiment on Indiana limestone, four rotational velocities, four nozzle traverse speeds, and four pressures were used, making a total of 64 tests. Table XXXVIII was set up. Following each specimen number in the table is the pressure in ksi, the rotational speed of the chuck in rev/min and the nozzle traverse speed in in/rev. For the rotational experiment on Berea sandstone, a similar table was used. In each experiment, the test blocks were run according to a random distribution of the sample population.

TABLE XXXVII. ORDER OF TESTS-INTERRUPTED JET

Specimen number	1	2	3	4	5
Pressure Level	12345	23451	34512	45123	51234
Time Level	23451	34512	45123	41234	12345
Distance Level	34512	51234	23451	45123	12345
	6	7	8	9	10
	12345	23451	34512	45123	51234
	34512	45123	51234	12345	23451
	45123	12345	34512	51234	23451
	11	12	13	14	15
	12345	23451	34512	45123	51234
	45123	51234	12345	23451	34512
	51234	23451	45123	12345	34512
	16	17	18	19	20
	12345	23451	34512	45123	51234
	51234	12345	23451	34512	45123
	12345	34512	51234	23451	45123
	21	22	23	24	25
	12345	23451	34512	45123	51234
	12345	23451	34512	45123	51234
	23451	45123	12345	34512	51234

TABLE XXXVIII. ROTATIONAL TEST TABLE

Specimen Number, Pressure, ksi-Rotation Speed, rev/min-Traverse Speed 10^{-3} in/rev

1.	10-58-20	17.	10-342-20	33.	10-58-80	49.	10-342-80
2.	15-136-40	18.	15-536-40	34.	15-136-160	50.	15-536-160
3.	20-342-80	19.	20-58-80	35.	20-342-20	51.	20-58-20
4.	25-536-160	20.	25-136-160	36.	25-536-40	52.	25-136-40
5.	10-58-40	21.	10-342-40	37.	10-58-160	53.	10-342-160
6.	15-136-80	22.	15-536-80	38.	15-136-20	54.	15-536-20
7.	20-342-160	23.	20-58-160	39.	20-342-40	55.	20-58-40
8.	25-536-20	24.	25-136-20	40.	25-536-80	56.	25-136-80
9.	10-136-80	25.	10-536-80	41.	10-136-20	57.	10-536-20
10.	15-342-160	26.	15-58-160	42.	15-342-40	58.	15-58-40
11.	20-536-20	27.	20-136-20	43.	20-536-80	59.	20-136-80
12.	25-58-40	28.	25-342-40	44.	25-58-160	60.	25-342-160
13.	10-136-160	29.	10-536-160	45.	10-136-40	61.	10-536-40
14.	15-342-20	30.	15-58-20	46.	15-342-80	62.	15-58-80
15.	20.536-40	31.	30-136-40	47.	20-536-160	63.	20-136-160
16.	25-58-80	32.	25-342-80	48.	25-58-20	64.	25-432-20

APPENDIX B

COMPUTER PROGRAM USED FOR REGRESSION OF FACTORIAL EXPERIMENT

The following computer program was used for regression of the factorial experiments described previously. For the rotational experiments, it calculated hole volumes assuming a slot was cut that is 3.5 times the nozzle diameter. Specific energy was then calculated. Penetrations, hole volumes, and specific energies were then averaged for a correlation with pressure, speed, and number of passes using the least squares technique. For the single pulse static experiment, hole volumes were known, so specific energy was calculated directly. For speed, the stand-off distances were read in and for pass number, the impact times were used. Penetration, hole volume, and specific energy were then correlated with pressure, stand-off, and time.

```
PUT EDIT('THIS PROGRAM IS FOR REGRESSION OF A FACTORIAL EXPERIMENT')
     (X(10),A)
DECLARE SPENG ENTRY EXT, SPENG2ENTRY EXT, MPRNT1 ENTRY EXT, AVG
     ENTRY EXT, MULTR ENTRY EXT
DECLARE PLOT ENTRY EXT KEY(XEQ) LIB(PUBLIC)
PUT EDIT('PLEASE GIVE NOZZLE DIAMETER IN INCHES')(X(2),A)
GET LIST (DIAM)
PUT EDIT('PLEASE GIVE NUMBER OF PRESSURES, SPEED AND PASS LEVELS')
     (X(2),A)
GET LIST(n,m,l)
DECLARE A(1,1,1) CONTROLLED, B(1,1,1) CONTROLLED, C(1,1,1) CONTROLLED
ALLOCATE A(n,m,l), B(n,m,l), C(n,m,l)
PUT EDIT('PLEASE GIVE PENETRATED DEPTH AS A MATRIX BY COLUMNS')(X(2),A)
GET LIST (A)
DECLARE P(1) CONTROLLED, S(1) CONTROLLED, NO(1) CONTROLLED, T2(1)
     CONTROLLED, U2(1) CONTROLLED, W2(1) CONTROLLED
DECLARE T5(1) CONTROLLED, U5(1) CONTROLLED, W5(1) CONTROLLED, T4(1)
     CONTROLLED, U4(1) CONTROLLED, W4(1) CONTROLLED
ALLOCATE P(n),S(m),NO(l),T2(n),U2(m),W2(l),T5(n),T4(n),U5(m),U4(m),
     W5(l),W4(l).
PUT EDIT('PLEASE GIVE VALUES OF PRESSURE IN PSI')(X(2),A)
GET LIST (P)
PUT EDIT('PLEASE GIVE VALUES OF SPEED IN FT/MIN')(X(2),A)
GET LIST (S)
```

```
PUT EDIT('PLEASE GIVE THE VALUES OF THE NUMBERS OF PASSES') (X(2),A)
GET LIST (NO)
PUT EDIT('DO YOU KNOW HOLE VOLUME IF YES PUT 2 OTHERWISE 3') (X(2),A)
GET LIST (OPTION)
DECLARE INPUT CHAR(6), HOVOL CHAR(6), SPEGY CHAR(6), PRESS CHAR(6),
     PASNO CHAR(6), SPEED CHAR(6)
CALL MPRNT1 (A,n,m,1,'INPUT')
AREA=3.1416*(DIAM*25.4/2)**2
DECLARE MASS(1) CONTROLLED, V(1) CONTROLLED, ENERGY(1) CONTROLLED
ALLOCATE MASS(n),V(n),ENERGY(n)
DO I=1 TO n
V(I)=12.5*SQRT(P(I)/14.7)
MASS(I)=AREA*V(1)
ENERGY(I)=.5*MASS(I)**2/(1.02*1000)
END
IF OPTION=2 THEN GO TO KNOWN
CALL SPENG(A,B,n,m,1,ENERGY,S,NO,DIAM,C)
GO TO BYPASS
KNOWN:  CALL SPENG2(A,B,n,m,1,ENERGY, NO,C)
BYPASS:  CALL MPRNT1(B,n,m,1,'HOVOL')
CALL MPRNT1(C,n,m,1,'SPEGY')
CALL AVG(C,n,m,1,T2,U2,W2)
CALL AVG(B,n,m,1,T4,U4,W4)
CALL AVG(A,n,m,1,T5,U5,W5)
PUT EDIT('PRESSURE','DEPTH','VOLUME','SPECIFIC ENERGY')
     (SKIP,X(10),A,X(10),A,X(10),A,X(10),A)
DO I=1 TO n
PUT EDIT(P(I),T5(I),T4(I),T2(I))(SKIP,X(10),F(8),X(10),F(6,3)X(10),
     F(7,3),X(10),E(11,4))
END
PUT EDIT('SPEED','DEPTH','VOLUME','SPECIFIC ENERGY')(SKIP,X(10),A,X(10),
     A,X(10),A,X(10),A)
DO J=1 TO m
PUT EDIT(S(J),U5(J),U4(J),U2(J))(SKIP,X(10),F(6,2),X(10),F(6,3),X(10),
     F(7,3),X(10),E(11,4))
END
PUT EDIT('PASNO','DEPTH','VOLUME','SPECIFIC ENERGY') (SKIP,X(10),A,X(10),
     A,X(10),A,X(10),A)
DO K=1 TO 1
PUT EDIT(NO(K),W5(K),W4(K),W2(K))(SKIP,X(10),F(6,2),X(10),F(6,3),X(10),
     F(7,3),X(10),E(11,4)
END
CALL MULTR(P,n,T2,'PRESS')
CALL MULTR(S,m,U2,'SPEED')
CALL MULTR(NO,1,W2,'PASNO')
PUT EDIT ('THE ABOVE CORRELATIONS WERE WITH SPECIFIC ENERGY')(X(2),A)
CALL MULTR(P,n,T4,'PRESS')
CALL MULTR(S,m,U4,'SPEED')
CALL MULTR(NO,1,W4,'PASNO')
PUT EDIT('THE ABOVE CORRELATIONS WERE WITH HOLE VOLUME')(X(2),A)
CALL MULTR(P,n,T5,'PRESS')
CALL MULTR(S,m,U5,'SPEED')
CALL MULTR(NO,1,W5,'PASNO')
```

```
PUT EDIT('THE ABOVE CORRELATIONS WERE WITH DEPTH')(X(2),A)
PUT EDIT('THE PROGRAM IS OVER, THANK YOU')(SKIP(3),X(20),A)
END
MPRNT1:  PROCEDURE (X2,nn,mm,11,CHARA)
DECLARE X(1) CONTROLLED
ALLOCATE X(11)
PUT EDIT(CHARA,'DATA',nn,'x',mm,'x',11)(SKIP(3),A,X(2),A,F,(2),A,F(2))
DO I=1 TO nn
PUT EDIT('PRESSURE LEVEL = ',1)(SKIP(3),X(10),A,F(3))
DO J=1 TO mm
DO K=1 TO 11
X(K)=X2(I,J,K)
END
PUT EDIT(J,X)(SKIP,F(3),X(10),(10) E(11,4)
END
END
FREE X
RETURN
END MPRNT1

SPENG:  PROCEDURE (AA,BB,a,b,c,PP,SS,NNO,DIA,CC)
DO I=1 TO a
DO J=1 TO b
DO K=1 TO c
BB(I,J,K)=AA(I,J,K)*.5*DIA*SS(J)*2.54*3/NNO(K)
END
END
END
DO I=1 TO a
DO J=1 TO b
DO K=1 TO c
CC(I,J,K)=PP(I)/BB(I,J,K)
END
END
END
RETURN
END SPENG

SPENG2:  PROCEDURE (AA,BB,a,b,c,PP,NNO,CC)
PUT EDIT('YOU HAVE INDICATED YOU KNOW HOLE VOLUMES-PLEASE INSERT IN
CUBIC CMS.')(A)
GET LIST (BB)
DO I=1 TO a
DO J=1 TO b
DO K=1 TO c
CC(I,J,K)=PP(I)*NNO(K)/BB(I,J,K)
END
END
END
RETURN
END SPENG2

AVG:  PROCEDURE (CCC,nnn,mmm,111,T,U,W)
DO I=1 TO nnn
DO J=1 TO mmm
DO K=1 TO 111
```

```
T(I)=0
U(J)=0
W(K)=0
END
END
END
DO I=1 TO nnn
DO J=1 TO mmm
DO K=1 TO 111
T(I)=T(I)+CCC(I,J,K)
U(J)=U(J)+CCC(I,J,K)
W(K)=W(K)+CCC(I,J,K)
END
END
END
DO I=1 TO nnn
T(I)=T(I)/(111*mmm)
END
DO J=1 TO mmm
U(J)=U(J)/(nnn*111)
END
DO K=1 TO 111
W(K)=W(K)/(nnn*mmm)
END
RETURN
END AVG

MULTR:  PROCEDURE (PPP,n4,TTT,CHARA)
IF n4=1 THEN GO TO ZERO
q=0
BEGIN:  SUMX=0
SUMY=0
SUMXY=0
SUMX2=0
SUMY2=0
SUMX3=0
SUMX2Y=0
SUMX4=0
DO I=1 TO n4
SUMX=SUMX+PPP(I)
SUMY=SUMY+TTT(I)
SUMXY=SUMXY+TTT(I)*PPP(I)
SUMX2=SUMX2+PPP(I)**2
SUMY2=SUMY2+TTT(I)**2
SUMX2Y=SUMX2Y+PPP(I)**2*TTT(I)
SUMX3=SUMX3+PPP(I)**3
SUMX4=SUMX4+PPP(I)**4
END
E=(SUMY*SUMX2-SUMX*SUMXY)/(n4(SUMX2-SUMX**2)
F=(n4*SUMXY-SUMX*SUMY)/(n4*SUMX2-SUMX**2)
ex=n4*SUMX2-SUMX**2
ey=n4*SUMY2-SUMY**2
G=(n4*SUMXY-SUMX*SUMY)/(SQRT(ex8ey))
```

```
PUT EDIT('THE EQUATION IS Y EQUALS',E,'+',F,'X')(SKIP,X(2),A,X(1),
      E(11,3),X(2),A,X(1),E(11,3),X(2),A)
PUT EDIT('THE COEFFICIENT OF CORRELATION IS ',G)(SKIP,X(2),A,X(2),
      E(11,3)
q=q+1
DENOM=(SUMX*SUMY-n4*SUMXY)*(n4*SUMX3-SUMX*SUMX2)-(n4*SUMX2Y-SUMX2*SUMY)
      *(SUMX**2-n4*SUMX2)
ARG=(SUMX2*SUMX-n4*SUMX3)*(n4*SUMX3-SUMX*SUMX2)-(n4*SUMX4-SUMX2**2)
      *(SUMX**2)*(SUMX**2-n4*SUMX2)
A2=DENOM/ARG
A1=(SUMX*SUMY-n4*SUMXY-A2*(SUMX2*SUMX-n4*SUMX3))/(SUMX**2-n4*SUMX2)
A0=(SUMY-A1*SUMX-A2*SUMX2)/n4
PUT EDIT('THE LEAST SQUARE PARABOLA IS')(SKIP,X(2),A)
PUT EDIT(A0,'+',A1,'X','+',A2,'X2')(SKIP,X(10),E(11,3),X(2),A,X(2),
      E(11,3),A,X(2),A,E(11,3),A)
DECLARE YEST(1) CONTROLLED
ALLOCATE YEST(n4)
AVY=SUMY/n4
EXVAR=0
TOVAR=0
DO I=1 TO n4
YEST(I)=A0+A1*PPP(I)+A2*PPP(I)**2
EXVAR=EXVAR+(YEST(I)-AVY)**2
TOVAR=TOVAR+(TTT(I)-AVY)**2
END
g=SQRT(EXVAR/TOVAR)
PUT EDIT('WITH CORRELATION COEFFICIENT EQUAL TO', g)(SKIP,X(10),X,X(2),
      E(11,3))
FREE YEST
IF q=2 THEN GO TO OTHER
IF q=2 THEN GO TO DOG
PUT EDIT('INVERTING',CHARA, 'GIVES')(SKIP,X(10),A,A,A)
DO I=1 TO n4
PPP(I)=1/PPP(I)
END
GO TO BEGIN
OTHER:  PUT EDIT('INVERTING VARIATE GIVES')(SKIP,X(10),A)
DO I=1 TO n4
PPP(I)=1/PPP(I)
TTT(I)=1/TTT(I)
END
GO TO BEGIN
ZERO:  PUT EDIT('NO CORRELATION OF VARIABLE WITH',CHARA)(SKIP,X(2),
      A,X(2),A)
DOG:  PUT EDIT('CORRELATIONS GIVEN ARE WITH', CHARA)(SKIP,X(10),
      A,X(2),A)
RETURN
END MULTR
```

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APPENDIX C

ROCK PROPERTIES

	Berea Sandstone		Georgia Marble		Missouri Granite	
	Average	Range	Average	Range	Average	Range
Young's Modulus, E, psi	$2.62x10^6$	$2.56x2.68x10^6$	$8.21x10^6$	$7.35\text{-}8.7x10^6$	$9.63x10^6$	$9.34\text{-}9.68x10^6$
Max. Compressive Stress, psi	7402	6866-7877	8749	7093-9979	27,600	26,880-29,540
Max. Tensile Stress t						
Brazilian, psi	368	310-458	440	363-569	1280	1216-1350
Direct, psi	228	210-255	537	479-579	1004	979-1030
Modulus of Rupture, psi	827	762-874	1986	1809-2123	-	-
Apparent Porosity, %	15.6		0.48		0.58	
Specific Gravity	2.11	2.09-2.13	2.68		2.15	
Density, lbs/ft^3	131.7		167.2		134.2	
Water Content, %	0.113		0.036		0.042	
Degree of Saturation, %	1.5		20.0		15.4	