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Analysis of Rock Chips Produced During Water-Jet-Assisted Cutting

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UNITED STATES DEPARTMENT OF THE INTERIOR

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ILLUSTRATIONS

UNITS OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft/min	foot per minute	in•lbf/in^3	inch pound (force) per cubic inch
ft	foot	in•lbf/in^2	inch pound (force) per square inch
ft/h	foot per hour		
ft•lbf	foot pound (force)	in/s	inch per second
gal/min	gallon per minute	lb	pound
hp	horsepower	pct	percent
hp/in	horsepower per inch	psi	pound per square inch
in	inch	rpm	revolution per minute
in^2/in^3	square inch per cubic inch	wt pct	weight percent

ANALYSIS OF ROCK CHIPS PRODUCED DURING WATER-JET-ASSISTED CUTTING

By A. N. Styler[1] and E. D. Thimons[2]

ABSTRACT

As part of its water-jet assisted rock cutting research, the Bureau of Mines has initiated a study into the mechanism of rock fragmentation by water-jet-assisted mechanical tools. The objective of this research is to increase coal extraction efficiency by seeking an improved understanding of the synergistic relationship between mechanical cutters and water jets, enabling the design of more effective cutterheads. Rock chips collected during laboratory traverse speed jet-assisted cutting tests were analyzed with respect to the size distribution of the chips and the forces measured during cutting. As the water-jet pressure was increased, the size distribution of the product became coarser with V-face type cutting tools producing less fine material than conical cutting tools. Fracture mechanics theory accounted for less than 10 pct of the energy consumed during fragmentation of the rock. The energy consumed by processes other than rock breakage decreased with the use of water jets and increasing advance rate.

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INTRODUCTION

This report presents the results of a study to investigate the rock breakage process, by analysis of the rock debris produced during laboratory jet-assisted cutting tests. Recently there has been interest in water-jet-assisted cutting of rock, using low-volume water jets, with pressures up to 10,000 psi (1-2).[3] The motivation for this is to reduce the amount of fines generated and to reduce cutting head torque and thrust, enabling deeper and more widely spaced cuts to be taken, hopefully overcoming problems of torque fluctuation. This led a joint project between the Bureau of Mines and the British National Coal Board. Under this project a Dosco roadheader was retrofitted with high pressure water-jet-assist system in order to increase its ability to cut the harder coal measure rocks (3). Observations during cutting trials showed a reduction in dust generation and frictional sparking, as well as significant increases in tool life (4). Water-jet-assist also has the potential to reduce machine vibration and improve the productivity of shearers and continuous miners, especially in seams where difficult cutting conditions are encountered.

In order to obtain the full benefit from water-jet-assisted cutting, it is not adequate to just add a high-pressure jet-assist system to drums designed for mechanical cutting. To try and bridge the gap between existing laboratory data and full-scale drum design, the Bureau has been conducting research into the effects of traverse speed on water-jet-assisted cutting, and into the mechanism of rock breakage during jet-assisted cutting. Concurrently the Bureau has been conducting surface trials with a jet-assisted shearer, to investigate cutting efficiency on a full-scale machine and to develop a practical water-jet phasing system.

As is the case with mechanical cutting, the majority of the experimental work conducted to date with water-jet-assisted cutting has been restricted to linear cutting machines with low traverse speeds and fixed shallow depths of cut. These slow-speed tests ignore potential changes in the mode of jet action, from penetration by hydrodynamic effect to penetration by water hammer effect (5), as the jet traverse speed is increased. Also the effects of dynamic interaction between the jet and the tool are ignored at low tool speeds. The influence of increased traverse speed is to decrease the residence time of the jet and to significantly decrease the ratio of jet energy to mechanical energy below 50 (6), typical of slow speed laboratory tests.

The rock chips analyzed in this report were collected during tests on the traverse-speed cutting facility, which is described later. The test material consisted of German (Imberg) sandstone, which is a light-gray, fine- to medium-grained quartz sandstone having an unconfined compressive strength of 19,000 psi. The results of 12 tests are analyzed in this paper, with jet pressures ranging from 0 to nearly 9,000 psi, flow rates of 0 to 1.63 gal/min, and average tool speeds of 35 to 248 ft/min.

During these tests, penetration (advance rate), thrust, torque, rotational speed, flow, and water pressure were measured. This will enable correlation of the benefits of water-jet-assisted cutting upon the production of fines, reduced mechanical forces, and the mechanism of fracture. Further studies are planned to investigate the effects of factors such as rock properties, jet traverse speed, and preexisting fractures.

[3]Underlined numbers in parentheses refer to items in the list of references preceding the appendix.

EXPERIMENTAL FACILITIES

Testing was conducted at the Colorado School of Mines, using the traverse speed test facility constructed under a Bureau contract. The test facility (7) consists of a cutterhead driven by a Subterranean raise boring machine gearbox (fig. 1). The rotational speed of the cutterhead could be varied from 0.5 to 40 rpm, with a maximum available thrust of 120,000 lb. During a test, the thrust was held constant allowing the depth of cut to vary according to the cutting resistance. The thrust was varied between tests and ranged from 18,300 to 37,900 lb. The high-pressure water was supplied by two 10-gal/min triplex pumps, generating a maximum pressure of 9,500 psi, with flow controlled by varying the speed of the diesel drive. The full face cutterhead has a 33.5-in diameter, with a central guide to fit in a 13-in-diam pilot hole. The cutterhead is equipped with either six V-face (radial) or six conical type cutting tools, and a nozzle for each bit, with the water jets directed to impinge on the rock just in front of the cutting tool. The bit spacing is 2-1/2 in between each bit, with double tracking at the gauge bits.

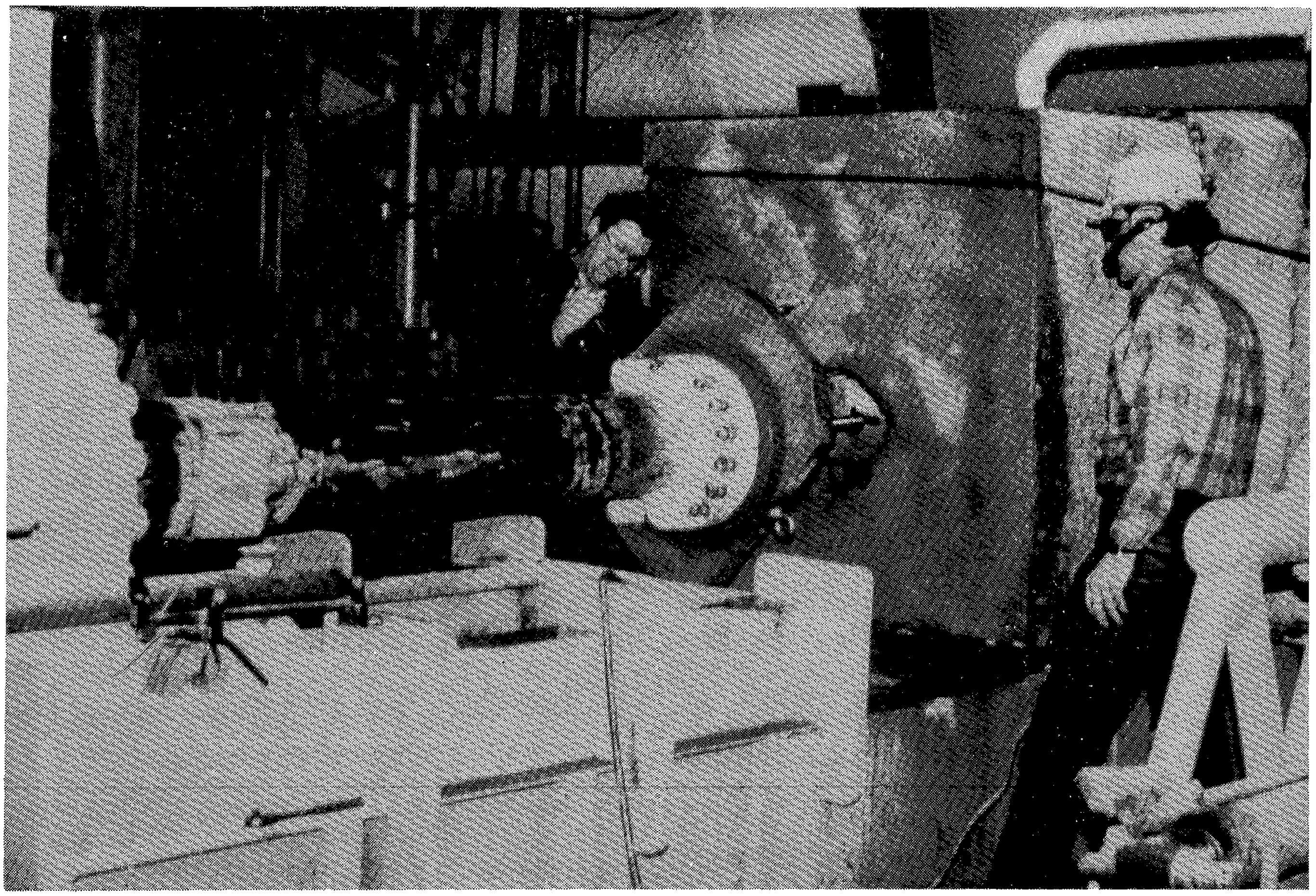

FIGURE 1.—Test setup at Colorado School of Mines.

THEORIES OF CHIP FORMATION

Studies into the fracture process of rock by mechanical tools have primarily concentrated upon quasistatic indentation tests. Paul (8) reported that some rocks will merely be crushed and indented, whereas others will crack and form chips under the static penetration of a wedge, with the formation of chips depending upon the geometry of the indenter, type of rock, and depth of penetration. For a brittle material such as German sandstone, the penetration of a wedge can be thought of as a cyclic, two-phase process (9). The first is a crushing phase in which the indenter is forced into the material, causing local crushing, then as the indenter load and penetration increases, fracture occurs in the surrounding material. Increased penetration causes compression of the crushed zone, which is confined around the tool tip. This triaxially compressed crushed zone produces a radial tensile stress field in the surrounding rock, leading to the formation of fractures (10).

The process of fracture leading to the formation of a chip has been described by Lawn (11) and is shown schematically in figure 2, ignoring the effects of elastic deformation. With reference to this figure, and the fracture mechanism described by Lawn; on application of the load a crushed zone is formed (*A*), as the load is increased this crushed zone increases until at some critical load a crack suddenly initiates beneath the point of load application (*B*). As the load is increased further this crack extends in a stable manner (*C*), and as the load is being removed the crack begins to close (*D*). As the load is further removed expansion of the crushed zone relative to the surrounding material leads to residual tensile stresses, creating sideways extending cracks (*E*). Upon complete unloading these lateral cracks continue to extend and possibly cause the formation of chips (*F*).

For rock cutting, the cutting tool is moving across the surface of the rock under a combined tangential and normal load, while with water-jet-assisted cutting, the process is further complicated and is still not yet fully understood. Hurt (12) stated that in cutting brittle rock a conical tool induces fractures ahead of the tool, leading to saucer-shaped chips as the rock breaks at a shallow angle ahead of, and to the sides of the tool (fig. 3). The tool then has to clear a path through the remaining material (termed profiling), cutting into the sloping surface left by the formation of the chips. This profiling is inefficient and leads to

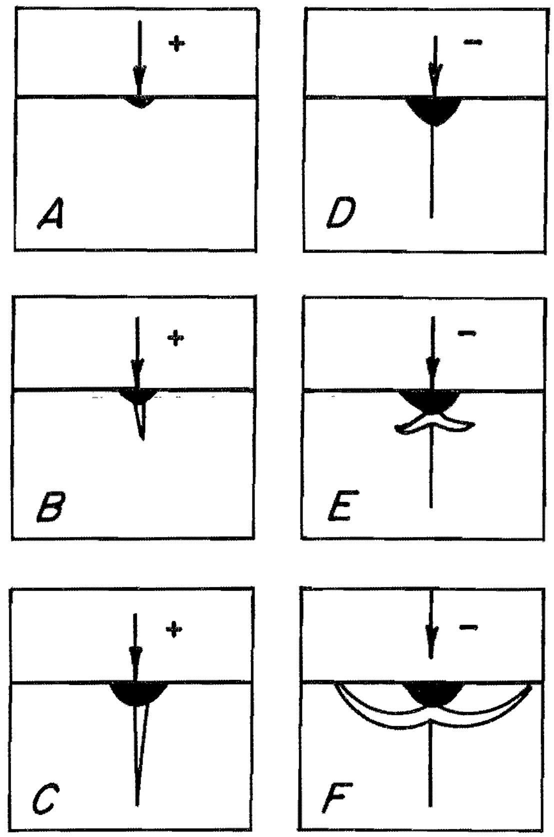

FIGURE 2.—Fracture mechanics model of indentation.

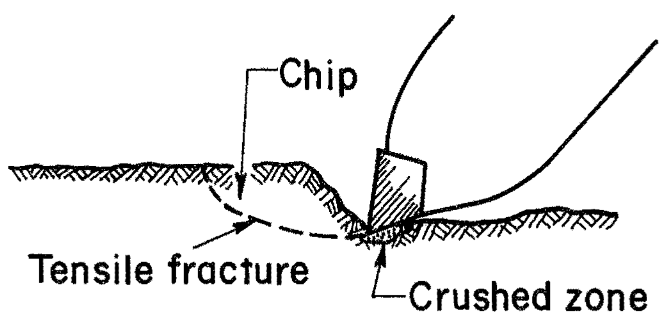

FIGURE 3.—Chip formation during rock cutting.

high dust levels because of the rubbing contact between the tool sides and the groove. As previously described, a crushed zone of rock develops beneath the tool tip, which according to Fowell (13) acts as an effective bluntness to the tool.

On the basis of Hurt's (12) model for rock cutting and laboratory investigations, Fowell (13) proposed the following model of hybrid cutting: The water jet reduces the size of the crushed zone by flushing and by decreasing the effective bluntness of the tool. Therefore the jet can preserve the tool tip as an effective stress concentrator, thus maintaining the "theoretical minimum level" required to achieve the critical stress for crack initiation. Profiling in turn may be assisted by water jets through both flushing of debris and lubrication of the tool-rock interface.

According to Fowell (13), there is a theoretical optimum jet pressure when the jet just reaches the tool tip, and flushes away the crushed zone, which gives the minimum required cutting forces. At higher pressures, the jet penetration is deeper than the mechanical depth of cut thus preventing the tool tip from acting as a stress concentrator, which leads to the formation of chips. In this situation, cutting is mainly by the inefficient profiling process requiring higher mechanical forces. From jet-assisted cutting tests, Fowell (13) found that forces were a minimum when the jet penetration is 20 to 50 pct of the mechanical depth of cut. When the jet penetration is 60 to 70 pct of the mechanical depth of cut, the forces increase and significantly less rock chips are formed.

Water jets can also assist mechanical tools by cutting a slot in the rock in front of the cutting tool. Pritchard (14) showed that a water-jet-cut slot ahead of a roller cutter used on tunnel boring machines reduced the forward thrust requirements during tests on German sandstone. The effectiveness of this slot depends on its depth, which is determined by the water jet pressure. In cutting tests on German sandstone (14), a water jet with a 0.025-in orifice cut a slot 0.01 in deep with a jet traverse speed of 10-in/s and a jet pressure of 5,000 psi. At a water jet pressure of 10,000 psi and a traverse speed of 2 in/s, the water jet cut a slot of 0.11 in deep.

Another possible mechanism for water-jet-assisted cutting was suggested by Hood (15). As mentioned previously, during indentation tests a crack is initiated in rock at low levels of applied load, however, in order to propagate this crack to form a rock chip, it is necessary to increase the load on the indenter. Hood (15) suggested that the water jets exploit this crack and propagate it to form a chip, in which case the efficient rock cracking chip formation process would dominate over the inefficient crushing beneath the bit.

SIZE DISTRIBUTION OF ROCK CHIPS FORMED BY CUTTING

One of the purported benefits of jet-assisted cutting is a reduction in the amount of fines produced. However, in a recent study, Tutluoglu (6) reported no significant change in size distribution between dry cuts and cuts with jets. To investigate this further, the size distributions for the chips collected during traverse speed testing in German sandstone were determined. The average size distribution for each of the water pressures used have been plotted (fig. 4). A comparison of the curves for water pressures of 0, 6,000, and 9,000 psi, shows that the product becomes coarser with increasing jet pressure. It is generally accepted that the most efficient cutting generates less fine material, with efficiency being inversely proportional to specific energy. Therefore, it would be expected that the specific energy should decrease as the jet pressure increases. The size distribution curve for a 2,000-psi jet shows a smaller percentage of minus 80-mesh material than a dry cut but a larger percentage of material in the 1-in by 80 mesh fraction. A possible explanation for this is that 2,000-psi is below the optimum pressure for cutting in German sandstone.

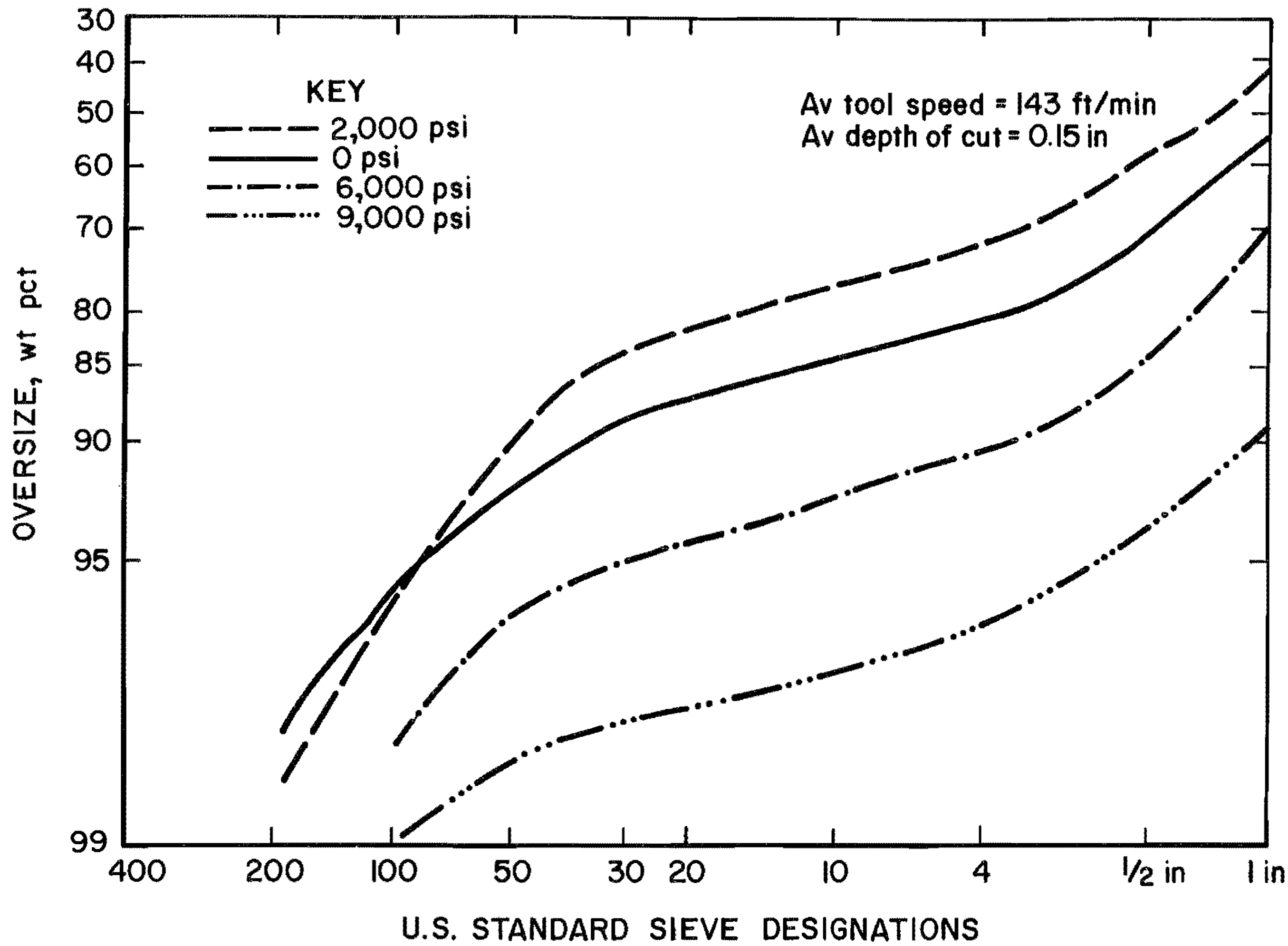

FIGURE 4.—Product size distribution versus jet pressure.

INFLUENCE OF DEPTH OF CUT ON JET ENERGY

The mechanical energy per unit depth of cut is plotted against the total specific energy expressed as a percentage of the mechanical specific energy (fig. 5). A value of 100 pct represents a dry cut, and a value of 120 pct represents a jet energy equal to 20 pct of the mechanical energy. The mechanical specific energy is defined as the mechanical energy required to remove a unit volume of rock. The total specific energy is the sum of the mechanical and the jet energy required to remove a unit volume of rock. As the jet energy as a proportion of the mechanical energy increases, the mechanical force to achieve a unit depth of cut decreases. This is because an increase in jet energy results in an increase in the depth of cut. The thrust and therefore the depth of cut were varied between each test; however, the penetration was limited with an average depth of cut for all the tests of only 0.15 in.

The two points that exhibit the worst fit with the line drawn through the data (fig. 5) are for the 2,000-psi and the 9,000-psi jets. For the test conducted

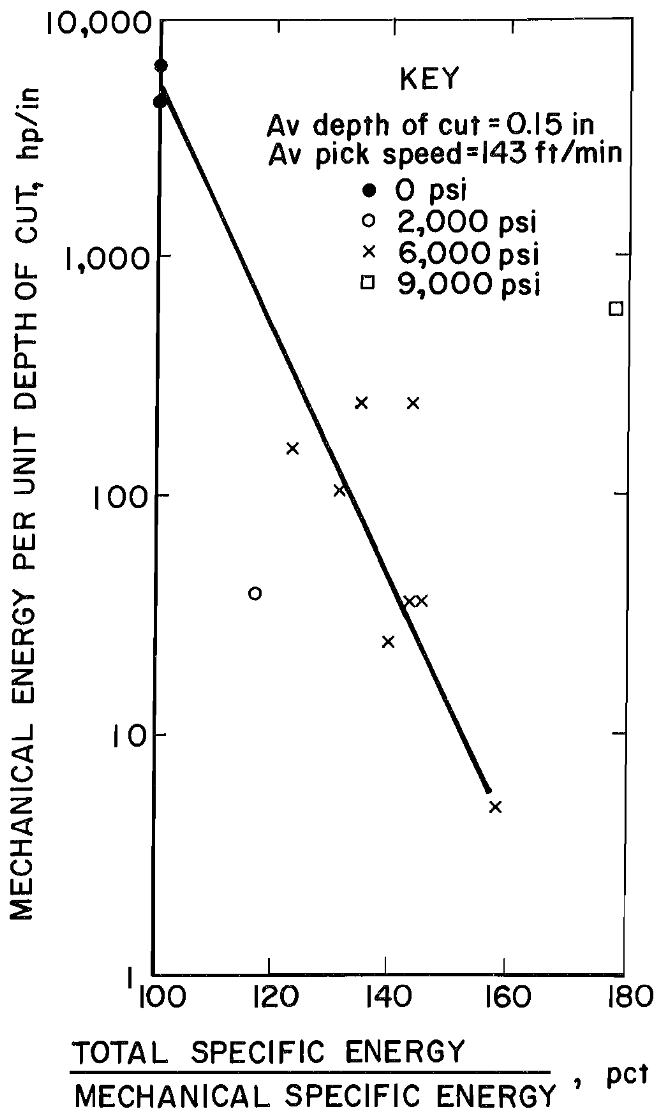

FIGURE 5.—Energy per unit depth of cut versus specific energy ratio.

at 9,000-psi, the extra energy used in forming a higher pressure jet does not yield any benefit in terms of reduced cutting forces. Clearly from the size distribution data (fig. 4), the extra energy from the 9,000-psi jet does not go into fracturing the rock, as the product is coarser than that produced with a 6,000-psi jet. The 2,000-psi jet exhibits exactly the opposite type of behavior, in so much as it gives a much greater reduction in the mechanical energy per unit depth of cut than expected, and the product size distribution is finer than for a dry cut on average (fig. 4).

A possible explanation for the results shown in figure 5 can be found by referring to the fracture process under the combined action of a mechanical tool and a water jet. Dubugnon (16) reported achieving substantial reductions in normal force using low-pressure jets of approximately 1,500 psi, while the cutting force was not reduced until higher pressures were used. He attributed this to the low-pressure jet being capable of removing the crushed zone from around the tool tip and thus reducing the resistance normal to the cutting direction. Whereas water injection into a single crack produces chipping, which requires relatively higher pressures to reduce the cutting force. In the traverse speed tests, the depth of cut varied under a constant thrust, or normal force, therefore the use of a 2,000-psi jet increased the depth of cut as opposed to decreasing the thrust. However, the mechanical energy and the specific energy are mainly influenced by the cutterhead torque, which is proportional to the cutting force, and therefore were not reduced significantly by the use of a 2,000-psi jet.

INFLUENCE OF TOOL TYPE ON SIZE DISTRIBUTION

The traverse speed cutting tests were conducted using conical and V-face type cutting tools (fig. 6). In order to determine the influence, if any, of tool type on the test results, a discriminant analysis was used. In using this analysis, the only factor found to be statistically significant in distinguishing between the two types of cutting tool was the size distribution of the rock debris produced by cutting. The average size distributions for the tests conducted at a jet pressure of 6,000 psi for the V-face and conical type tools are shown in figure 7. The V-face tool produces a larger percentage of fine material than does the conical tool. A possible explanation for this is the larger contact area with the V-face tool, leading to a greater volume of crushed rock beneath the tool. However this seems unlikely as other investigators (12, 17) have found that conical tools produce more dust than V-face tools for dry cutting. The dry traverse speed test results agreed with this, so it would seem reasonable to speculate that this effect is due to the action of the water jets, with the use of water-jet-assisted cutting giving a more substantial reduction in fine material with conical tools as opposed to V-face tools.

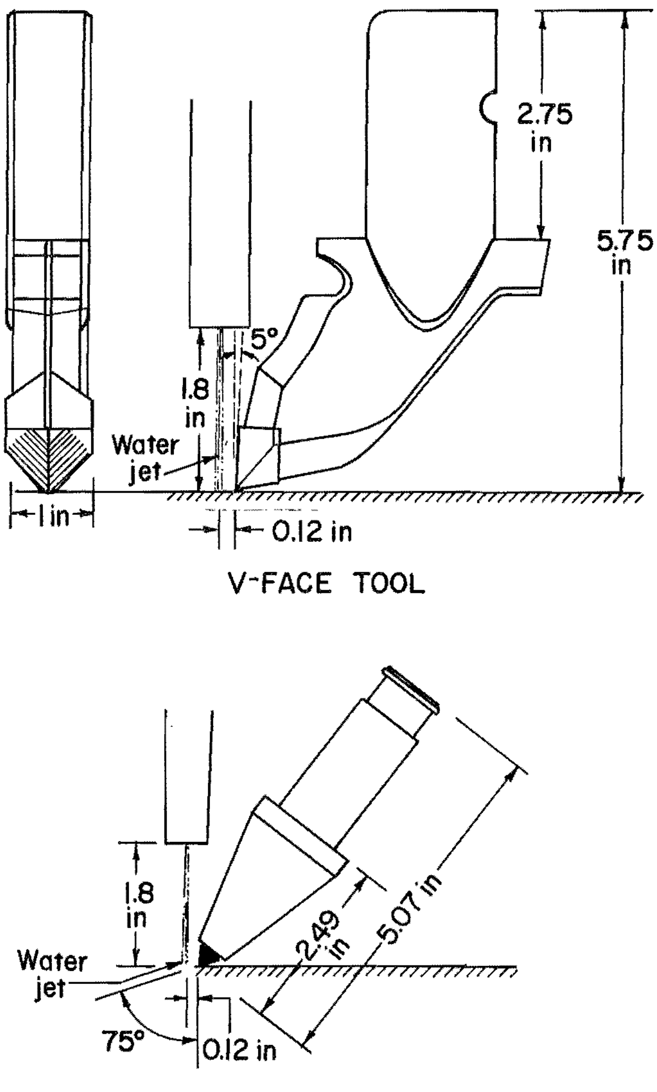

FIGURE 6.—Dimensions of tools used in cutting tests.

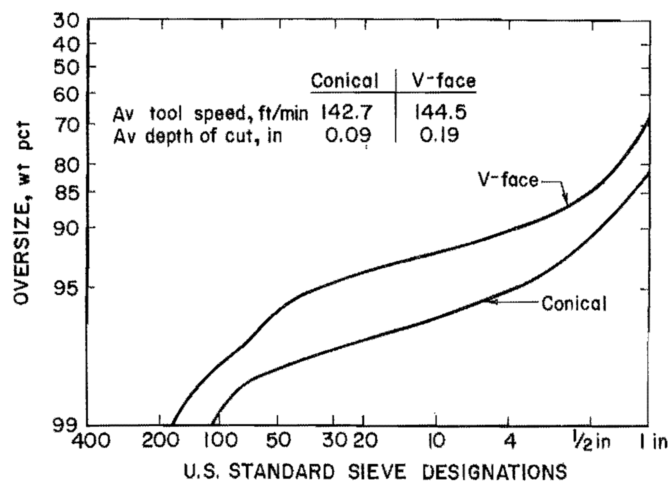

FIGURE 7.—Product size distribution versus tool type.

MECHANISM OF JET ASSISTANCE INDICATED BY TEST RESULTS

One of the mechanisms that has been proposed to explain how water jets improve cutting efficiency, is that the water jet has a lubricating effect. This lubricating action is purported to reduce the fine material generated during profiling, and should be reflected by a change in the ratio of the normal and cutting forces. No correlation was found between this force ratio and any of the jet parameters, perhaps because of the large influence of traverse speed upon this force ratio. Another mechanism proposed is that water-jet-assisted cutting reduces the effective bluntness of the cutting tool by removing the crushed zone surrounding the tip of the cutting tool. This reduces the amount of fine material formed and increases the depth of cut for a constant normal force. As the jet pressure is increased, the water jets also help in the formation of rock chips, leading to a decrease in cutting force. However, the water jets did not significantly alter the size distribution of the plus 30-mesh material (fig. 4).

With reference to the conclusions concerning jet-assisted cutting, and noting that in all cases the jet was aimed to impinge very close to the tip of the tool, a possible explanation of the chip size results is as follows: For the conical tool, the water jet is in fact reducing the extent of the crushed zone as predicted, while for the V-face tool the larger extent of the crushed zone considerably reduced the effectiveness of a single jet directed at the bit tip. In the case of a V-face chisel shaped tool, these results would appear to back up the conclusions reached by Hood (15), who found for a chisel-shaped tool the greatest benefit was realized using two jets, one directed at each corner of the bit.

ENERGY CONSUMED IN BREAKAGE

In the fracturing of all materials, and rock in particular, the mechanical energy is lost to the material in creating the fracture surfaces (18). In a truly brittle material such as glass, or some rocks, the energy for crack growth is the surface energy required to form the new surfaces. Griffith was the first to try and explain this with his theory of brittle fracture, in which he stated that crack propagation will occur if the energy released upon crack growth is sufficient to provide all the energy that is required for crack growth, if not, then the stress has to be raised. By measuring the stress, σ, required to fracture a plate of glass with an elliptical crack of length 2a, Griffith determined the critical energy release rate, Gic, as a function of the modulus of elasticity, E, which must be exceeded for crack growth to occur:

$$Gic = \frac{\pi\sigma^2 a}{E}.$$

The critical energy release rate can be expressed in terms of the stress concentration around the crack tip by use of the stress intensity factor or fracture toughness, Kic, which is the value when fracture can be expected to occur. In the case of plane strain,

$$Gic = \frac{Kic^2\ (1 - V^2)}{E},$$

where V is Poissons ratio and Kic is the material property, which can be determined from laboratory testing (19-20). The energy release rate is an energy per unit crack extension, therefore the energy consumed in fracture, U, can be found by multiplying the critical energy release rate by the area of new surfaces, A, created during fracture (8),

$$U = \frac{Kic^2\ (1 - V^2)\ A}{E}.$$

In applying this equation to rock cutting it is necessary to determine the area of the new surfaces created during cutting. This was achieved by analyzing the rock chips collected during cutting to determine a shape factor for each of the size fractions. The shape factor relates the surface area of a particle to its volume, hence knowing the rock density, weight, and shape factor for each size fraction, it is possible to obtain an estimate of the total surface area in a chip sample. Using the measured values for areas of fracture surface and typical material values for sandstone, it was possible to theoretically calculate the energy consumed in cutting the rock.

The total specific energy calculated from the water jet energy and the forces measured during the traverse speed tests showed an inverse relationship with the advance rate (fig. 8). The correlation coefficient for the straight line drawn through the data was over 0.98. For purposes of comparison, the specific energy has also been calculated theoretically using the area of new surfaces produced and the critical strain energy release rate. The critical strain release rate was not available for German sandstone so it was necessary to obtain a suitable value from the literature. A literature survey revealed that for sandstone the critical strain energy release rate varied from 0.3 to 9.0 in·lbf/in^2. Since the German sandstone is a strong fine-grained sandstone, the high value of 9.0 in·lbf/in^2 obtained from reference 21 was used in these calculations. The theoretically calculated specific energy showed no correlation with the advance rate or with any other variable (fig. 9). The only exception to this is tool type, which is to be expected since the specific energy is equal to Gic (constant for a given rock) times the new surface area per unit volume, which is a function of the product size distribution.

It is generally accepted that the increase in cutting efficiency with

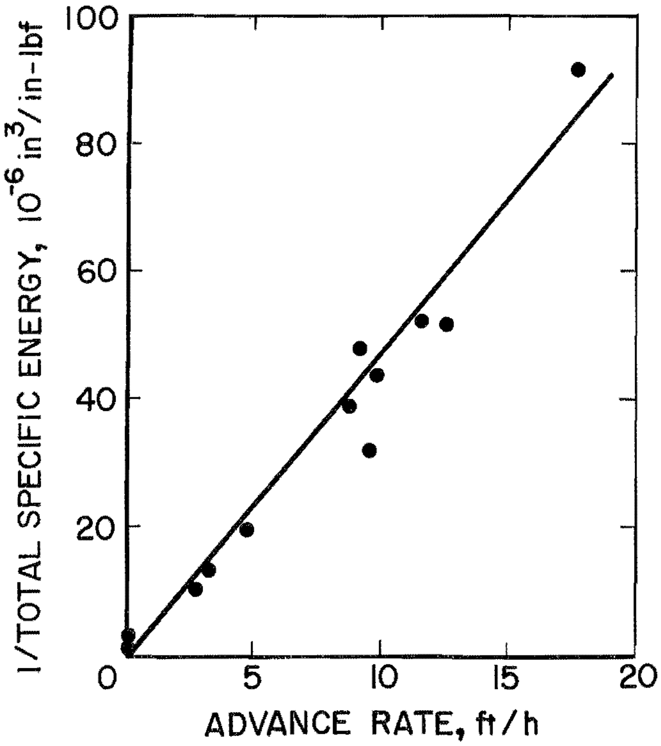

FIGURE 8.—Total specific energy versus advance rate.

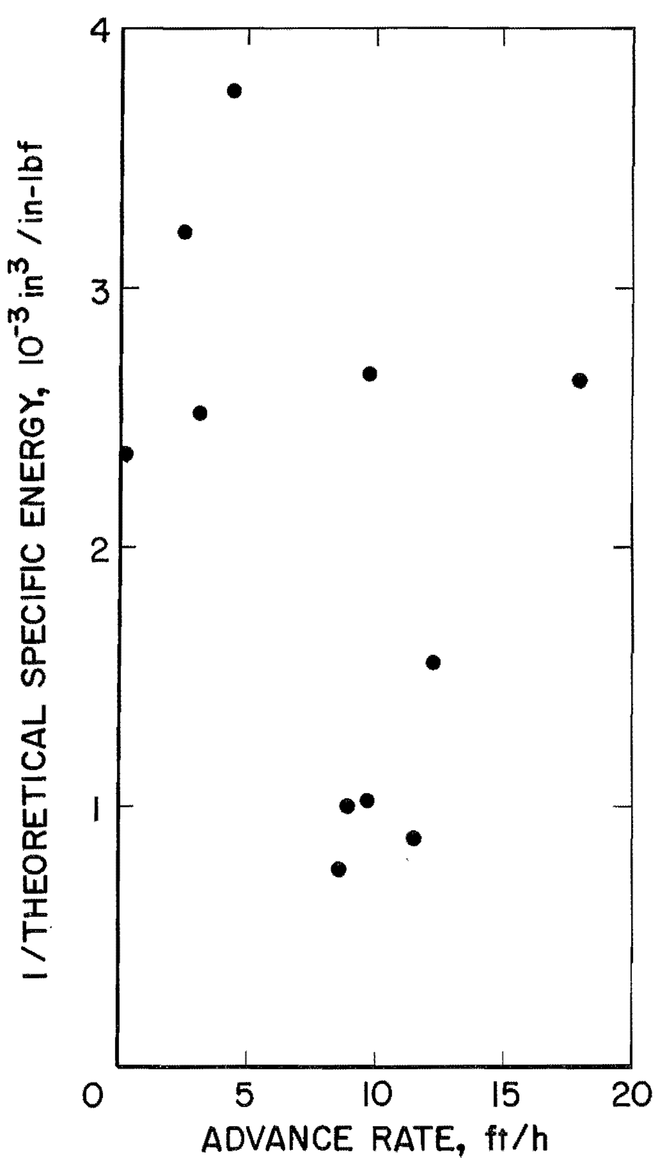

FIGURE 9.—Theoretical specific energy versus advance rate.

advance rate (fig. 8) is due to the creation of a coarser product. To evaluate if this is true for the water-jet-assisted traverse speed tests, the energy consumed per unit area of new surface created was calculated from the measured forces and the surface area of the rock chips produced. The energy consumed per unit area of new surface is plotted against advance rate (fig. 10) and clearly decreases with increasing advance rates. This indicates that the increase in efficiency with advance rate (fig. 8) is not completely attributable to produce size differences. From fracture mechanics theory, the energy required to create a new surface of unit area is represented by a material property termed the critical energy release rate. For an elastic rock the critical energy release rate is constant, therefore the variation shown in figure 10 must be due to the existence of a plastic zone and energy consumed in processes other than the fracture of rock. This supports the work of Tutluoglu (6), who concluded that energy losses due to friction can account for over 90 pct of the energy consumed.

From the results discussed previously, it is possible to reach some conclusion as to the effect of water jets on these energy losses. At low advance rates, profiling is more dominant since a lot of energy is consumed by processes other than rock breakage (fig. 10). As the advance rate increases as a result of the water jet application, chipping becomes more dominant and the cutting efficiency increases. As the water jet energy as a proportion of the total energy is increased, the relative dominance of profiling over chipping increases. This leads to a reduction in energy losses and a corresponding reduction in the energy consumed per unit area of new surface created. Therefore, prior to using fracture mechanics to model rock cutting, it is necessary to identify whether the predominant means of cutting is by profiling or by chipping in order to be able to estimate the energy consumed by processes other than rock breakage.

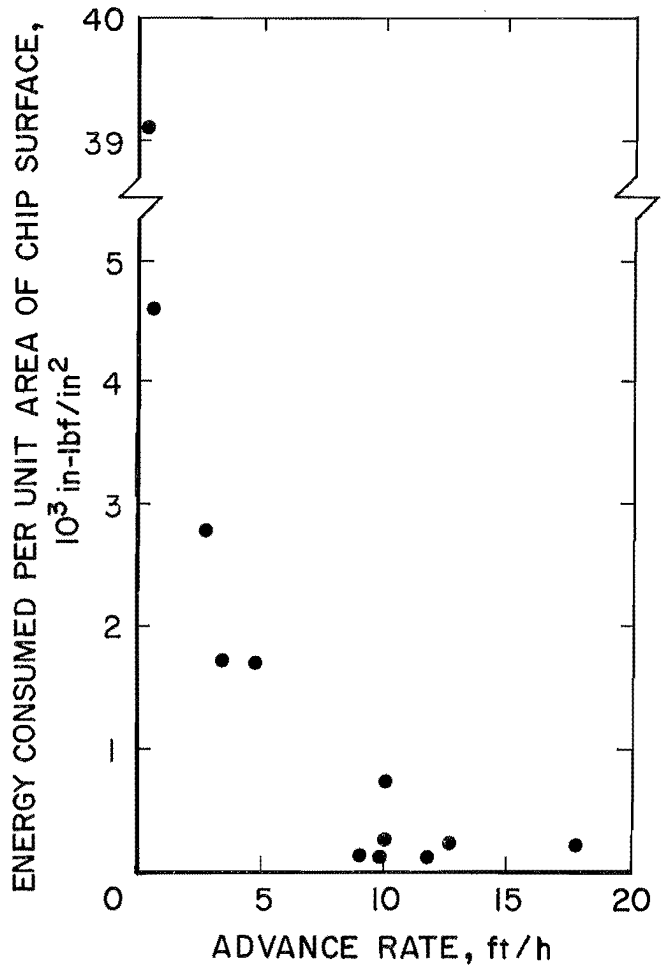

FIGURE 10.—Energy per unit area of chip surface versus advance rate.

SUMMARY AND CONCLUSIONS

This report describes analyses of the influence of water jets upon the size distribution of rock chips produced during laboratory cutting tests. The results are compared with various theoretical models for rock breakage under the combined action of a mechanical tool and a water jet to find the most appropriate jet pressures, jet locations, mechanical tool types, and tool speed.

Rock chips were collected from cutting tests conducted on a traverse speed test fixture, which was run at tool speeds of 35 to 248 ft/min. This test fixture simulated real-world cutting situations, as it maintained a constant thrust on the cutterhead while allowing the depth of cut to vary according to the conditions. However, the average cutting tool speed of 143 ft/min and the average depth of cut of 0.15 in are low in comparison with those achieved by mining machines such as shearers and continuous miners. The principal conclusions from this study are as follows:

For jet pressures of 0, 6,000, and 9,000 psi, the size distribution of the rock chips produced during cutting became coarser with increasing jet pressure. However a 2,000-psi jet produced a lower percentage of minus 80-mesh material than a dry cut.

As the jet energy as a proportion of the total energy is increased, the mechanical energy to achieve a unit depth of cut decreases in an approximately logarithmic fashion. A 2,000-psi jet is sufficient to remove the fine crushed material beneath the tip of the tool and thus reduce the thrust force. However, this pressure is not sufficient to cause fracture in German sandstone, and thus does not decrease the cutting force.

The only statistically significant difference in the results obtained using conical or V-face type tools was in the size distribution of the product from cutting. At an 85-pct level of significance, the conical tools produce less fine material than the V-face tool during jet assisted cutting.

Fracture mechanics theory states that in order for crack growth to occur, a certain critical energy release rate has to be exceeded. The critical energy release rate is a physical property of the rock and is constant if elastic behavior is assumed. The cutting tests showed that as the advance rate increased, the energy consumed per unit area of new surface created decreased, leading to increased cutting efficiency. This indicates that the amount of energy consumed by processes other than rock breakage decreases because of the use of water jets.

On the basis of figures 4 and 5, it is possible to draw some tentative conclusions concerning the rock breakage process during jet-assisted cutting. Low pressure (2,000 psi) water jets directed just in front of the tip of a cutting tool remove the crushed material from beneath the tool, thus reducing the effective bluntness of the tool. This results in a larger depth of cut for a constant thrust. As the jet pressure is increased (6,000 psi), the jets begin to exploit fractures created in the rock by the mechanical tool to produce chips at lower levels of cutting force. As the jet pressure is increased further, the cutting efficiency decreases because the jet penetration is sufficient to reduce the stress concentrating effect of the cutting tool tip.

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APPENDIX.--TEST DATA

Bit type	Thrust, lb	Torque, ft·lbf	rpm	Advance rate, ft/h	Chip area, in^2/in^3	Water	
						Pressure, psi	Flow, gal/min
Conical...	18,290	18,450	19.4	0.1	47.0	0	0
	21,870	36,350	9.22	12.31	71.9	6,039	1.22
	24,290	16,860	19.6	2.45	34.6	6,035	1.31
	24,860	17,600	19.1	9.67	41.5	8,743	1.63
V-face....	21,390	18,650	20.0	4.5	29.6	6,035	.77
	22,050	19,150	19.6	.15	273.2	0	0
	33,810	25,900	11.6	9.72	107.9	6,015	1.23
	33,920	15,200	22.94	3.11	43.9	6,021	1.10
	35,450	61,150	3.97	17.79	42.1	5,977	1.29
	35,560	21,250	14.46	11.49	126.4	5,845	1.22
	35,960	12,350	28.27	8.77	149.8	6,020	.97
	37,890	29,200	11.03	8.99	112.9	2,036	1.48

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