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Cutting Experiments Using a Rotating Water Jet in a Borehole



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CUTTING EXPERIMENTS USING A ROTATING WATER JET IN A BOREHOLE

by

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and Jacob N. Frank⁴

ABSTRACT

An experimental hydraulic jetting device intended to operate in a 16-in-diam borehole was designed, fabricated, and used to cut coal and simulated coal samples. This device consisted of two 0.107-in-diam nozzles that rotated in a plane perpendicular to a 50-inch length of high-pressure tubing. Experiments were also conducted with stationary jets issuing from a single 0.142-in-diam nozzle. Numerous experiments were performed using systematic variations of jet parameters coupled with assessments of cutting rates.

These Bureau of Mines tests showed that when operated at 4,000 psi pressure and a 40-gpm flow rate (1) the device can fragment coal up to a distance of 8 feet from the nozzle, (2) 4,000-psi jets cut more effectively than lower pressure jets with the same nozzle diameter, (3) stationary jets do not cut as effectively as moving jets, (4) interkerf breaking occurs when the kerf spacing is less than 2 inches, and (5) if the kerfs are spaced $<1/2$ inch, the jet is deflected and thereby reduces cutting effectiveness.

INTRODUCTION

The breaking action of a high-pressure water jet in a borehole shows considerable promise in a number of industrial applications. In the petroleum industry, high-powered (740 hydraulic horsepower) jet cutting tools are used in boreholes to clear coking towers (14).⁵ Hydraulic borehole mining has been of interest for many years in the United States. In 1932, a patent was issued for an invention relating to the recovery of minerals by borehole mining (5).

More recent patents have been issued for under-reaming wells with hydraulic jets (8), for mining granular ores through boreholes (4), and for a subterranean slurry mining apparatus (15).

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⁵Underlined numbers in parentheses refer to items in the list of references preceding the appendixes.

Borehole mining in a production setting was initiated in the United States in 1961 by the American Gilsonite Co. at Bonanza, Utah (7). Vertical veins of the solid hydrocarbon "gilsonite" were extracted by a vertical rotary reaming method (3). In this method a series of 6- to 8-in-diam pilot holes were drilled from the surface 20 feet apart to intersect a drift driven in the vein. A drill rig containing pressure pipe terminated with a reaming head consisting of two opposed 0.375-in-diam nozzles was used to ream the holes from the drift up to the surface. The breakage was accomplished with 2,200-psi, 185-gpm jets rotated at 1 rpm while being raised 40 to 120 fph.

In 1962, Coleman Collieries Ltd. conducted hydraulic borehole mining of a pitching coal seam at its Vicary Creek coal mine, near Coleman, Alberta, Canada, using a technique similar to that employed by the American Gilsonite Co. (6). During September and October 1963, 14,100 tons were produced with an average production of 32 tph. Maximum cutting time of an average day was 20 hours with a daily production of 640 tons.

A general description of borehole mining has been published (9) that includes a description of the equipment and techniques developed to mine subsurface mineral deposits hydraulically through boreholes. This paper discusses borehole mining of consolidated sandstones, weathered limestones, and laminated shales at depths of 350 feet and at extraction rates of up to 1 cu yd/min.

Since 1950, hydraulic jets have been used in decoking operations in refineries. Typically, a tank 100 feet high and 20 feet in diameter is filled with crude oil and heated to drive off the lighter fraction. A residue of coke fills all except the upper 15 feet of the tank, and a hydraulic borehole fragmentation process clears the tank of this solid coke. First, a 4-ft-diam pilot hole is drilled the length of the tank using a boring tool composed of a cutting edge and multiple boring nozzles (3/8 inch in diameter) at the end of 100 feet of 5-in-diam drill stem. The drill stem is rotated by an air motor coupled to a swivel joint and supported by a traveling cross head. After the pilot hole is drilled, the bit is replaced with a hydraulic cutting tool that fragments the remainder of the coke; the fragments fall through a hole at the base of the tank. Water is supplied to the cutting tool at 1,800 psig at the rate of 700 gpm. A typical decoking operation produces about 13,000 tons of coke per day using this process.

Hydraulic jets are also used in oil well boreholes for such applications as well stimulation, cutting slots or windows in the well casing, and cutting pipe for removal. In most of these applications, an abrasive, such as sand, is mixed with a fluid and forced under pressure through nozzles to attain a high jet velocity.

High-pressure jetting equipment is also used in industrial cleaning applications. The Halliburton Hydraulic Line Mole (11)⁶ is a remotely controlled automated pipeline and heat exchanger cleaner. The system uses a

⁶Reference to specific manufacturers or trade names does not imply endorsement by the Bureau of Mines.

hydraulic jetting head attached to a high-pressure flexible hose. The apparatus is placed in the line to be cleaned, and its multiple jets blast a volume of 100 to 300 gpm at pressures up to 5,000 psi to flush out deposits. This system operates in 4- to 36-in-ID lines and has been used in process piping, waste conduits, and many other types of transmission piping.

Although water jet cutting in boreholes is technologically important, the literature contains no systematic study of the jet parameters that affect jet cutting in boreholes. This Bureau of Mines Report of Investigations describes such a study in an attempt to set forth the critical values of jet parameters that optimize jet cutting in boreholes. This report describes the design and fabrication of an experimental borehole jet cutting device that was used to conduct cutting experiments on coal and on composite concrete-straw samples. These experiments consisted of a systematic variation of jet parameters and an assessment of specimen damage and removal rates.

EQUIPMENT DESIGN AND FABRICATION

Hydraulic System

An experimental borehole device was designed to be used in conjunction with a Wilson-Snyder Model 326 P triplex pump (fig. 1) to perform the jet cutting experiments in a 16-in-diam borehole. This pump is rated at 125 hp and is capable of producing a flow of 40 gpm at 4,500 psi stagnation pressure. The theoretical hydraulic power is computed from the following relationship

$$P = \frac{pQ}{1,714} \quad (1)$$

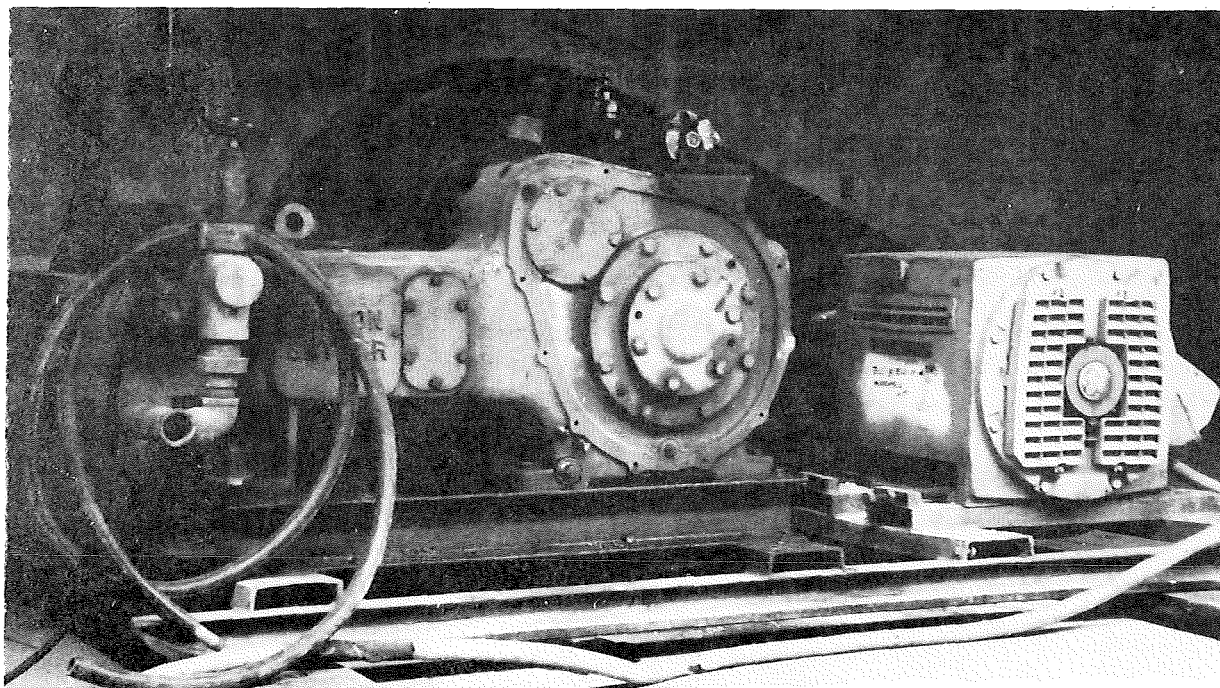


FIGURE 1. - Wilson-Snyder pump.

where P = theoretical hydraulic horsepower,

p = gage pressure in pounds per square inch,

and Q = flow rate in gallons per minute.

The pump is thus capable of delivering approximately 105 hydraulic horsepower.

The Wilson-Snyder pump is of the fixed displacement type where the stagnation pressure depends upon the resistance to the flow. In the present application, this resistance is supplied mainly by a nozzle, which is merely a small outlet through which the fluid is driven by the pump. For a given nozzle, additional variation in pressure can be obtained by bypassing some of the pressurized fluid back to the reservoir. Bypassing fluid is permissible for an experimental program, but because of the excessive heat generation as a result of decompression of fluid, bypassing is not normally recommended, and pumps are either run at their full capacity or they are capable of variable displacement.

The experimental program required an apparatus that passed the pump discharge through either one of two nozzles. The flow velocity passing through the nozzle was calculated to determine the required nozzle exit diameters. The appropriate Bernoulli energy conservation equation, relating velocity and pressure for steady flow, is

$$p_a + \frac{\rho V^2}{2} + p_e = p_o, \quad (2)$$

where p_a = atmospheric pressure,

ρ = liquid density,

V = jet velocity,

p_e = pressure loss between pump exit and nozzle exit,

and p_o = stagnation pressure.

The atmospheric pressure, p_a , and the pressure loss, p_e , are negligible when compared with the stagnation pressure, and so the jet velocity may be approximated by

$$V = (2p_o / \rho)^{\frac{1}{2}}. \quad (3)$$

For a flow with stagnation pressure 4,500 psi and with density of water about 1.93 slugs/cu ft the velocity is 819 fps. The correct nozzle exit area is chosen to accommodate the flow rate and velocity according to the equation

$$Q = 1/4 \pi d^2 V, \quad (4)$$

where Q = flow rate in cubic feet per second,

d = nozzle exit diameter in feet,

and V = jet velocity in feet per second.

Using this relationship, the nozzle diameter appropriate to a flow of 40 gpm was 0.142 inch for one nozzle and 0.1007 inch for two nozzles. The chosen nozzle had a 13° conical taper from the incoming conduit with a straight section length of three nozzle outlet diameters (3D). This type of nozzle has been reported on favorably by Leach and Walker (12). The nozzle, shown in figure 2, was constructed from beryllium-copper and heat treated after machining to minimize wear from the action of the fluid. A profilometer (1-2) was used to measure the roughness of the flow channel of these nozzles. The average of 768 roughness determinations was $4.00 \pm 0.33 \mu\text{m}$ at the 95-pct confidence level.

Borehole Device

The design criteria for the experimental borehole device were as follows:

1. The borehole device should be capable of rotating a jet about a vertical axis, perpendicular to the longitudinal axis of jet at rotation speeds from 1/4 to 10 rpm.
2. The jet should be movable in a vertical direction either continuously or in discrete steps.

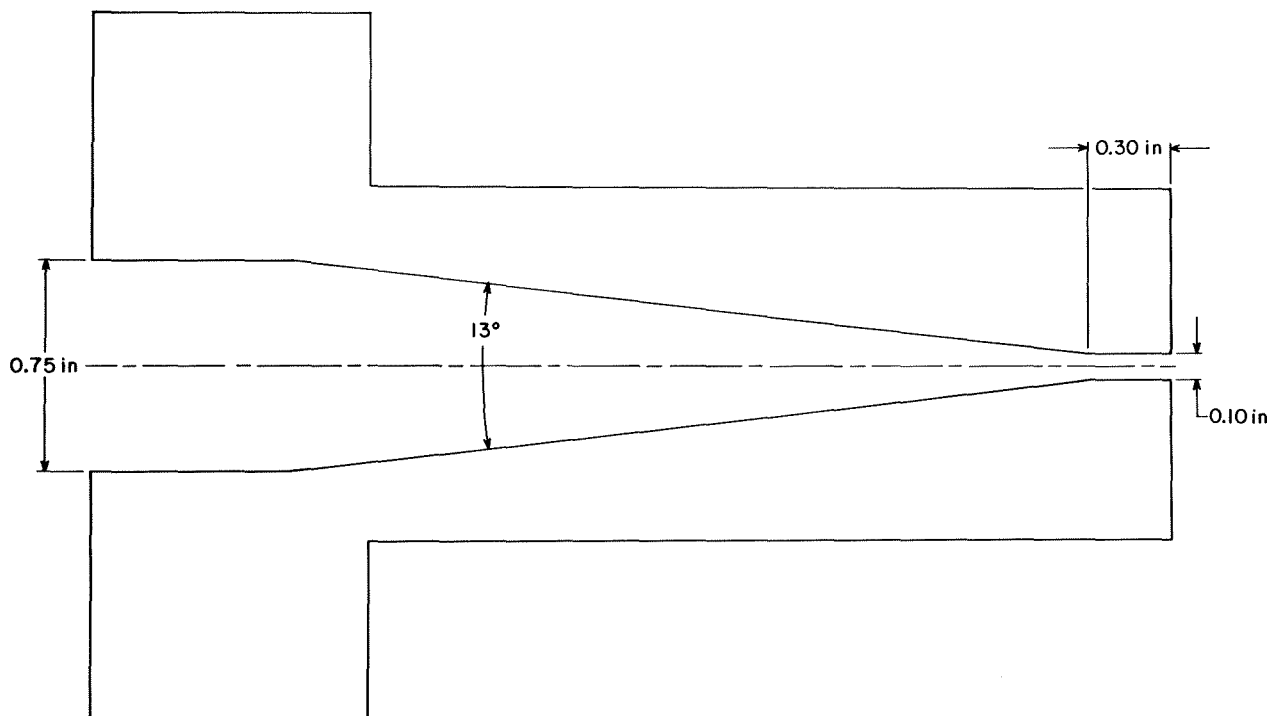
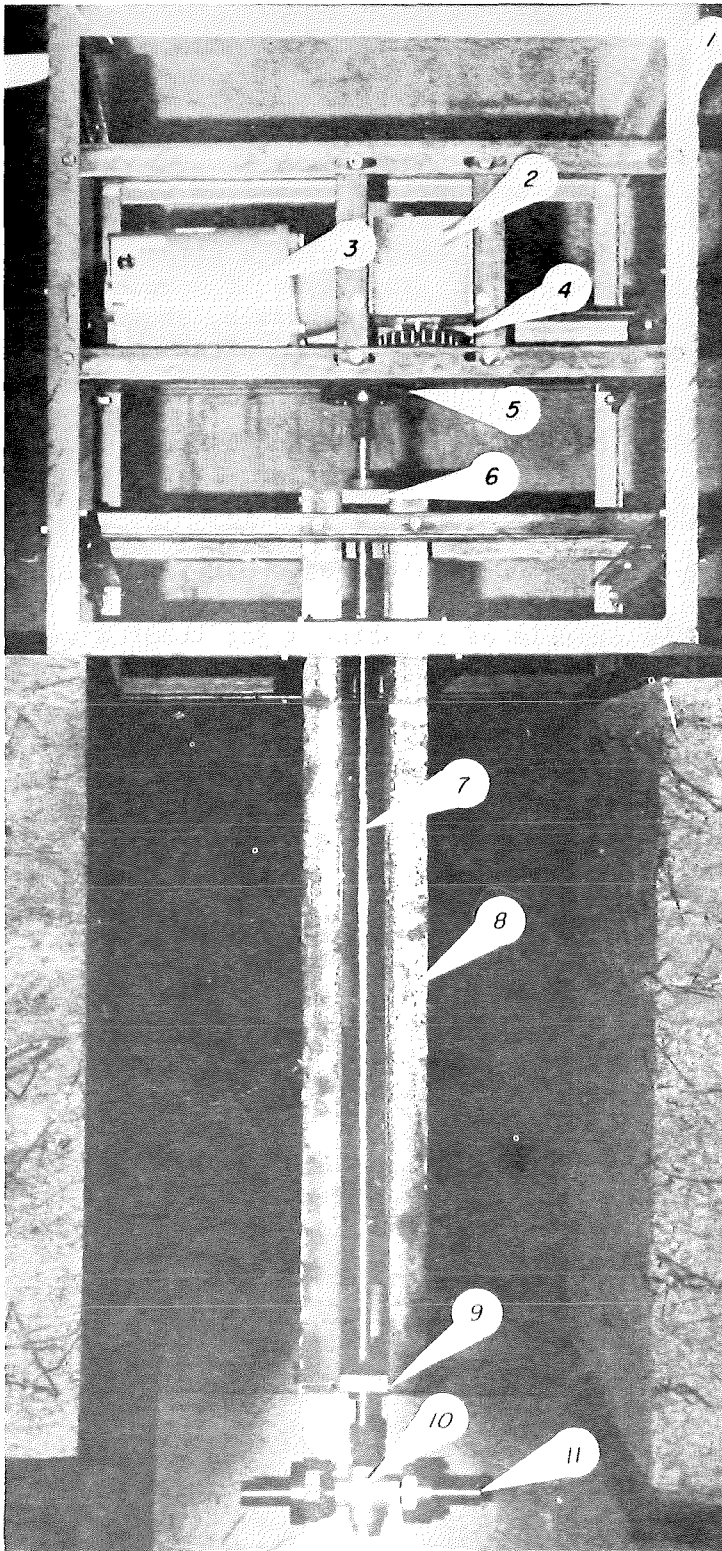


FIGURE 2. - Section view of nozzle.



KEY

- 1 Cubic frame
- 2 Gear box reducer
- 3 DC motor
- 4 No. 40 chain on sprocket
- 5 Swivel
- 6 Sleeve
- 7 High-pressure conduit
- 8 Cantilever frame
- 9 Sleeve
- 10 Pipe cross
- 11 Nozzle

FIGURE 3. - Borehole device.

3. The borehole device should be able to cut in a borehole 3 feet in length and 16 inches in diameter.

The device was supported in a cubic frame constructed from 30-inch length of 1-1/2- by 1/4- by 1/4-inch angle steel (fig. 3). This frame gave the rigidity required to support and move the device and was a lattice on which the rotation mechanism, high-pressure conduit, and nozzles were anchored. Vertical motion of the nozzle was provided by attaching the frame to a forklift or an overhead electric hoist.

Nozzle rotation was made possible by connecting the nozzle high-pressure conduit ensemble to a 3/4-inch Chicksan swivel rated at 6,000 psi with a resisting torque of 125 in-lb. The swivel was driven by a 1/4-hp, dc motor equipped with a variable-speed motor control.

To achieve low rotational speeds, the motor output was routed through a 100:1 gearbox reducer. The output shaft of this reducer was fitted with a sprocket; another sprocket was attached to the swivel and the conduit-nozzle ensemble by a No. 40 chain. The 1/4-hp, dc motor was able to overcome the friction losses in the swivel and gearbox.

Between the frame and the pump was a 3/4-in-diam flexible hose, rated at 5,000 psi working pressure, that could follow the frame during vertical motions. This hose was connected by an elbow and nipple to the fixed end of the swivel. The rotating end of the swivel was connected by a 60-inch length of 0.75-in-OD, 0.51-in ID seamless tubing with a working pressure of 4,500 psi. This tubing was supported at both ends by self-lubricating sleeves that protect the tubing from the reaction of the sprocket chain and guard against possible unbalanced reaction of the nozzles. The sleeve located near the nozzle was supported by a 42-inch cantilever frame of four 2-1/2- by 2-1/2- by 1/4-inch angle steel sections. This cantilever frame reduced bending moments in the tubing caused by unequal nozzle loads and protected the tubing-nozzle suspension from damage during operation and handling. The lower end of the tubing was connected to a pipe cross with 3/4-in-diam ports. The nozzles were fitted to the two ports perpendicular to the incoming tubing (to oppose one another). The remaining port can be fitted with a burst disk to guard against the plugging of the nozzle.

The flow rate of water through the borehole mining device was measured by weighing the water discharged into a 55-gal drum in a known time interval. This measured flow rate was used to calculate the flow velocity, the Reynolds number (Re), and the frictional head loss (h_f) in each section of the flow path. These results are listed in table 1 along with form losses in the elbow and pipe cross, and losses at the entrance and exit of the high-pressure tubing as a result of contraction and expansion of flow. The head losses in the nozzles was assumed at 5 pct of the velocity head at the nozzle exit while the frictional losses in the conduit were calculated using the Darcy-Weisbach (13) relationship:

$$h_f = f \frac{L}{D} \frac{v^2}{2g}, \quad (5)$$

where f is the friction factor,

L is the length of the flow path,

D is the diameter of the conduit,

and $v^2/2g$ is the velocity head.

TABLE 1. - Pressure and head losses in borehole mining apparatus

Flow path	Pressure, psi	Flow volume, gpm	Veloc- ity, fps	Reynolds number	Pressure loss, psi	Head loss, feet
21 feet of high-pressure hose (3/4 in ID).	{ 1,000	18.61	13.35	68560	8.06	18.60
	{ 2,000	23.32	16.74	85969	11.40	26.32
	{ 3,000	28.26	20.29	104200	16.76	38.67
	{ 4,000	32.16	23.09	118580	20.49	47.29
1-foot length of nipple and swivel (3/4 in ID).	{ 1,000	18.61	13.35	68560	.38	.88
	{ 2,000	23.32	16.74	85969	.60	1.39
	{ 3,000	28.26	20.29	104200	.80	1.84
	{ 4,000	32.16	23.09	118580	.98	2.25
50 inches of high-pressure tubing (0.51 in ID).	{ 1,000	18.61	29.57	103264	10.38	23.96
	{ 2,000	23.32	37.07	129455	15.41	35.56
	{ 3,000	28.26	44.92	156869	22.63	52.22
	{ 4,000	32.16	51.14	178590	27.61	63.71
Elbows (3/4 in ID).....	{ 1,000	18.61	13.35	68560	1.08	2.49
	{ 2,000	23.32	16.74	85969	1.70	3.91
	{ 3,000	28.26	20.29	104200	2.49	5.75
	{ 4,000	32.16	23.09	118580	3.23	7.45
Pipe cross (3/4 in ID).....	{ 1,000	18.61	13.35	68560	2.10	4.84
	{ 2,000	23.32	16.74	85969	3.30	7.61
	{ 3,000	28.26	20.29	104200	4.85	11.19
	{ 4,000	32.16	23.09	118580	6.28	14.49
Nozzle A.....	{ 1,000	9.31	375.02	258590	47.32	109.19
	{ 2,000	11.66	469.43	323698	74.14	171.09
	{ 3,000	14.13	568.87	392257	108.88	251.25
	{ 4,000	16.08	647.37	446386	141.00	325.38
Nozzle B.....	{ 1,000	9.31	375.02	258590	47.32	109.19
	{ 2,000	11.66	469.43	323698	74.14	171.09
	{ 3,000	14.13	568.87	392257	108.88	251.25
	{ 4,000	16.08	647.37	446386	141.00	325.38
Contraction between swivel and tubing.	{ 1,000	-	-	-	1.00	2.31
	{ 2,000	-	-	-	1.57	3.63
	{ 3,000	-	-	-	2.31	5.33
	{ 4,000	-	-	-	2.99	6.90
Expansion between tubing and pipe cross.	{ 1,000	-	-	-	4.68	10.81
	{ 2,000	-	-	-	7.36	16.99
	{ 3,000	-	-	-	9.99	23.05
	{ 4,000	-	-	-	14.00	32.33

The measured flow rate was also used to calculate the coefficient of discharge (C) through the borehole device using the relation (10)

$$C = \frac{Q}{A\sqrt{2gH}}, \quad (6)$$

where Q is the measured flow rate,

A is the cross-sectional area of the nozzle orifice,

and H is the total head causing flow.

This coefficient is tabulated in table 2 for pressures of 1,000, 2,000, 3,000, and 4,000 psi.

TABLE 2. - Coefficient of discharge (C)
through borehole device

Pressure, psi	Discharge, gpm	C
1,000	18.61	0.97
2,000	23.32	.86
3,000	28.26	.85
4,000	32.16	.84

The reaction force for a single 4,500-psi, 20-gpm jet was calculated from the relationship expressing the rate of change of momentum through the nozzle

$$F = \rho VQ = 2 P_0 A, \quad (7)$$

where F is the reaction force on the nozzle,

ρ is the liquid density,

V is the jet velocity,

Q is the discharge,

P_0 is the stagnation pressure,

and A is the area of the nozzle outlet.

The force was 72 pounds for each nozzle. The two oppositely directed jets yielded a negligible net reaction force and moment. These reactions are not exactly zero because of inevitable misalignment and imperfect symmetry in the nozzles and pipe cross. The assembled device weighed less than 400 pounds and has a range of angular velocities from approximately 0.25 to 10 rpm.

SAMPLE PREPARATION

Coal and composite concrete-straw samples were the test specimens. Concrete-straw composites were used because it was impractical to obtain coal

specimens large enough to fulfill the geometrical requirements of some of the tests. The concrete-straw composites had fragmentation properties simulating those of coal; that is, the concrete mixture was chosen to give a cured compressive strength of 2,500 psi, and the layers of straw simulated horizontal planes of weakness. These samples were cast into 3-foot cubes with a 16-inch diam hole through two opposing faces. The blocks were made from a 1:3.5:5 mixture of concrete to sand and gravel. Layers of straw were placed at 3-inch intervals in a plane perpendicular to the long dimension of the borehole. The blocks had a unit weight of 130 lb/cu ft when cured. The coal samples, collected in Illinois, were irregular blocks approximately 1 foot on a side and had an average Shore hardness of 37. The coal blocks, encased on five sides with concrete, were used to test the efficiency of jet cutting at varying standoff distances.

EXPERIMENTAL PROCEDURE AND RESULTS

The hydraulic jet experiments were divided into four phases that examined different aspects of the jet cutting process:

1. Hydraulic jet force measurements as a function of standoff distance,
2. Cratering tests with stationary jets,
3. Circular slot cutting tests with rotating jets, and
4. Traversing and rotating jet breakage tests.

Hydraulic Jet Force Measurements as a Function of Standoff Distance

The objective of this phase was to assess and suggest methods for minimizing jet divergence through measurements of force exerted on a flat plate by jets of various compositions. The effect of the addition of low concentrations of long chain polymeric compounds on the coherency of water jets was determined by measuring the rate of decrease of force exerted on a flat plate by a jet with increasing standoff distance. Maximizing the standoff distance at which effective cutting occurs is the most important factor in determining the economic feasibility of hydraulic borehole mining because the amount of material removed from a borehole increases as the square of the maximum distance at which the jets can fragment rock.

The jet force was measured with a 300-pound capacity load cell with a 4-in-sq hardened steel loading surface attached to a sensory element. The force was read out on a commercially available digital strain indicator calibrated in pounds and accurate to the nearest tenth of a pound.

Two additives, commercially available under the trade names Revert and Polyox WSR-301, were tested. Revert (manufactured by the Johnson Div. of Universal Oil Products Co., St. Paul, Minn.) is a fluid additive used in lieu of native clay or bentonite in conventional rotary drilling of water wells.

It is essentially a mixture of guar gum with methylene blue having the following composition:

<u>Component</u>	<u>Wt-pct</u>
Galactomannan.....	78 -82
Moisture.....	10 -13
Protein.....	4
Ash.....	.5
Methylene blue.....	.1
Crude fiber.....	5.0- 2.0

Polyox WSR-301, a water-soluble resin, is composed of a nonionic polyethylene oxide homopolymer with a molecular weight of approximately 4,000,000. It is manufactured by Union Carbide Corp. and is widely used to reduce hydrodynamic drag.

Each of these additives was received in powdered form. A 1-pct solution of these additives was prepared using the following procedure outlined in stepwise fashion:

1. A quantity of powder (4.75 pounds) was placed in a bucket. It was necessary to make a slurry with 500 ml of isopropyl alcohol if Polyox was being mixed in order to facilitate solution of the Polyox powder. This was not necessary when preparing Revert water solutions.
2. A 55-gal drum was two-thirds filled with water. An immersion heater was used to heat the water if Polyox solutions were being prepared. Hot water is not required when preparing Revert solutions.
3. A Lighten Model NC4 mixer was used to agitate the water in the drum.
4. The Polyox slurry or the Revert powder was added slowly to the water, and mixing proceeded until the powder was in solution. Typically the Revert takes 30 min to completely dissolve whereas 24 hours of mixing is required to get all the Polyox powder into solution.
5. A quantity (400 ml of 37 pct formaldehyde) was added to the Revert mixture to retard the growth of bacteria. This was not necessary when mixing Polyox solutions.
6. The drum is filled with water to make up a 1-pct solution.
7. This 1 percent solution was diluted with water in a 110-gal holding tank to a prescribed concentration.

A 110-gal holding tank was used so that the additive solutions could be made in premixed batches. Most tests with tapwater jets were run from the same tank to allow direct comparison with the results obtained using additives. A 40-gpm centrifugal pump was used to provide a steady flow of fluid from the tank to the intake of the Wilson-Snyder pump.

A single nozzle (0.142 in diam) setup tested the ability of the polymeric additives to collimate water jets. Since the entire discharge of the pump was routed through this nozzle, the area of the nozzle outlet was twice that of the individual nozzles on the borehole device where the pump discharge was routed through two identical nozzles. The test solutions were prepared by mixing the additive with tapwater in the tank. The load cell was initially 1.5 feet directly in front of the nozzle so that the jet impinged normally on the flat force plate; jet force measurements were replicated three times at gage pressures of 1,000, 2,000, 3,000, and 4,000 psi. This procedure was repeated for standoff distances of 3.0, 6.0, 9.0, and 12.0 feet. The average values for all force tests for each fluid are presented in table 3; the values of all force tests are in appendix A.

These data show that jets containing some concentrations of polymeric additives gave consistently higher force readings than plain tapwater jets only at higher pressures and longer standoff distances; that is, the lower right-hand portion of table 3. This is understandable in view of the fact that jet divergence increases with pressure and standoff distance. Thus, at higher pressures and standoff distances, the tapwater jets diverge markedly, dissipating a high proportion of their energy through viscous interaction with the air. The energy remaining in the jet is thereby reduced resulting in lowered impact forces. The higher forces shown in the lower right portion of the table are interpreted as the result of the polymeric additives acting to keep the jet collimated and thus keeping more of the water in the core of the jet where its energy can be deposited on the force plate resulting in higher impact forces.

Table 3 shows that jets composed of a solution of 0.1 pct Revert in tapwater gave the highest impact forces suggesting that jets of this concentration are more effective in collimating the jet than are the other solutions tested.

Force plate measurements as a function of standoff distance were also made for the dual nozzle borehole device. These tests employed only tapwater. Each nozzle was tested separately at standoff distances from 2 to 96 inches at static pressures of 1,000, 2,000, 3,000, and 4,000 psi. Relatively short standoff distances were used since the device was designed to be used in 16-in-diam boreholes where the initial distance before cutting was of the order of 2 inches. The tests were performed for both nozzles to determine whether they produced identical forces at a given static pressure.

The results, shown in table 4 for nozzles A and B, show that the forces produced by jets from nozzle B are consistently higher than those from A at static pressures above 2,000 psig. This difference can be explained in terms of the observation that at a standoff distance of 96 inches the jet from nozzle B was about 3 inches lower than the jet from nozzle A. This was noted because the load cell was placed at the same location for each test and nozzle A was compared with nozzle B simply by rotating the nozzles through 180°. The relative offset of jets A and B indicated that the nozzle axis was not precisely normal to the pivotal axis down the length of the device and probably accounted for the difference in the jet forces measured.

TABLE 3. - Average hydraulic jet forces for solutions tested

Standoff distance, feet	Hydraulic jet fluid	Nozzle pressure, psig			
		1,000	2,000	3,000	4,000
1.5	Tapwater (line).....	34.2	64.8	96.0	126.0
	Tapwater (tank).....	33.6	66.8	103.0	128.8
	0.05-pct Revert solution.....	35.7	65.2	100.6	134.2
	0.1-pct Revert solution.....	36.5	66.1	110.3	137.3
3.0	Tapwater (line).....	31.7	64.0	93.2	122.7
	Tapwater (tank).....	33.2	63.8	96.8	123.9
	0.05-pct Polyox solution.....	34.9	67.3	92.3	106.8
	0.05-pct Revert solution.....	32.8	61.7	93.7	127.4
	0.1-pct Polyox solution.....	36.1	67.3	97.0	126.7
	0.1-pct Revert solution.....	32.4	62.8	99.0	130.1
	0.2-pct Polyox solution.....	32.4	63.6	97.6	115.6
	0.2-pct Revert solution.....	32.1	61.4	89.5	119.8
6.0	0.3-pct Polyox solution.....	33.0	66.2	92.9	114.4
	Tapwater (line).....	28.0	55.6	81.6	104.8
	Tapwater (tank).....	29.3	56.4	86.4	107.9
	0.05-pct Polyox solution.....	25.7	56.0	87.7	98.9
	0.05-pct Revert solution.....	27.7	56.5	87.2	116.2
	0.1-pct Polyox solution.....	31.8	61.2	87.2	115.1
	0.1-pct Revert solution.....	27.2	48.8	93.0	122.8
	0.2-pct Polyox solution.....	29.0	56.4	85.0	105.7
9.0	0.2-pct Revert solution.....	26.4	53.1	83.9	114.2
	0.3-pct Polyox solution.....	23.4	54.2	77.5	80.9
	Tapwater (line).....	25.2	45.2	64.2	84.6
	Tapwater (tank).....	25.0	46.0	69.1	80.8
	0.05-pct Polyox solution.....	15.6	41.7	60.1	53.2
	0.05-pct Revert solution.....	20.6	49.7	77.3	97.1
	0.1-pct Polyox solution.....	24.9	54.6	76.7	88.9
	0.1-pct Revert solution.....	22.4	43.5	71.3	100.4
12.0	0.2-pct Polyox solution.....	20.7	39.6	59.7	78.1
	0.2-pct Revert solution.....	18.6	31.0	54.6	78.7
	0.3-pct Polyox solution.....	18.9	32.6	32.0	53.1
	Tapwater (line).....	19.5	34.7	47.2	57.9
	Tapwater (tank).....	18.9	33.5	47.3	59.3
	0.05-pct Revert solution.....	12.6	28.1	57.9	74.7
	0.1-pct Polyox solution.....	13.6	39.1	65.4	74.0
	0.1-pct Revert solution.....	14.2	22.3	46.3	78.3
12.0	0.2-pct Polyox solution.....	9.7	21.7	48.3	53.5
	0.2-pct Revert solution.....	15.4	22.6	36.7	52.7
	0.3-pct Polyox solution.....	10.7	20.7	27.6	33.7

TABLE 4. - Hydraulic jet forces from the two nozzles
on the borehole cutting device

Standoff distance and nozzle	Nozzle pressure, psig				Standoff distance and nozzle	Nozzle pressure, psig			
	1,000	2,000	3,000	4,000		1,000	2,000	3,000	4,000
2.0 inches:					28.0 inches:				
A	13.4	25.9	41.0	56.1	A	12.7	24.8	38.7	51.5
A	13.2	25.3	39.6	56.8	B	13.6	26.4	42.5	57.7
B	13.5	27.7	43.6	57.6					
4.0 inches:					36.0 inches:				
A	13.5	25.6	11.5	56.1	A	11.5	22.1	33.2	44.8
A	12.8	26.3	47.9	56.4	A	12.3	23.4	34.1	47.0
B	15.3	29.4	45.5	61.0	A	13.0	27.5	43.5	56.3
8.0 inches:					A	13.4	26.8	42.9	56.3
A	13.0	25.6	41.5	54.8	A	13.3	27.9	43.9	56.7
A	13.0	26.2	40.9	54.3	B	13.8	25.8	41.1	55.2
B	15.8	29.5	45.9	61.0	B	13.5	27.0	40.7	55.0
12.0 inches:					B	14.0	26.9	44.1	59.6
A	14.5	29.2	43.7	59.2	B	14.6	28.1	44.4	60.4
A	12.9	25.7	41.8	54.6	48.0 inches:				
A	15.0	29.4	45.0	60.2	A	12.0	25.0	37.5	52.5
B	14.5	27.4	42.3	58.9	A	13.1	25.3	38.3	52.7
B	14.7	28.3	45.5	61.2	B	13.3	24.7	39.5	55.3
B	15.2	29.0	45.9	62.4	B	13.2	25.2	39.1	54.9
20.0 inches:					72.0 inches:				
A	13.1	25.6	39.5	52.7	A	11.9	21.8	30.1	43.6
B	13.9	27.5	42.8	56.8	A	12.2	21.3	32.1	42.7
B	13.8	27.3	41.7	57.0	B	10.5	21.7	34.3	45.7
24.0 inches:					B	11.1	20.8	33.7	44.2
A	13.9	26.7	42.6	58.4	96.0 inches:				
A	13.7	28.1	44.0	57.1	A	8.8	15.2	20.3	29.6
B	14.3	27.9	44.7	61.2	A	8.4	14.9	20.4	30.3
B	14.2	27.8	44.2	59.5	B	8.8	17.7	26.9	33.4
					B	8.9	16.8	25.9	34.2

Cratering Tests With Stationary Jets

This phase of the research determined the weight of the broken material removed by a stationary jet impinging onto composite concrete-straw and coal samples, first as a function of the duration of jet impingement (with fixed pressure) and then as a function of stagnation pressure (with the duration fixed). These results were compared with the results of rotating jet circular slot cutting tests, since they represent the special case of rotating jet tests; namely, the case of nonrotation.

Most of the cratering tests were performed in the composite concrete-straw samples. Each series involving the variation of one jet parameter (duration or pressure) was run in the same horizontal plane in the block so that the material properties would be as uniform as possible. Each test in a series was performed at a different location in the horizontal plane of the borehole wall by rotating the nozzles. Rotation was always enough to preclude interaction between craters during successive tests. The device was repositioned between series to different horizontal planes with the same sample. Results from different planes within a given sample are difficult to compare because material properties vary along the length of the hole as the result of horizontal layering. Thus, the raw data (the weight of broken material) must be normalized in order to show trends. The raw data can only be used to establish the maximum and minimum amount of material removed by cratering.

The results of the jet cratering tests are given in table 5, which lists both the raw and the normalized weights of broken material. Normalized values were calculated by dividing the weight removed in a particular test by the weight removed in the first tests of that series. The test number consists of the letter C (denoting cratering test) followed by a series number (each series has a constant test duration or stagnation pressure) and a test run number for the series. The weight removed values represent breakage caused by the two nozzles operating simultaneously.

The cratering test raw data exhibit a high degree of scatter, and trends even in normalized data are difficult to establish. This scatter is probably a reflection of nonhomogeneity, even within layers of the concrete on the scale of the craters. For example, in one test the jet may be striking cement paste, while in the next, it may strike aggregate. As will be seen, less scatter was found in circular slot cutting since the jet hits cement paste, aggregate, voids, and embedded straw; that is, the rotating jet encounters a more representative sample of the entire block. This is in contrast to the cratering tests, which reflected only one of these conditions.

Stationary jet cratering tests were performed in the coal samples to determine the maximum standoff distance at which the borehole device could cut coal. Only nozzle A was used. Tests were run with tapwater and with jets composed of 0.1 pct solution of polyethylene oxide (Polyox) in tapwater. The broken fragments scattered and could not be collected and weighed. Fragments from the samples were collected in an attempt to correlate hardness with the maximum standoff distance at which cratering occurred. The results of these tests are presented in table 6. The test number consists of the letter CC (denoting coal cratering tests), followed by the sample number and the test number for the sample. The tapwater data indicate that, at distances greater than 8 feet, jets formed at stagnation pressures below 2,000 psi cut better than those formed at greater pressures. This is apparently a result of severe jet divergence beyond 8 feet.

An unexpected result was that the addition of 0.1 pct Polyox to tapwater did not improve this situation.

TABLE 5. - Hydraulic jet cratering tests on composite concrete-straw samples

Test	Nozzle pressure, psi	Test duration, sec	Breakage weight, grams	Normalized breakage	Comments
C1-1	4,000	30	14.89	1.00	Series C1 had all test runs in a plane 6 inches below top of block with pressure fixed at 4,000 psi for all tests. Observed water coming out of top of borehole--resulted in lost muck. Forgot collecting screen at bottom of borehole--again water coming out of top. Decided to start new series deeper in borehole and with top covered.
C1-2	4,000	60	6.76	.45	
C1-3	4,000	90	-	-	
C2-1	4,000	30	23.46	1.00	Series C2 had all test runs in a plane 11.5 inches below top of block with pressure fixed at 4,000 psi for all tests.
C2-2	4,000	60	143.6	6.11	
C2-3	4,000	90	86.80	3.69	Do.
C2-4	4,000	120	483.8	20.6	Do.
C2-5	4,000	174	31.71	1.35	Planned on 180-sec test but 110-gal holding tank ran out at 174 sec.
C2-6	4,000	150	256.9	10.9	None.
C3-1	4,000	120	22.17	1.00	Series C3 had all test runs in a plane 20 inches below top of block with duration of tests fixed at 120 sec. Jet hitting on layer discontinuity. Water coming out through side of block, jet going between layers of block.
C3-2	4,000	120	19.90	.90	
C3-3	3,000	120	4.79	.22	
C4-1	4,000	30	26.11	1.00	Series C4 had all test runs in a plane 23.5 inches below top of block with pressure fixed at 4,000 psi for all tests. Water coming out of side of block so moved nozzles to a plane 22 inches from top of block for rest of series.
C4-2	4,000	60	25.52	.98	

TABLE 5. - Hydraulic jet cratering tests on composite concrete-straw samples--Continued

Test	Nozzle pressure, psi	Test duration, sec	Breakage weight, grams	Normalized breakage	Comments
C4-2r	4,000	60	19.78	0.76	Small r denotes repeat test. Nozzles were rotated to give new test surface in borehole.
C4-3	4,000	90	61.16	2.36	Water coming out of side of block but not nearly as much as test C4-2.
C4-4	4,000	120	101.3	3.89	None.
C4-5	4,000	150	129.1	4.95	Do.
C5-1	4,000	120	53.40	1.00	Series C5 had all test runs in a plane 28 inches below top of block with duration of tests fixed at 120 sec.
C5-2	3,000	120	14.89	.28	None.
C5-3	2,000	120	5.07	.095	Do.
C5-4	1,000	120	10.13	.19	Do.
C6-1	4,000	120	243.2	1.00	Series C6 had all test runs in a plane 11.5 inches below top of block with duration of tests fixed at 120 sec.
C6-2	3,000	120	49.31	.20	None.
C6-3	2,000	120	10.29	.042	Do.
C6-4	1,000	120	2.26	.0093	Do.
C7-1	4,000	120	32.58	1.00	Series C7 had all test runs in a plane 17.5 inches below top of block with duration of tests fixed at 120 sec.
C7-2	3,000	120	17.21	.53	None.
C7-3	2,000	120	7.51	.23	Do.
C7-4	1,000	120	1.20	.037	Do.
C8-1	4,000	30	21.45	1.00	Series C8 had all test runs in a plane 22 inches below top of block with pressure fixed at 4,000 psi for all tests.
C8-2	4,000	60	51.45	2.39	None.
C8-3	4,000	90	364.2	17.0	Do.
C8-4	4,000	120	27.99	1.30	Do.
C8-5	4,000	150	88.76	4.14	Do.
C9-1	4,000	30	18.73	1.00	Series C9 had all test runs in a plane 27 inches below top of block with pressure fixed at 4,000 psi for all tests.
C9-2	4,000	60	42.08	2.25	None.
C9-3	4,000	90	23.89	1.28	Do.
C9-4	4,000	120	40.83	2.18	Do.
C9-5	4,000	150	84.06	4.49	Do.

TABLE 5. - Hydraulic jet cratering tests on composite concrete-straw samples--Continued

Test	Nozzle pressure, psi	Test duration, sec	Breakage weight, grams	Normalized breakage	Comments
C10-1	4,000	120	33.94	1.00	Series C10 had all test runs in a plane 11.5 inches below top of block with duration of tests fixed at 120 sec.
C10-2	3,000	120	24.97	.736	None.
C10-3	2,000	120	24.25	.715	Do.
C10-4	1,000	120	4.99	.191	Do.
C11-1	4,000	120	20.76	1.00	Series C11 had all test runs in a plane 17.5 inches below top of block with duration of tests fixed at 120 sec.
C11-2	3,000	120	21.96	1.06	None.
C11-3	2,000	120	11.49	.553	Do.
C11-4	1,000	120	.461	.022	Do.
C12-1	4,000	30	21.76	1.00	Series C12 had all test runs in a plane 22 inches below top of block with pressure fixed at 4,000 psi for all tests.
C12-2	4,000	60	18.85	.866	None.
C12-3	4,000	90	20.84	.959	Do.
C12-4	4,000	120	23.84	1.10	Do.
C12-5	4,000	150	21.54	.990	Do.
C13-1	4,000	30	74.04	1.00	Series C12 had all test runs in a plane 27.5 inches below top of block with pressure fixed at 4,000 psi for all tests.
C13-2	4,000	60	14.42	.195	None.
C13-3	4,000	90	24.98	.336	Do.
C13-4	4,000	120	29.32	.396	Do.
C13-5	4,000	150	44.40	.598	Do.

NOTE.--Series C1 through C5 were conducted on sample 9-4-73 No. 2.
 Series C6 through C9 were conducted on sample 9-24-73 No. 9.
 Series C10 through C13 were conducted on sample 9-10-73 No. 4.

TABLE 6. - Hydraulic jet cratering tests on plane
surface coal samples

Test	Standoff distance, feet	Nozzle pressure, psi	Test duration, sec	Comments
PLAIN TAPWATER				
CC-1-1	8	1,000	30	Shore hardness 20.1 wet and 27.9 dry. Significant crater (about 4 inches in diameter by 1 inch depth).
CC-2-1	12	1,000	30	Shore hardness 28.0 wet and 44.0 dry. Same cutting.
CC-2-2	17	1,000	30	No visible damage.
CC-2-3	17	2,000	30	Do.
CC-2-4	17	3,000	30	Do.
CC-3-1	15	1,000	10	Shore hardness 47.9 wet and 57.1 dry. No visible damage.
CC-3-2	15	2,000	10	No visible damage.
CC-3-3	15	3,000	10	Do.
CC-3-4	12	1,000	10	Flat layered chips removed--no cutting.
CC-3-5	12	2,000	10	Do.
CC-3-6	12	3,000	10	Flat layered chips removed--no cutting. Moved block down to new cutting location.
CC-3-7	9	1,000	10	No visible damage. Moved block down to new cutting location.
CC-3-8	9	2,000	10	No visible damage.
CC-3-9	8	1,000	10	Do.
CC-3-10	8	2,000	10	Do.
CC-3-11	8	3,000	10	Flat layered chips removed--no cutting.
CC-3-12	8	4,000	10	Some cutting--started getting crater.
0.1 PCT POLYOX SOLUTION				
CC-2-5	17	1,000	10	No visible damage.
CC-2-6	17	2,000	10	Do.
CC-2-7	17	4,000	10	Do.
CC-2-8	15	4,000	10	Do.
CC-2-9	12	1,000	10	Do.
CC-2-10	12	2,000	10	Do.
CC-2-11	12	4,000	10	Do.
CC-2-12	10	1,000	10	Do.
CC-2-13	10	2,000	10	Possible damage--or chips removed.
CC-2-14	10	2,000	10	Moved block so jet hit at new location. No visible damage at same pressure as test 9.
CC-2-15	10	3,000	10	Minute crater. Chips removed.
CC-2-16	10	4,000	10	Chips removed.
CC-2-17	8	1,000	10	Several craters started.
CC-2-18	8	2,000	10	Surface appears pitted, more cratering.
CC-2-19	8	4,000	10	Large crater produced--definite cutting.

Circular Slot Cutting With Rotating Jets

This phase of the work determined the effects of jet traverse speed, pressure, and duration (the time jets are striking the target) on the cutting rate in composite concrete-straw samples for the borehole jet cutting system. The testing sought to establish the optimum rotational speed. Above this optimum speed, the jet passes over the cutting surface too quickly to cut efficiently, and below the optimum speed, the jet spends so much time in a given area that the jet impact is cushioned by water in the kerf.

In most of the circular slot cutting test series, the rotational speed and test duration were fixed while separate tests were run at 1,000, 2,000, 3,000, and 4,000 psig pressure. A different horizontal plane in the sample was required for each test. The vertical distance between the tests was chosen to preclude interaction between successive test slots.

In general, the slot cutting tests produced more broken material than was obtained from corresponding cratering tests. In addition, the broken particles were smaller and more uniform. The more efficient cutting action in the moving jet liberated a large amount of sand from the concrete-straw test blocks. This sand passed through the muck collecting screen located at the bottom of the test borehole and was collected separately and weighed. The percentage of sand weight was prorated for each run by dividing test run muck weight by the total muck weight for all runs completed before sand collection and multiplying by 100. The gravel/cement muck weights, the weight of sand added, and the total product weight for each slot-cutting run are given in appendix B. Included in table B-1 are results of tests (designated with RR) involving traversing and rotating jets that are described in the following section. The test number consists of an R denoting a rotating jet or an RR denoting a rotating jet ridge test, the series number, and a test run number in a given series. A lowercase r at the end of the test number denotes "repeat."

The test conditions and results for the circular slot cutting tests are given in table 7. As in appendix B, the test number consists of an R denoting a rotating jet, the series number, and the run number. As in the cratering tests results (table 6), the normalized cutting weight for a given test is based on the first test of the series.

TABLE 7. - Hydraulic jet circular slot cutting tests on composite concrete-straw borehole samples

Test	Nozzle pressure, psi	Rotational speed, rpm	Test duration, sec	Breakage weight, grams	Normalized weight of cuttings	Comments
R1-1	4,000	2.5	120	3,641.4	1.00	Series R1 had test durations fixed at 120 sec for all tests. Rotational speeds 2.0 rpm with zero nozzle pressure. R1-1 in a plane 11.5 inches down borehole.
R1-2	3,000	3.0	120	1,372.7	.377	R1-2 in a plane 15.5 inches down borehole.
R1-3	2,000	NAp	NAp	NAp	NAp	R1-3 in a plane 18 inches down borehole. Forgot to position collecting screen.
R1-3r	2,000	2.5	120	886.7	.243	R1-3r in a plane 20.5 inches down borehole.
R1-4	1,000	2.0	120	288.8	.079	R1-4 in a plane 22 inches down borehole.
R2-1	4,000	3.8	120	1,120.9	1.00	Series R2 had test durations fixed at 120 sec for all tests. Rotational speed 3.44 rpm with zero nozzle pressure. R2-1 run in a plane 25.3 inches down borehole.
R2-2	3,000	4.7	120	1,032.2	0.921	R2-2 in a plane 27 inches down borehole.
R2-3	2,000	4.8	120	593.4	.528	R2-3 in a plane 30 inches down borehole.
R2-4	1,000	4.0	120	95.7	.085	R2-4 in a plane 32 inches down borehole.
R3-1	4,000	2.0	120	667.5	1.00	Series R3 had test durations fixed at 120 sec for all tests. R3-1 in a plane 13.5 inches down borehole.
R3-2	3,000	2.0	120	491.2	.737	R3-2 in a plane 15 inches down borehole.
R3-3	2,000	2.0	120	294.2	.441	R3-3 in a plane 16.75 inches down borehole.
R3-4	1,000	2.0	120	1,285.9	1.93	R3-4 in a plane 19.25 inches down borehole.

NAp--Not applicable.

TABLE 7. - Hydraulic jet circular slot cutting tests on composite concrete-straw borehole samples--Continued

Test	Nozzle pressure, psi	Rotational speed, rpm	Test duration, sec	Breakage weight, grams	Normalized weight of cuttings	Comments
R4-1	4,000	0.5	120	1,673.2	1.00	Series R4 had test durations fixed at 120 sec for all tests. R4-1 in a plane 22 inches down borehole.
R4-2	3,000	.5	120	1,067.5	.637	R4-2 run in a plane 25.25 inches down borehole.
R4-3	2,000	.5	120	1,122.5	.670	R4-3 in a plane 29 inches down borehole.
R4-4	1,000	.5	120	166.2	.099	R4-4 in a plane 31 inches down borehole.
R5-1	4,000	NAp	NAp	NAp	NAp	Series R5 had test durations fixed at 120 sec for all tests. R5-1 in a plane 12 inches down borehole. Forgot collecting screen--no cuttings caught.
R5-1r	4,000	1.0	120	1,444.6	1.00	R5-1r in a plane 14 inches down borehole.
R5-2	4,000	.6	120	1,352.8	.937	R5-2 in a plane 16 inches down borehole.
R5-3	4,000	.3	120	1,266.3	.875	R5-3 in a plane 16 inches down borehole.
R5-4	4,000	2.0	120	1,568.9	1.082	R5-4 in a plane 19 inches down borehole.
R6-1	3,700	2.0	120	1,720.3	1.00	Series R6 had test durations fixed at 120 sec for all tests. R6-1 ran in a plane 23 inches down borehole.
R6-2	3,700	1.0	120	1,122.9	.653	R6-2 ran in a plane 26 inches down borehole.
R6-3	3,700	NAp (0.5)	NAp (120)	NAp (762.0)	NAp	R6-3 in a plane 28.5 inches down borehole. Muck collecting screen moved.
R6-3r	3,700	.5	120	819.3	.475	R6-3r in a plane 30.5 inches down borehole.
R6-4	3,700	.2	120	598.7	.348	Run R6-4 in a plane 32 inches down borehole.

NAp--Not applicable.

TABLE 7. - Hydraulic jet circular slot cutting tests on composite concrete-straw borehole samples--Continued

Test	Nozzle pressure, psi	Rotational speed, rpm	Test duration, sec	Breakage weight, grams	Normalized weight of cuttings	Comments
R7-1	4,000	2.0	120	2,654.3	1.00	Series R7 had nozzle pressure fixed at 4,000 psi and rotational speed fixed at 2 rpm for all tests. R7-1 in a plane 11 inches down borehole.
R7-2	4,000	2.0	120	1,066.0	.402	R7-2 in a plane 14 inches down borehole.
R7-3	4,000	2.0	120	1,045.9	.394	R7-3 in a plane 16.5 inches down borehole.
R7-4	4,000	2.0	120	1,906.5	.718	R7-4 in a plane 18.5 inches down borehole.
R7-5	4,000	2.0	120	1,628.9	.614	R7-5 in a plane 20 inches down borehole.
R8-1	4,000	2.0	240	1,349.5	1.00	Series R8 had nozzle pressure fixed at 4,000 psi and rotational speed at 2 rpm for all tests. R8-1 in a plane 24 inches down borehole.
R8-2	4,000	2.0	240	1,723.5	1.28	R8-2 in a plane 27 inches down borehole.
R8-3	4,000	2.0	240	2,955.7	2.19	R8-3 in a plane 29.5 inches down borehole.
R8-4	4,000	2.0	240	4,166.1	3.09	R8-4 in a plane 31.5 inches down borehole.
R8-5	4,000	2.0	240	7,010.8	5.21	R8-5 in a plane 33 inches down borehole.
R9-1	4,000	4.0	120	1,643.2	1.00	Series R9 had nozzle pressure fixed at 4,000 psi for all tests. R9-1 in a plane 10 inches down borehole.
R9-2	4,000	4.0	120	3,893.9	2.37	R9-2 in a plane 12.5 inches down borehole.
R9-3	4,000	2.0	120	1,891.0	1.15	R9-3 in a plane 15 inches down borehole.
R9-4	4,000	2.0	120	1,548.2	.941	R9-4 in a plane 17 inches down borehole.
R9-5	4,000	1.0	120	1,773.3	1.08	R9-5 in a plane 19 inches down borehole.

TABLE 7. - Hydraulic jet circular slot cutting tests on composite concrete-straw borehole samples--Continued

Test	Nozzle pressure, psi	Rotational speed, rpm	Test duration, sec	Breakage weight, grams	Normalized weight of cuttings	Comments
R9-6	4,000	1.0	120	2,012.7	1.22	R9-6 in a plane 20.5 inches down borehole.
R9-7	4,000	.5	120	1,876.1	1.14	R9-7 in a plane 22 inches down borehole.
R9-8	4,000	.5	120	2,077.9	1.26	R9-8 in a plane 23.5 inches down borehole.
R10-1	4,000	4.0	240	1,339.1	1.00	Series R10 had nozzle pressure fixed at 4,000 psi for all tests. R10-1 in a plane 26.5 inches down borehole.
R10-2	4,000	2.0	240	2,270.7	1.69	R10-2 in a plane 28.5 inches down borehole.
R10-3	4,000	1.0	240	2,853.6	2.13	R10-3 in a plane 30.5 inches down borehole.
R10-4	4,000	.5	240	4,625.1	3.39	R10-4 in a plane 32.5 inches down borehole.

NOTE.--Series R1 and R2 were conducted on sample 9-12-73 No. 5.
 Series R3 and R4 were conducted on sample 9-21-73 No. 8.
 Series R5 and R6 were conducted on sample 9-17-73 No. 6.
 Series R7 and R8 were conducted on sample 9-28-73 No. 10.
 Series R9 and R10 were conducted on sample 9-6-73 No. 3.

The data in table 7 are shown in graphical form in figures 4 and 5 where the weight of the cuttings were plotted against pressure and rotation speed, respectively. Figure 4 represents the first four test series and shows that the most effective cutting for a given rotation speed occurs at the highest pressure available; that is, 4,000 psig. Thus, the remaining tests were performed only at 4,000 psig. The four points in the upper right corner of figure 4 all represent a data point at 1.00 and 4,000 psig but were drawn separated for clarity.

Figure 5 shows the result of the tests at 4,000 psi concerned with the effects of rotation speed on cutting. All these tests were performed for 120 sec. The average values of the cutting rates are plotted as an X in figure 5. This plot reveals no peak representing an optimum rotation speed in the range of 0.5 to 4 rpm.

The nonhomogeneity of the composite concrete-straw samples complicates the interpretation of the results. It is certain that some of the tests, performed in weaker planes than others, produced a relatively high mud weight. This difference has evidently masked any effect the difference of rotation speed might have had on the weight of muck removed.

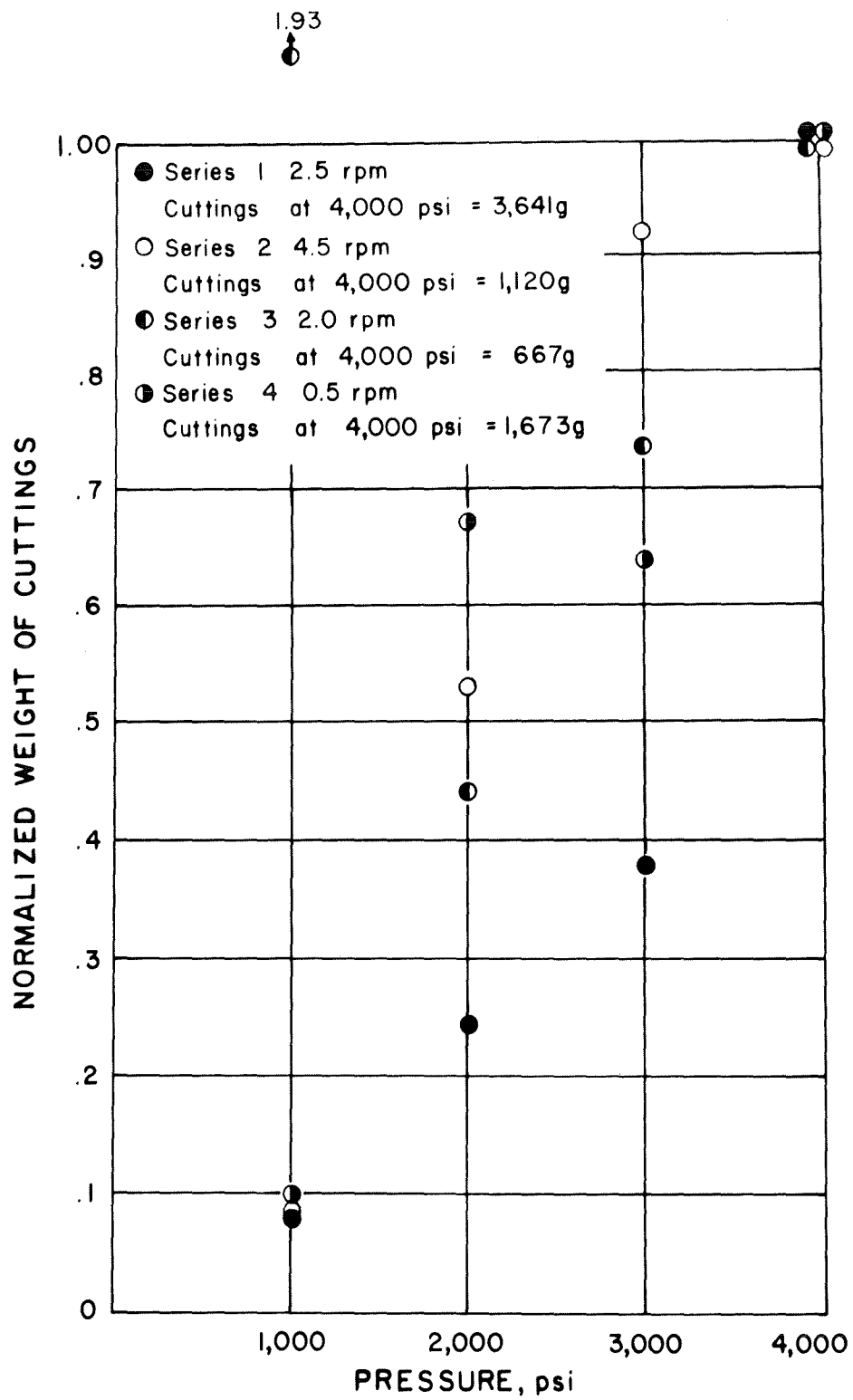


FIGURE 4. - Plot of amount of material removed as a function of pressure.

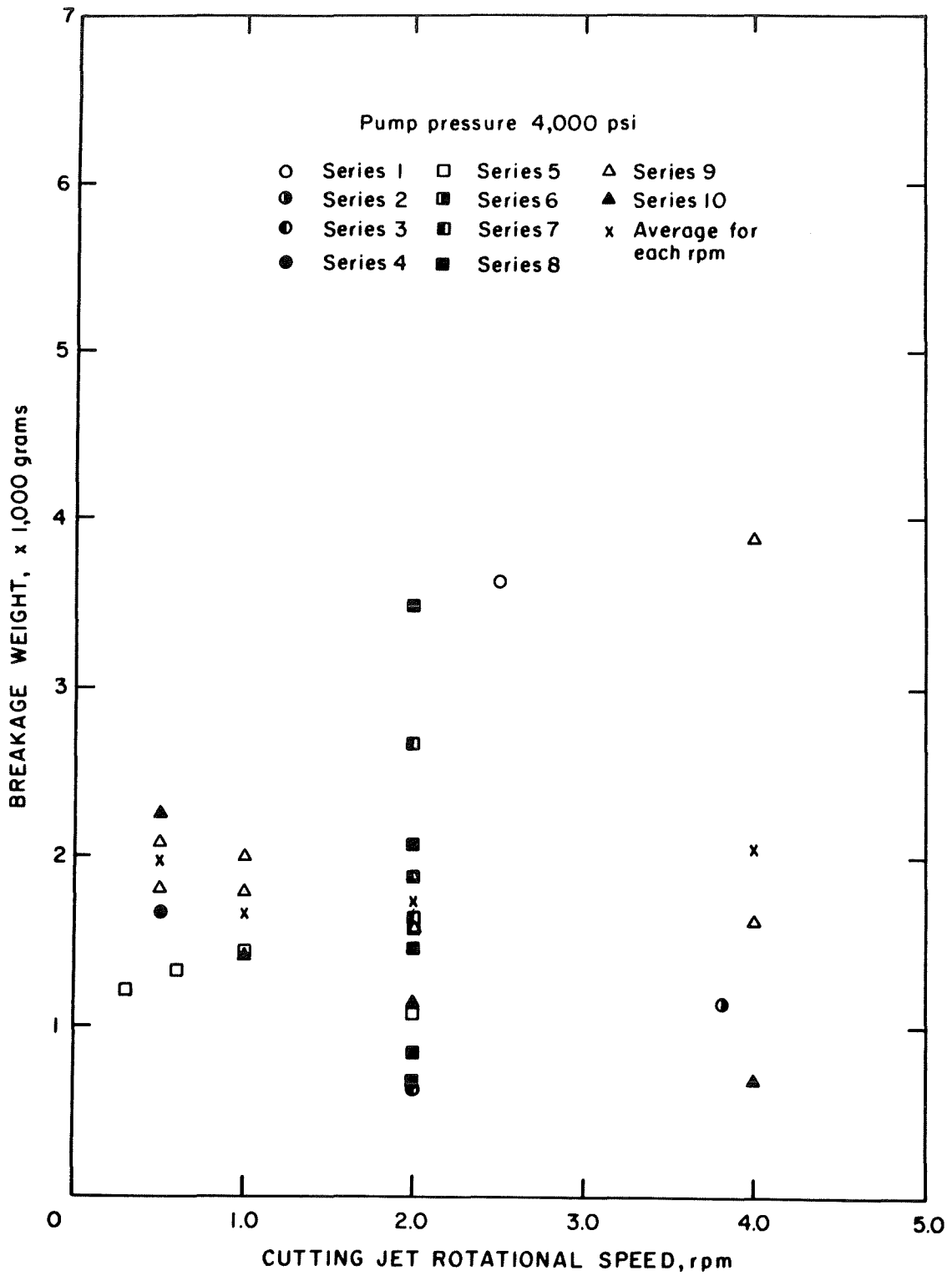


FIGURE 5. - Plot of amount of material removed as a function of rotation speed.

Traversing and Rotating Breakage Tests

The objective of this phase was to optimize the amount of fragmentation produced by a rotating jet as it moves vertically in a borehole. Because the device was fitted with no means for continuously moving the jet vertically, the vertical dimension was incorporated into the experiment by discontinuously moving the jet a discrete distance and performing the tests in a horizontal plane. By this procedure, the vertical spacing of the circular kerfs

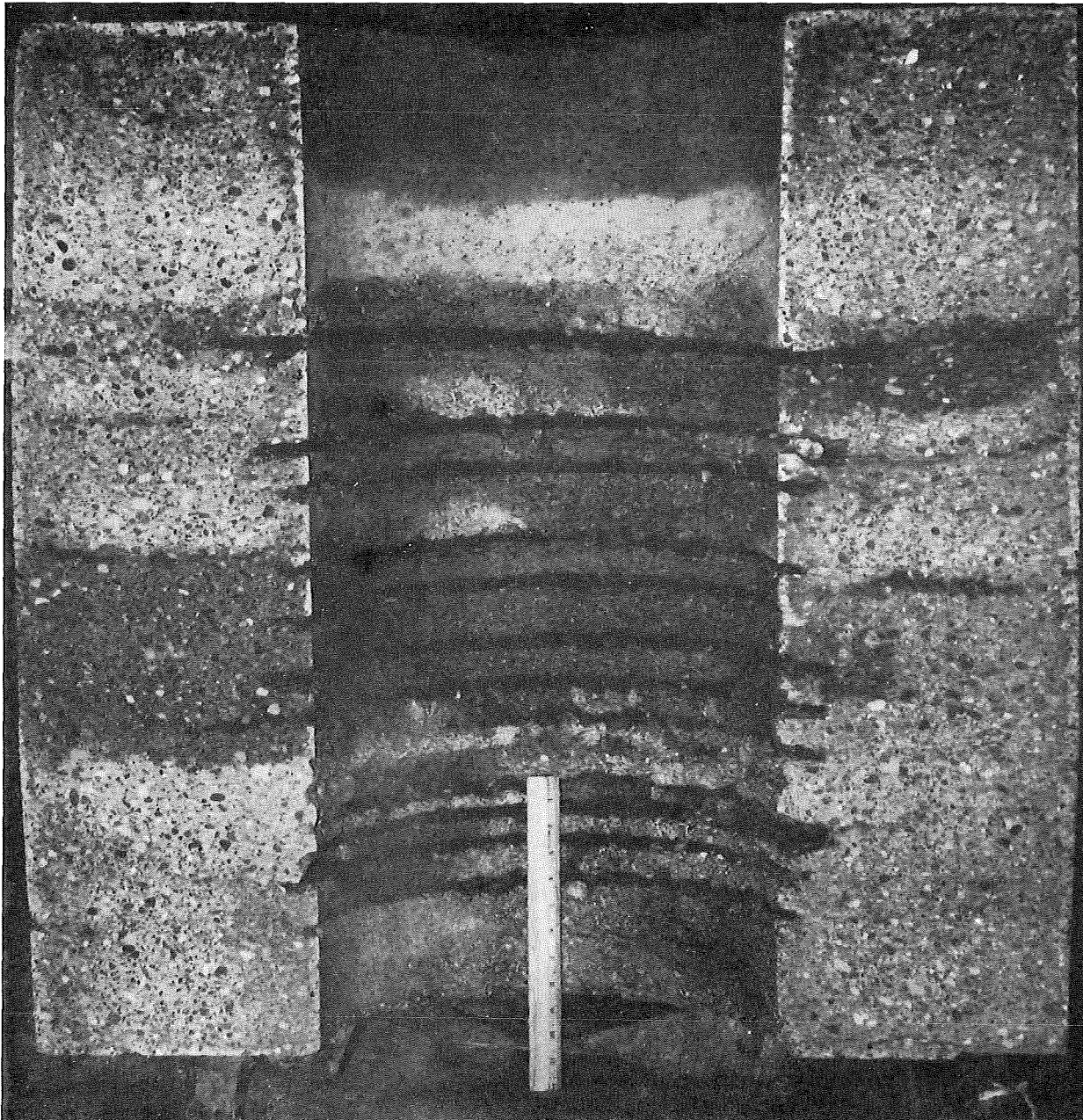


FIGURE 6. - Test block bisected to show kerfs cut by rotating water jet.

that produced maximum fragmentation could be determined. The tests were performed on the same samples used in the circular slot cutting tests (fig. 6). These samples contained kerfs cut at intervals down the borehole. The test procedure consisted of placing the rotating jet midway between two of these kerfs in between 0.5 and 1.5 inches in the material tested. It was found that if the kerfs were spaced less than 0.5 inch apart, the jet was deflected and lost cutting effectiveness.

DISCUSSION

A device was designed, fabricated, and used for continuous jet cutting experiments with coal and composite concrete-straw samples. The composite samples were 3-foot cubes with a 16-in-diam cylindrical borehole and had properties simulating coal; that is, they had a compressive strength of 2,500 psi, and straw simulated bedding. Nozzles were placed in the borehole, and kerfs were cut at various heights along the length of the hole.

These tests showed that the maximum excavation rate occurs when the interkerf spacing is between 0.5 and 1.5 inches and that jet spacing less than 0.5 inch resulted in reduced cutting effectiveness because of jet deflection.

Since the volume of material extracted by borehole process varies as the square of the standoff distance, the economics of borehole mining depend on the maximum standoff distance at which the jet can effectively fragment coal. The device used in this study broke coal only at distances less than 8 feet and thus would not be powerful enough to mine coal economically. Jets of this size, however, could be used in lieu of hydrofracturing to produce breakage along horizontal boreholes into coal and thereby increase methane production.

Practical hydraulic jet borehole coal mining devices must be designed to break coal at standoff distances in the 40- to 60-foot range and, thus, must have much more powerful jets than were used in this laboratory study. Sufficiently large hydraulic jetting equipment, used in the petroleum industry, typically extracts 900 tons of coke from 100-ft-high, 20-ft-diam vessels in 4 hours. The most recent hydraulic decoking installations operate at 3,000 psi with a flow rate of 1,000 gpm. The scale of these decoking operations is similar to that necessary for coal mining. Hydraulic borehole decoking technology could perhaps be adapted for the remote extraction of coal through boreholes if slurry handling systems could be made compatible with the jetting system.

REFERENCES

1. Bendix Corporation, Industrial Metrology Division. The Proficorder. Brochure No. S-211, August 1969, 14 pp.
2. _____. Technical Bulletin on Surface Texture, Surface Measurement and the American Standard ASA B46.1-1962. Bull. T111, March 1968, 12 pp.
3. Borden, P. E. Latest Technological Developments in Mining Methods. Proc. 9th Ann. Miner. Symp., Moab, Utah, May 22, 1964, pp. 1-7.
4. Cannon, H. G., Sr., H. B. Cannon, Jr., and H. H. Cannon. Apparatus and Methods for Mining Granular Ore. U.S. Pat. 3,311,414, Mar. 28, 1967.
5. Clayton, E. E. (assigned to Charles Mackie, Newark, N.J.). Process and Apparatus for Mining. U.S. Pat. 1,851,565, Mar. 29, 1932.
6. Disken, J. J. Hydraulic Pitch Mining at Vicary Creek. Proc. Rocky Mountain Coal Min. Inst., 60th Meeting, June 1964, pp. 63-65.
7. Engineering and Mining Journal. Tunnel Borer and Shaft Drill Teamed at AGC's Hydraulic Mining Operation. V. 165, No. 7, July 1964, pp. 68-70.
8. Fly, A. B. (assigned to Hydrojet Services, Inc., Amarillo, Tex.). Hydraulic Jet Well Under Reaming. U.S. Pat. 3,155,177, Nov. 3, 1964.
9. _____. Subsurface Hydraulic Mining Through Small Diameter Boreholes. Proc. 1st Internat. Conf. on the Hydraulic Transportation of Solids in Pipes, University of Warwick, England, Sept. 1-4, 1970, Paper B-1, pp. B1-1--B1-6.
10. Giles, R. V. Schaum's Outline of Fluid Mechanics and Hydraulics. Schaum Publishing Co., New York, 2d ed., 1962, p. 133.
11. Halliburton Services. Sales and Service Catalog. No. 37, January 1974, p. 2586.
12. Leach, S. J., and G. L. Walker. Some Aspects of Rock Cutting by High Speed Water Jets. Philos. Trans. Royal Soc. (London), v. 260, Series A, 1965, pp. 295-308.
13. Olson, R. M. Essentials of Engineering Fluid Mechanics. International Educational Publishers, New York, 1973, 637 pp.
14. Rose, H. E. Delayed Coking--What you Should Know. Hydrocarbon Processing, v. 50, No. 7, July 1971, pp. 85-92.
15. Wenneborg, W. A., B. R. Payne, and P. R. Bunnell (assigned to FMC Corp., New York). Subterranean Slurry Mining Apparatus. U.S. Pat. 3,747,696, July 24, 1973.

APPENDIX A.--RESULTS OF ALL FORCE TESTS

TABLE A-1. - Hydraulic jet forces for tests with tapwater

Standoff distance, feet	Nozzle pressure, psig				Standoff distance, feet	Nozzle pressure, psig					
	1,000	2,000	3,000	4,000		1,000	2,000	3,000	4,000		
TAPWATER--FROM WATERLINE FAUCET					TAPWATER--FROM HOLDING TANK--Continued						
1.5	{	33.4	64.8	96.2	124.8	6.0	{	28.6	56.2	85.6	110.4
		32.8	65.4	95.2	125.7			29.4	56.2	87.8	105.4
		35.9	65.4	93.2	124.6			28.4	56.6	85.6	109.4
		32.1	63.0	99.7	127.4			26.1	53.8	82.4	93.4
		36.6	65.4	95.7	127.5			30.8	55.5	85.6	109.7
3.0	{	29.3	66.7	93.3	119.7			28.0	56.2	87.8	108.2
		30.7	63.5	94.7	119.6			29.2	58.0	86.7	108.3
		31.6	61.7	93.8	125.7			31.4	54.9	86.8	110.7
		33.4	63.7	92.4	124.5			30.8	57.0	90.0	112.7
		33.5	64.3	91.7	124.2			30.2	59.8	85.8	110.9
6.0	{	28.4	54.1	77.4	97.7	9.0	{	22.0	45.6	66.8	81.2
		23.1	51.1	71.4	96.8			24.7	46.3	68.4	89.2
		27.8	57.2	86.7	111.3			23.9	46.2	68.3	77.5
		29.1	58.0	86.2	108.4			20.2	48.6	69.2	72.1
		31.8	57.7	87.4	110.0			25.1	31.0	55.6	69.8
9.0	{	26.5	42.5	59.1	86.5			26.7	49.0	73.6	80.8
		29.4	47.6	64.0	85.1			26.6	46.4	75.0	78.3
		22.3	44.6	65.1	84.2			26.8	47.3	71.6	82.7
		22.4	46.2	68.5	82.4			26.4	48.3	70.9	88.5
								27.2	45.1	70.4	87.5
12.0	{	19.9	31.8	42.7	53.7		24.3	49.6	70.5	81.3	
		18.1	40.9	49.6	55.7		25.8	48.3			
		20.4	35.3	45.0	63.1		18.0	30.1	46.1	61.5	
		19.5	30.8	51.6	58.9		18.8	33.6	37.5	44.7	
							8.1	31.0	41.8	49.1	
TAPWATER--FROM HOLDING TANK											
1.5	{	32.8	64.7	97.7	126.2	12.0	{	18.9	37.8	51.8	61.4
		33.1	66.2	104.3	129.8			20.4	36.2	52.8	65.9
		35.4	64.6	100.4	129.2			17.6	39.8	51.9	57.8
		33.0	71.6	110.5	130.1			19.6	34.2	51.6	70.9
								20.8	37.5	51.4	65.1
3.0	{	33.0	63.2	100.2	123.4			20.8	30.3	41.2	55.7
		34.0	63.2	97.2	117.6			19.3	26.9	47.0	60.4
		31.7	59.6	93.3	122.0			26.1	30.8		
		32.9	62.0	93.0	126.5						
		32.6	65.6	95.6	109.2						
		33.0	63.5	99.0	127.2						
		33.6	63.1	96.2	127.2						
		33.2	65.3	95.9	127.5						
		36.1	68.8	103.0	127.6						
		33.3	62.8	97.6	125.9						
	32.3	64.4	94.0	128.6							

TABLE A-2. - Hydraulic jet forces for tests with 0.05-pct
Polyox and Revert solutions

Standoff distance and additive	Nozzle pressure, psig				Standoff distance and additive	Nozzle pressure, psig			
	1,000	2,000	3,000	4,000		1,000	2,000	3,000	4,000
1.5 feet:					9.0 feet:				
Revert.....	35.4	66.5	104.1	138.9	Polyox.....	15.6	41.7	60.1	51.4
Do.....	34.9	65.6	97.9	131.8	Do.....	-	-	-	54.9
Do.....	36.8	63.6	99.9	131.8	Revert.....	24.3	54.2	79.7	98.0
3.0 feet:					Do.....	19.5	48.9	74.4	94.4
Polyox.....	35.2	68.6	87.7	106.4	Do.....	17.9	45.9	77.7	98.9
Do.....	34.5	65.9	96.8	107.1	12.0 feet:				
Revert.....	33.0	61.2	94.3	126.9	Revert.....	13.3	34.1	61.0	77.9
Do.....	31.9	61.0	92.1	128.7	Do.....	13.1	32.6	63.0	68.5
Do.....	33.6	62.9	94.6	126.7	Do.....	11.9	23.6	53.8	79.0
6.0 feet:					Do.....	11.9	22.0	53.8	73.4
Polyox.....	25.7	53.4	84.2	93.6					
Do.....	-	58.6	91.1	104.1					
Revert.....	25.5	55.6	86.4	115.6					
Do.....	27.3	56.7	85.2	115.9					
Do.....	30.3	57.1	90.1	117.1					

TABLE A-3. - Hydraulic jet forces for tests with 0.1-pct
Polyox and Revert solutions

Standoff distance and additive	Nozzle pressure, psig				Standoff distance and additive	Nozzle pressure, psig			
	1,000	2,000	3,000	4,000		1,000	2,000	3,000	4,000
1.5 feet:					9.0 feet:				
Revert.....	36.7	65.1	113.6	137.6	Polyox.....	24.9	54.6	76.7	88.9
Do.....	37.1	67.6	109.1	136.4	Revert.....	26.4	45.2	70.5	102.3
Do.....	35.6	65.7	108.3	137.9	Do.....	22.4	43.8	70.8	97.8
3.0 feet:					Do.....	18.4	41.5	72.6	101.2
Polyox.....	36.1	67.3	97.0	126.7	12.0 feet:				
Revert.....	31.8	63.1	98.5	130.1	Polyox.....	13.6	39.1	65.4	74.0
Do.....	31.4	64.0	98.7	130.2	Revert.....	13.6	18.8	44.6	79.5
Do.....	34.1	61.3	99.7	130.0	Do.....	14.2	24.4	46.8	79.0
6.0 feet:					Do.....	14.8	23.7	47.5	76.5
Polyox.....	31.8	61.2	87.2	115.1					
Revert.....	25.2	37.9	96.6	121.2					
Do.....	28.3	54.2	89.9	125.1					
Do.....	28.1	54.4	92.6	122.1					

TABLE A-4. - Hydraulic jet forces for tests with 0.2-pct Polyox and Revert solutions

Standoff distance and additive	Nozzle pressure, psig				Standoff distance and additive	Nozzle pressure, psig			
	1,000	2,000	3,000	4,000		1,000	2,000	3,000	4,000
3.0 feet:					9.0 feet:				
Polyox.....	32.3	65.2	99.8	116.1	Polyox.....	22.0	41.8	57.8	78.0
Do.....	32.5	62.0	95.4	115.0	Do.....	19.4	37.4	61.6	78.2
Revert.....	32.0	61.7	92.1	120.4	Revert.....	19.0	29.6	55.4	73.2
Do.....	32.2	61.0	86.9	119.1	Do.....	18.1	32.4	53.7	84.1
6.0 feet:					12.0 feet:				
Polyox.....	32.8	57.2	84.1	116.2	Polyox.....	11.3	23.1	54.4	48.6
Do.....	25.2	57.5	86.0	100.8	Do.....	8.0	20.3	42.2	58.3
Do.....	-	54.4	85.0	100.2	Revert.....	19.3	24.2	41.2	45.0
Revert.....	26.5	55.3	83.7	114.5	Do.....	11.4	20.9	32.1	60.4
Do.....	26.2	50.9	84.0	113.8					

TABLE A-5. - Hydraulic jet forces for tests with 0.3-pct Polyox solution

Standoff distance, feet	Nozzle pressure, psig			
	1,000	2,000	3,000	4,000
3.0	33.0	66.2	92.9	114.4
6.0	{ 23.4	54.2	76.8	80.9
	{ -	-	78.1	-
9.0	{ 18.9	34.0	21.0	51.3
	{ -	31.1	42.9	54.9
12.0	{ 10.5	20.7	27.1	33.7
	{ 10.8	-	28.1	-

APPENDIX B. --TOTAL PRODUCT WEIGHT FOR EACH SLOT CUTTING RUN

TABLE B-1. - Final weights of cuttings showing how the sand was distributed (on a percentage basis) to each test run

Test	Gravel/cement muck weight, grams	Weight of sand added, grams	Final weight of cutting, grams
R1-1.....	1,977.2	1,664.2	3,641.4
R1-2.....	745.3	627.4	1,372.7
R1-3r.....	481.5	405.2	886.7
R1-4.....	156.8	132.0	288.8
R2-1.....	608.7	512.2	1,120.9
R2-2.....	560.4	471.8	1,032.2
R2-3.....	322.3	271.1	593.4
R2-4.....	52.1	43.6	95.7
Total.....	4,904.3	4,127.5	9,031.8
R3-1.....	331.1	336.4	667.5
R3-2.....	243.6	247.6	491.2
R3-3.....	146.0	148.2	294.2
R3-4.....	637.5	648.4	1,285.9
R4-1.....	829.7	843.5	1,673.2
R4-2.....	529.1	538.4	1,067.5
R4-3.....	556.6	565.9	1,122.5
R4-4.....	82.4	83.8	166.2
R5-1r.....	716.1	728.5	1,444.6
R5-2.....	670.6	682.2	1,352.8
R5-3.....	627.9	638.4	1,266.3
R5-4.....	777.8	791.1	1,568.9
Total.....	6,148.4	6,253.1	12,401.5
R6-1.....	1,012.2	708.1	1,720.3
R6-2.....	660.4	462.5	1,122.9
R6-3.....	448.5	313.5	762.0
R6-3r.....	482.0	337.3	819.3
R6-4.....	352.3	246.4	598.7
RR1-1.....	1,076.4	753.1	1,829.5
RR1-2.....	801.5	560.7	1,362.2
RR1-3.....	1,017.5	712.2	1,729.7
Total.....	5,850.8	4,093.8	9,944.6

TABLE B-1. - Final weights of cuttings showing how the sand was distributed (on a percentage basis) to each test run--Continued

Test	Gravel/cement much weight, grams	Weight of sand added, grams	Final weight of cutting, grams
R7-1.....	1,831.6	822.7	2,654.3
R7-2.....	735.3	330.7	1,066.0
R7-3.....	721.9	324.0	1,045.9
R7-4.....	1,315.5	591.0	1,906.5
R7-5.....	1,123.6	505.3	1,628.9
R8-1.....	931.5	418.0	1,349.5
R8-2.....	1,189.6	533.9	1,723.5
R8-3.....	2,039.0	916.7	2,955.7
R8-4.....	2,874.7	1,291.4	4,166.1
R8-5.....	4,837.9	2,172.9	7,010.8
RR2-1.....	1,692.4	760.5	2,452.9
RR2-2.....	1,334.7	599.4	1,934.1
RR2-3.....	2,246.4	1,009.0	3,255.4
RR2-4.....	2,411.3	1,082.9	3,494.2
RR3-1.....	1,712.4	768.8	2,481.3
RR3-2.....	3,215.2	1,444.3	4,659.5
RR3-3.....	7,159.3	3,216.2	10,375.5
Total.....	37,372.3	16,787.8	54,160.1
R9-1.....	1,017.6	625.6	1,643.2
R9-2.....	2,411.6	1,482.3	3,893.9
R9-3.....	1,171.3	719.7	1,891.0
R9-4.....	958.9	589.3	1,548.2
R9-5.....	1,098.1	675.2	1,773.3
R9-6.....	1,246.3	766.4	2,012.7
R9-7.....	1,162.1	714.0	1,876.1
R9-8.....	1,286.9	791.0	2,077.9
Total.....	10,352.8	6,363.5	16,716.3
R10-1.....	931.6	407.5	1,339.1
R10-2.....	1,579.9	690.8	2,270.7
R10-3.....	1,986.0	867.6	2,853.6
R10-4.....	3,218.9	1,406.2	4,625.1
RR4-1.....	1,598.6	699.0	2,297.6
RR4-2.....	2,030.7	887.5	2,918.2
RR4-3.....	2,236.9	977.7	3,214.6
RR4-4.....	1,110.1	484.7	1,594.8
RR5-1.....	3,269.9	1,428.3	4,698.2
RR5-2.....	3,897.1	1,702.2	5,599.3
RR5-3.....	4,937.9	2,157.8	7,095.7
Total.....	26,797.6	11,709.3	38,506.9

