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Effects of Water on Coal Cutting Forces and Primary Dust Distribution

By Wallace W. Roepke and Theodore A. Myren

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

g	gram	mL	milliliter
gal/min	gallon per minute	mL/min	milliliter per minute
in/min	inch per minute	pct	percent
ksi	kip (10^3 lb) per square inch	psi	pound per square inch
lb	pound	r/min	revolution per minute
min	minute	μm	micrometer
		μm^3	cubic micrometer

EFFECTS OF WATER ON COAL CUTTING FORCES AND PRIMARY DUST DISTRIBUTION

By Wallace W. Roepke[1] and Theodore A. Myren[2]

ABSTRACT

Research to evaluate the lubricity effects achieved by spraying water on the cutting bit of a mining machine or spraying water on the coal during cutting has shown that neither practice affects cutting forces, as had been believed. However, when water was supplied to the cutting zone axially through the bit at 3,000 to 5,000 psi pressure, tangential cutting forces were reduced an average of 30 pct at a 1-in depth of cut while normal bit forces were reduced an average of 65 pct. Lower normal forces mean reduced bit wear, faster advance with greater depth of cut, and fewer coal fines.

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INTRODUCTION

Since the enactment of the Coal Mine Health and Safety Act of 1969 (Public Law 91-173), the Bureau of Mines has been actively involved in research to support the regulatory effort on respirable dust control. The use of water as a secondary respirable dust control has been an area for extensive research, but all of this past effort has been directed toward secondary suppression or collection of the respirable fraction after air entrainment. Previous research has not included addressing the use of water as a primary reduction technique in the cutting system area at the bit and coal interface.

As part of its research on modification of the coal cutting system to reduce dust, the Bureau has evaluated the effects of water on the cutting system forces that affect the dust levels generated and energy used. Previous research results (1)[3] have shown the cutting force and normal force to typically have a nominal ratio of 1.0 when a conical bit is used at a 45° attack angle. (See figure 1 for schematic description.) Research has also shown that this ratio will not vary if a bit rotates during use so that it wears symmetrically (2). When a bit locks up in use and wears asymmetrically, the normal force will rise abruptly at a rate 3 to 5 times faster than the cutting force (3).

Normal force is the controlling feature within the cutting system that affects depth of cut, since a power-limited machine operating near the stall point will only cut at maximum depth when the bits are not worn. As bit wear starts, the operator listening to the frequency response change and feeling the vibrations change on the machine will automatically start to back out or cut less deep. If the normal force (wear) can be controlled, then the machine will be able to cut near maximum depth a greater portion of the time. This greater efficiency will help control both dust and energy for the operator and will reduce the fines.

One possibility for reducing normal force is to provide a lubricant at the bit-coal interface surface. Since water is always available to a continuous mining machine, it seemed a logical first choice as a candidate for a lubricant. This report describes the results of an initial brief fundamental research effort to establish a trend for the effects of water on the cutting system.

ACKNOWLEDGMENT

The authors would like to recognize the contribution of Sterling J. Anderson, mining engineer, Twin Cities Research Center, Bureau of Mines, Minneapolis, MN, who provided a major part of the technical assistance in designing and using the high-pressure test equipment.

TEST EQUIPMENT

The test system used for this work consisted of two major components. The first component was existing equipment previously used for other cutting research. This is fully described elsewhere (2-3), so only an abbreviated description will be included here. The second component was all equipment required to provide the necessary water flow to the cutting system.

The major component of existing equipment included a large planer mill modified for coal cutting tests. This system includes the mainframe, a quartz crystal dynamometer for orthogonal force measurements of the cutting bit, the bit holder with bit, sample support system, sample translation table, and a respirable dust measurement system. A microcomputer was used for data on-line aquisition.

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

The second major component included both a low-pressure and high-pressure system. The low-pressure system was an open-ended hypodermic needle (No. 22) with a micro pump and valve to supply the desired flow rate. The high-pressure system included a reservoir, a filter, an air-driven single-piston fixed-displacement pump capable of 15,000 psi, a pulsation damper, and a modified cutting bit designed as a nozzle.

GENERAL TEST DESCRIPTION

To establish baseline information on the effects of normal water use (i.e., spray distribution on cutting forces), two assumptions were made concerning the cutting system analogy to be tested. The first was the use of a drum-type continuous miner on sump with 80 conical bits on a 36-in-diam drum, rotating at 60 r/min and using 24 gal/min water. The second assumption was that the water would be equally distributed and optimally placed at a point for each of the bits on the drum, and used only during the time each bit was cutting coal. This would provide 1 mL/min water to the cutting area at each bit tip.

To determine whether any increase in water volume would enhance dust control or change cutting forces, the volume used was doubled (to 2 mL/min) for water-on-bit tests. Doubling the volume was not tried for water-on-coal tests, since the 1-mL volume amply demonstrated the effectiveness of water (fig. 2). Two positions were chosen for water placement

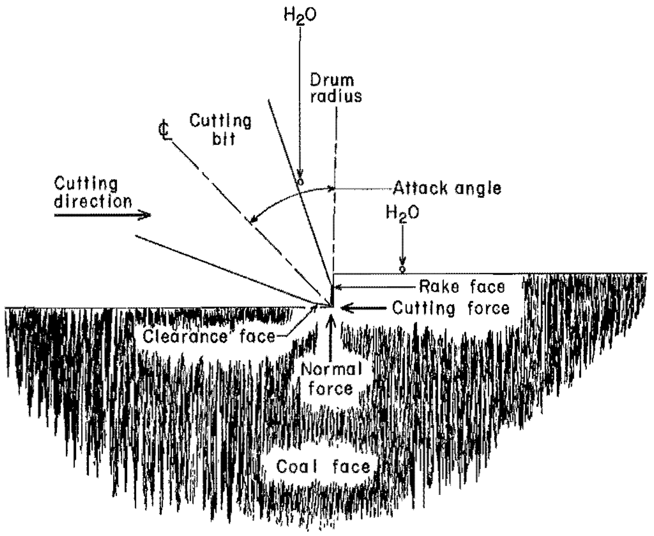

FIGURE 1. - Schematic of coal block in test configuration (i.e., vertical bedding planes) with cutting system definitions.

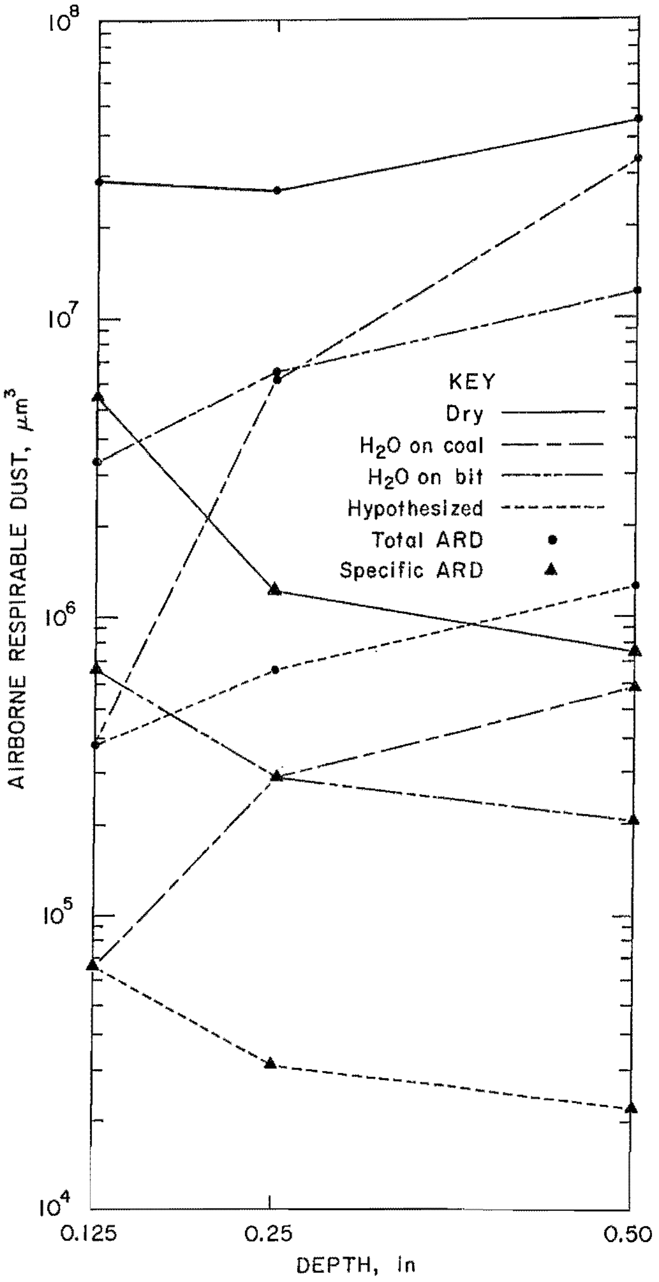

FIGURE 2. - Variation of dust versus depth for cutting dry or with water on coal or water on bit.

with these volume conditions. One was directly on the rake side of the cutting tool, 1/4 in back from the tip, to simulate a water-flushed tool (water on bit); the other was 3/8 in ahead of the bit, on the uncut coal surface (water on coal), to simulate a more general spray coverage (fig. 1).

Although these tests were performed by cutting horizontally in the coal samples, all cuts were made with the coal samples rotated 90° from the in situ condition so that cutting would be perpendicular to the bedding planes, as shown schematically in figures 1 and 4, and thus approximate the actual cutting condition.

The standard test procedure in the first two configurations moved the coal sample past the fixed cutting tool at a nominal 2 in/min. This test condition permits ample data acquisition in a 4-in test cut. Speed effects on fracture propagation could be expected to occur if cutting were at rates lower than the creep rate or greater than crack propagation rate. Since the intent of these tests was an evaluation of primary dust and cutting forces unaffected by air entrainment due to high-speed fanning or impact effects during cutting, the test speed chosen permitted optimum data acquisition with the system used without unwanted extraneous dust distribution. A full description of this test procedure is contained in earlier publications (1-2).

Although this method provides greater data recovery with small samples, it is also substantially different than an actual rotary test. In the present case, it produces a positive bias to the results, since the much slower cutting speed increases the dwell time of the water on the cutting zone. The travel distance, in inches per minute of each bit on a 36-in-diam drum operating at 60 r/min, is given by:

$$L_d = (\pi\ d)\ \text{r/min} = 36 \times 60 \qquad (1)$$

$$= 6785.84$$

Since the test speed used was 2 in/min, the dwell time of the test is $\frac{6,786}{2}$ times greater than the actual in-mine cutting condition. Dwell time for the water, which is approximately 3,400 times greater than under actual cutting conditions, significantly increases the permeation time for the water, allowing maximum surface water to penetrate to the crushing zone around a bit tip.

The effect of this on dust generation can be seen for water on the bit in the results (fig. 2). The dwell time of water on the bit rake face permitted water to penetrate to the high dust area around the tip, even at the maximum depth tested. The water reduced generation of airborne respirable dust (ARD) equally over the entire depth tested for both total ARD and ARD per unit volume (specific ARD). It can be seen in figure 3 that

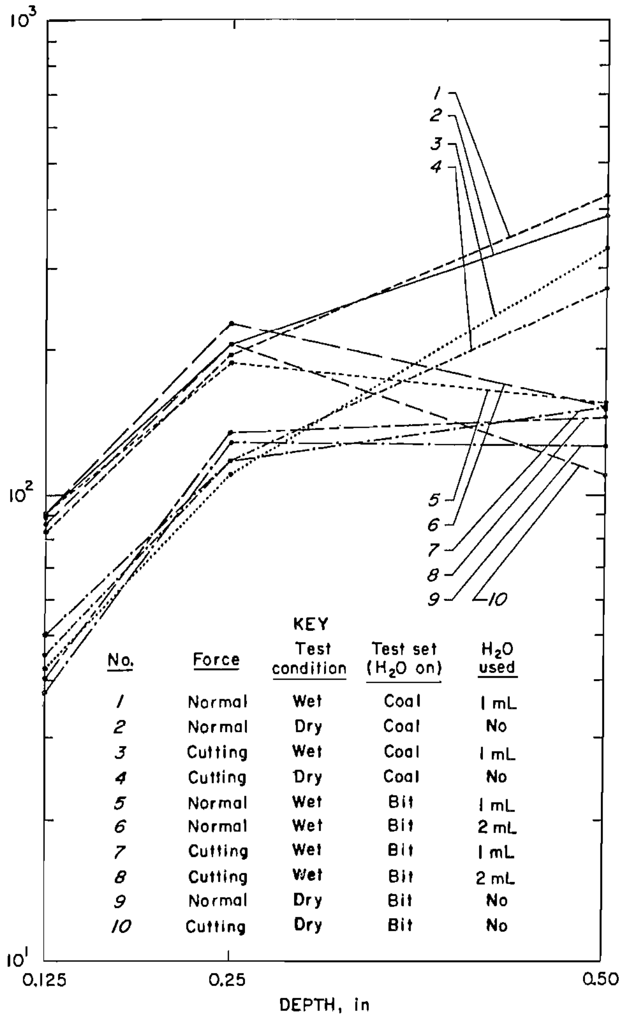

FIGURE 3. - Variation of forces versus depth for cutting dry or with water on coal or water on bit.

water on the bit caused an increase in normal forces, (curves 5, 6, and 9), but a decrease in cutting forces, (curves 7, 8, and 10). The effect of these changes tends to cancel each other, so the end result is no significant change in forces due to bit surface wetting.

When the water was placed on the surface of the coal 3/8 in ahead of the cutting tool, the effect of the extra penetration time on dust generation was even more obvious. The results (fig. 2) show that the extreme permeation time significantly enhanced the primary dust control in the crushing zone around the bit tip at 1/8-in depth cut. As the bit depth increased to 1/2 in, not only did this enchancement disappear, but the results showed an effect equivalent to dry cutting; i.e., there is no effect on primary dust generation due to water sprayed on the coal face. There was no significant difference in forces for water on coal (fig. 3, curves *1-4*).

A schematic representation in cross section is shown in figure 4 of the envisioned crushed zone to water reduction relationship for primary dust generation with the various depths of cut. The effect on dust at 1/8-in depth was an order-of-magnitude improvement (fig. 2) over the reduction effect on dust in the first test series, which had water on the bit. The inference can be made that water in the crushed zone would have the same relationship to dust at every depth cut as water on the bit. Hypothesized curves, plotted on figure 2, show the inferred effects of this if the 1/8-in depth of cut for water on coal is considered as optimum dust control at all depths of cut.

To test the inference, a conical bit with water down the axis was designed (4) to get the water directly into the primary dust zone around the bit tip for better control of dust at every depth of cut. When the first tests were done, it was obvious that while this might represent a solution to the primary dust problem, another problem was created. The optical particle sizer being used could not differentiate between coal dust and water droplets of the same size. Given the time restraints on doing a short

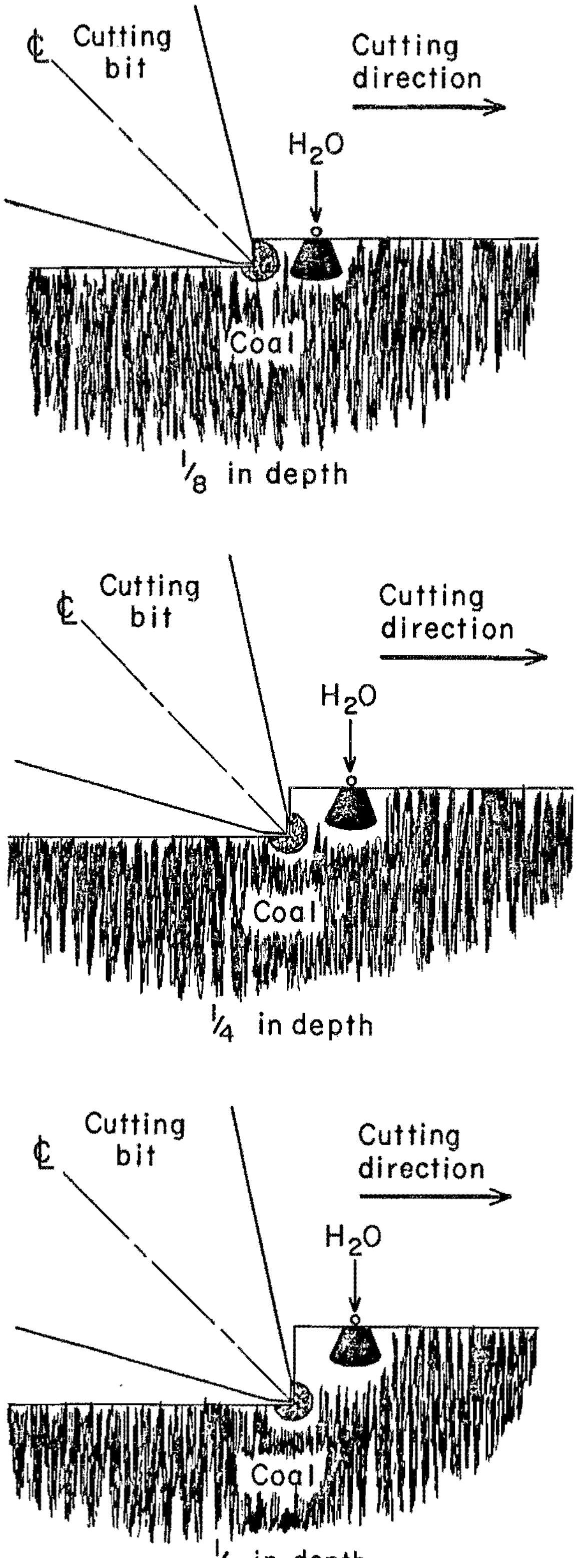

FIGURE 4. - Postulated configurations of water-on-coal permeations for different depths of cut showing proximity to the primary crushing zone for each case.

series of tests, no quick solution to this problem could be found, although several methods were considered and rejected.

Recovery of forces data is, fortunately, not affected by water vapor. Since previous research (1) had shown that specific energy and dust penetration are directly related, recovery of cutting forces data will also supply an indication of dust generation. It can be seen in figure 5 that the tangential cutting forces obtained (curves *1-4*) were reduced only slightly because of water at the tip area, but the normal force (curves *5-8*) showed a significant 65-pct reduction.

These tests were done in a different manner than the first two test sets. The bit design used had a very small orifice to place the water exactly at the center of the crushing zone around the bit tip. To be sure that plugging of this small orifice (0.010 in) by coal fragments did not occur, 2,500 psi to 6,000 psi water pressure was used. This introduced a larger volume of water than desirable at the original test speed of 2 in/min, so a sample speed of approximately 48.5 in/min was used. A summary of the Student's t analysis is given in table 1.

The raw data used for the statistical analysis are presented in appendix A. A short description of the analysis technique used is given in appendix B.

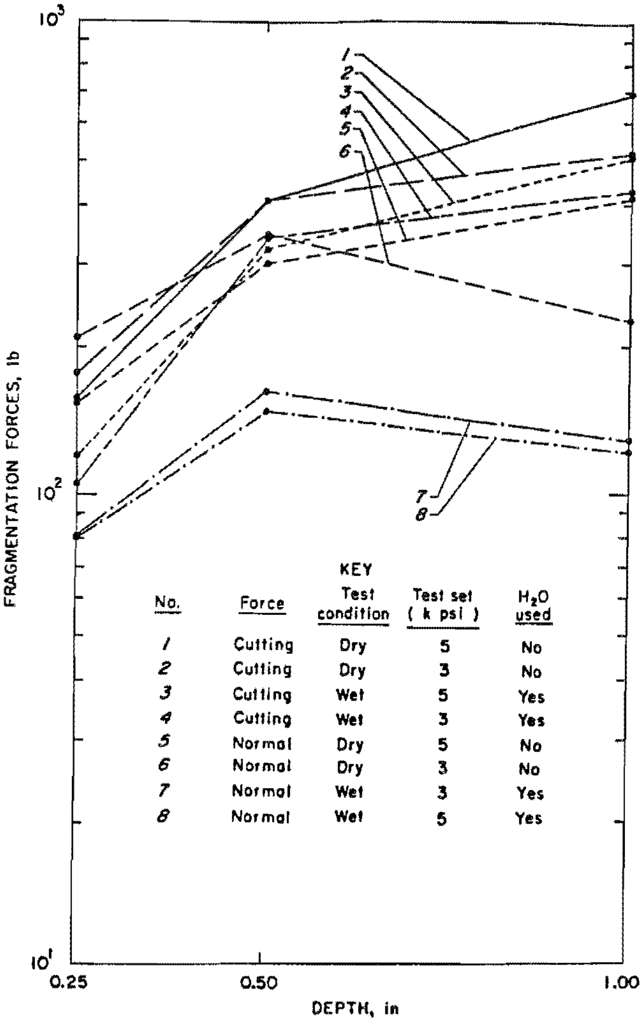

FIGURE 5. - Variation of average forces for cutting dry or with high-pressure water as a function of depth.

SUMMARY AND CONCLUSIONS

The Student's t analysis (table 1 *A*) and the curves in figure 2 show that water on the bit reduces airborne respirable dust (ARD) a nominal decade as compared with dry cutting. This reduction is consistent over the range of depth of cut tested.

The Student's t analysis (table 1 *B*) and the curves in figure 2 show that water on the coal ahead of the bit reduces the ARD by a nominal two decades at the shallowest (1/8 in) depth of cut. The effectiveness varies inversely with depth, however, so a 1/2-in depth of cut nominally shows no effect due to water, as postulated in figure 4.

Cutting and normal force are unaffected by either water on the bit or water on the coal (fig. 3). The results show that water permeating to the crushing zone around the bit tip during shallow cutting is a very effective dust control technique. This is no doubt due to the long dwell time for water on the surface of the coal. With the experimental design being used, this dwell time is approximately 3,400 times that of a drum-type miner operating at 60 r/min. It is unlikely that permeation would be so effective at normal cutting speeds. These tests were conducted without use of surfactant; it is very likely that such an addition would further improve the results. The results also show, however, that water must be in the crushed zone to be effective and, further, that permeation from water-on-the-coal surface, at least without surfactant, is not an effective technique for wetting the crushed zone beyond shallow cutting, even at the very slow cutting speed used in these tests.

The effectiveness of water in the crushed zone and the loss of effectiveness with increasing depth of cut suggest that proper placement is of paramount importance to optimum dust control with water during cutting.

TABLE 1. - Student's t values

Illinois coal	Av force		ARD	
	Cutting	Normal	Specific	Total
A, H_2O ON BIT				
1/8 in:				
Dry vs 1 mL.........	[1]1.225	0.276	[1]1.533	[1]1.394
Dry vs 2 mL.........	.172	.015	[1]1.610	[1]1.482
1 mL vs 2 mL........	[1]1.240	.200	.704	.997
1/4 in:				
Dry vs 1 mL.........	.380	.268	[2]2.037	[2]1.781
Dry vs 2 mL.........	.276	.710	[2]2.269	[2]2.057
1 mL vs 2 mL........	.622	[1]1.210	.455	.480
1/2 in:				
Dry vs 1 mL.........	.919	[1]1.051	[2]3.086	[2]3.99
Dry vs 2 mL.........	.640	[1]1.129	[2]3.171	[2]3.92
1 mL vs 2 mL........	.185	.110	.706	.807
B, H_2O ON COAL				
Dry vs 1 mL:				
1/8 in..............	0.319	0.407	[2]3.236	[2]2.945
1/4 in..............	.343	.278	[2]2.710	[2]2.649
1/2 in..............	[2]2.109	.639	.564	.618
C, H_2O DOWN THE BIT AXIS				
1/4 in:				
Dry vs 3 ksi........	[2]3.411	[2]4.867	0.963	[2]2.484
Dry vs 5 ksi........	[1]1.292	[2]2.631	.020	[2]3.227
3 ksi vs 5 ksi......	[2]2.029	[2]3.164	.029	[2]2.697
1/2 in:				
Dry vs 3 ksi........	[1]1.065	[2]3.609	[2]1.599	[2]4.824
Dry vs 5 ksi........	[2]1.437	[2]3.469	[2]1.834	[2]5.100
3 ksi vs 5 ksi......	.184	.853	.272	.479
1 in:				
Dry vs 3 ksi........	.754	[2]1.799	[2]2.058	[2]2.164
Dry vs 5 ksi........	[2]2.565	[2]6.429	[2]3.005	[2]6.925
3 ksi vs 5 ksi......	[1]1.081	[2]2.904	.297	[2]1.831

[1] Indicates a significant difference at the 80-pct confidence level.

[2] Indicates a significant difference at the 90-pct confidence level.

NOTE.--Since the data have some large variation between variances, ANOVA was not sufficiently precise for the statistical analysis. A modified Student's (one-tailed only) analysis was used. Lipson and Sheth (7) give a complete explanation of the technique.

It was inferred from these initial two test designs that water should always be placed directly in the crushed zone at the bit tip for optimum primary dust control. To do this, a bit was designed with an axial water channel and a nozzle orifice at the bit tip. Although no dust analysis was obtained when tests were run, cutting force and normal force data were obtained. The assumption may be made, based on the previous test results for water on coal at 1/8-in depth of cut, that water directly in the crushing zone will prevent primary respirable dust entrainment.

Previous water-on-coal and water-on-bit tests also indicate that water used in these configurations will have minimal effect on cutting and normal forces. When water is placed in the crushed zone at high pressure, a significant effect is observed in forces. It can be seen from figure 5 that, with high-pressure water, a significant reduction in normal force occurs. This reduction in normal force is an even greater basic improvement in the cutting system than a reduction in dust alone. A reduction in normal force will increase bit life by reducing frictional heating and abrasion failure. Reduction of normal force will also improve depth of cut, since for a given horsepower, sump rate (advance) will be increased. This greater depth will reduce specific dust and energy and will provide fewer fines.

The end result of high-pressure water through the bit is the ability to control normal force, the single most significant element of the cutting system. Normal force is the element most significant to primary dust generation, frictional ignitions, bit life, depth of cut, product size, and mainframe machine design.

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APPENDIX A

TABLE A-1. - Raw test data for dry versus water-on-bit coal cutting

Test conditions	Force, lb		Cut coal, g	Dust, µm^3	
	Cutting	Normal		Specific	Total
1/8-IN DEPTH OF CUT (SPACE 4X DEPTH)					
Dry:					
Test 1	49	117	4.9	2.4E+6	1.2E+7
Test 2	22	52	5.5	3.3E+6	1.8E+7
Test 3	22	64	2.4	3.7E+6	8.8E+6
Test 4	58	107	5.3	2.0E+7	1.0E+8
$\bar{X}$ (mean)	37.75	85	4.5	7.3E+6	3.6E+7
Std dev	18.55	31.82	1.4	8.3E+7	4.6E+7
Wet, 1 mL/min:					
Test 1	42	62	5.5	8.1E+5	4.5E+6
Test 2	50	109	4.5	1.3E+5	6.0E+5
Test 3	55	70	4.4	1.8E+6	7.9E+6
Test 4	50	110	4.7	1.2E+6	5.8E+6
Test 5	50	100	5.9	3.5E+5	2.1E+6
$\bar{X}$ (mean)	49	90	5.0	8.7E+5	4.2E+6
Std dev	4.7	22.6	.7	6.7E+5	2.9E+6
Wet, 2 mL/min:					
Test 1	29	54	4.0	2.0E+6	7.9E+6
Test 2	48	96	5.8	2.3E+5	1.4E+6
Test 3	17	25	3.6	7.1E+4	2.6E+5
Test 4	59	153	4.6	2.3E+5	1.1E+6
Test 5	46	99	7.8	8.1E+4	6.3E+5
$\bar{X}$ (mean)	40	85	5.2	5.2E+5	2.2E+6
Std dev	16.7	49	1.7	8.2E+5	3.2E+6
1/4-IN DEPTH OF CUT (SPACE 4X DEPTH)					
Dry:					
Test 1	103	164	23.3	1.1E+6	2.6E+7
Test 2	130	171	21.5	4.3E+5	9.2E+6
Test 3	152	277	29.2	1.4E+6	4.2E+7
$\bar{X}$ (mean)	128	204	24.7	9.9E+5	2.6E+7
Std dev	24.5	63.3	4.0	5.1E+5	1.6E+7
Wet, 1 mL/min:					
Test 1	126	183	20.0	2.7E+5	5.4E+6
Test 2	151	247	24.7	5.9E+5	1.5E+7
Test 3	79	144	17.4	1.3E+5	2.2E+6
$\bar{X}$ (mean)	119	191	20.7	3.3E+5	7.4E+6
Std dev	36.6	52	3.7	2.4E+5	6.5E+6
Wet, 2 mL/min:					
Test 1	138	226	20.8	8.5E+5	1.8E+7
Test 2	98	178	14.7	4.6E+4	6.8E+5
Test 3	146	239	23.8	2.9E+4	6.9E+5
Test 4	150	272	18.7	6.4E+4	1.2E+6
Test 5	133	246	26.2	1.9E+5	4.9E+6
$\bar{X}$ (mean)	133	232	20.8	2.4E+5	5.1E+6
Std dev	20.7	35	4.5	3.5E+5	7.3E+6

TABLE A-1. - Raw test data for dry versus water-on-bit coal cutting--Continued

Test conditions	Force, lb		Cut coal, g	Dust, μm^3	
	Cutting	Normal		Specific	Total
1/2-IN DEPTH OF CUT (SPACE 2-1/2X DEPTH)					
Dry:					
Test 1....................	118	65	64.0	1.0E+6	6.4E+7
Test 2....................	157	164	76.7	8.4E+5	6.4E+7
Test 3....................	78	71	100.8	3.0E+5	3.0E+7
Test 4....................	150	135	48.1	8.3E+5	4.0E+7
$\bar{X}$ (mean).................	126	109	72.4	7.4E+5	5.0E+7
Std dev..................	109	49	22.3	3.1E+5	1.7E+7
Wet, 1 mL/min:					
Test 1....................	128	80	63.6	1.9E+5	1.2E+7
Test 2....................	118	105	63.2	2.1E+5	1.2E+7
Test 3....................	201	194	70.6	1.8E+5	1.3E+7
Test 4....................	151	252	50.5	4.0E+5	2.0E+7
$\bar{X}$ (mean).................	150	158	62.0	2.4E+5	1.4E+7
Std dev..................	37	80	8.4	1.0E+5	3.8E+6
Wet, 2 mL/min:					
Test 1....................	117	114	33.3	7.7E+4	2.6E+6
Test 2....................	138	124	56.5	4.7E+4	2.6E+6
Test 3....................	94	122	76.3	2.1E+5	1.6E+7
Test 4....................	256	283	63.0	1.5E+4	9.7E+5
Test 5....................	105	96	59.8	2.5E+4	1.5E+6
Test 6....................	107	80	71.8	4.9E+4	3.5E+6
Test 7....................	192	247	54.0	7.4E+5	4.0E+7
$\bar{X}$ (mean).................	144	152	59.2	1.7E+5	9.5E+6
Std dev..................	59	79	14.0	2.6E+5	1.4E+7

TABLE A-2. - Raw test data for dry versus water-on-coal coal cutting

Test conditions	Force, lb		Cut coal, g	Dust, μm^3	
	Cutting	Normal		Specific	Total
1/8-IN DEPTH OF CUT (SPACE 4X DEPTH)					
Dry:					
Test 1....................	36	80	3.8	1.5E+6	5.6E+6
Test 2....................	33	52	5.8	9.6E+5	5.6E+6
Test 3....................	31	59	5.4	2.8E+6	1.5E+7
Test 4....................	29	70	3.4	1.6E+6	5.3E+6
Test 5....................	25	52	4.7	2.6E+6	1.2E+7
Test 6....................	25	31	8.1	8.7E+5	7.0E+6
Test 7....................	45	100	6.8	4.2E+6	2.8E+7
Test 8....................	84	172	10.9	1.4E+6	1.6E+7
Test 9....................	66	135	7.0	1.1E+7	7.5E+7
Test 10...................	77	156	5.9	6 4E+6	3.8E+7
$\bar{X}$ (mean).................	45.1	90.7	6.2	3.3E+6	2.1E+7
Std dev..................	22.3	48.3	2.2	3.1E+6	2.2E+7
Wet, 1 mL/min:					
Test 1....................	36	87	4.2	6.2E+4	2.6E+5
Test 2....................	27	57	6.7	3.0E+4	2.0E+5
Test 3....................	21	48	4.0	3.4E+3	1.3E+4
Test 4....................	28	63	5.8	3.1E+4	1.0E+5
Test 5....................	8	20	9.3	3.4E+4	3.2E+5

TABLE A-2. - Raw test data for dry versus water-on-coal coal cutting--Continued

Test conditions	Force, lb		Cut coal, g	Dust, µm^3	
	Cutting	Normal		Specific	Total
1/8-IN DEPTH OF CUT (SPACE 4X DEPTH)--Continued					
Wet, 1 mL/min--Continued:					
Test 6	37	61	3.6	2.1E+5	7.4E+5
Test 7	60	97	6.1	5.8E+4	3.5E+5
Test 8	79	149	6.3	1.4E+5	8.7E+5
Test 9	68	133	7.7	8.8E+4	6.8E+5
Test 10	55	111	5.0	2.5E+4	1.3E+5
X̄ (mean)	42	83	5.9	6.7E+4	3.7E+5
Std dev	22.6	40.3	1.8	6.1E+4	2.8E+5
1/4-IN DEPTH OF CUT (SPACE 4X DEPTH)					
Dry:					
Test 1	77	126	17.5	7.3E+5	1.3E+7
Test 2	62	92	29.5	5.2E+4	1.5E+6
Test 3	89	163	23.6	4.2E+5	9.9E+6
Test 4	45	107	18.8	2.1E+5	3.9E+6
Test 5	128	263	21.3	1.8E+6	3.8E+7
Test 6	172	253	32.7	1.4E+5	4.4E+6
Test 7	156	241	21.5	2.7E+6	5.8E+7
Test 8	190	348	20.6	2.6E+6	5.3E+7
Test 9	152	306	23.8	3.8E+6	9.1E+7
Test 10	105	171	26.8	1.6E+6	4.2E+7
X̄ (mean)	118	207	23.6	1.4E+6	3.1E+7
Std dev	49.4	87.6	4.8	1.3E+6	3.0E+7
Wet, 1 mL/min:					
Test 1	61	82	22.6	3.0E+5	6.7E+6
Test 2	127	263	20.0	6.2E+5	1.2E+7
Test 3	141	305	17.7	3.2E+5	5.7E+6
Test 4	75	161	19.0	2.0E+4	3.8E+5
Test 5	55	105	20.0	4.8E+5	9.5E+6
Test 6	63	80	17.4	6.0E+4	1.0E+6
Test 7	155	213	35.4	3.5E+5	1.2E+7
Test 8	150	217	27.2	2.3E+5	6.3E+6
Test 9	137	228	28.8	4.7E+4	1.4E+6
Test 10	142	308	20.0	3.2E+5	6.5E+6
X̄ (mean)	111	196	22.8	2.8E+5	6.2E+6
Std dev	41.5	86	5.8	1.9E+5	4.4E+6
1/2-IN DEPTH OF CUT (SPACE 2-1/2X DEPTH)					
Dry:					
Test 1	330	569	60.1	1.5E+6	8.9E+7
Test 2	261	542	59.7	2.2E+6	1.3E+8
Test 3	298	362	59.3	1.4E+5	8.3E+6
Test 4	313	388	52.6	2.0E+5	1.1E+7
Test 5	264	400	41.4	1.7E+5	7.0E+6
Test 6	295	433	47.8	1.3E+6	6.0E+7
Test 7	170	200	99.0	4.4E+5	4.4E+7
Test 7	210	177	77.2	2.7E+5	2.1E+7
Test 8	292	416	74.6	4.8E+5	3.6E+7
X̄ (mean)	270	387	63.5	7.4E+5	4.5E+7
Std dev	51.3	132.3	17.6	7.3E+5	4.2E+7

TABLE A-2. - Raw test data for dry versus water-on-coal coal cutting--Continued

Test conditions	Force, lb		Cut coal, g	Dust, μm^3	
	Cutting	Normal		Specific	Total
1/2-IN DEPTH OF CUT (SPACE 2-1/2X DEPTH)--Continued					
Wet, 1 mL/min:					
Test 1....................	356	471	71.2	1.2E+6	8.2E+7
Test 2....................	344	498	77.6	5.2E+5	4.0E+7
Test 3....................	450	580	52.1	2.1E+5	1.1E+7
Test 4....................	295	378	58.7	7.5E+5	4.4E+7
Test 5....................	238	231	70.1	6.6E+4	4.6E+6
Test 6....................	281	308	60.8	2.2E+5	1.3E+7
Test 7....................	376	551	47.5	1.4E+6	6.8E+7
Test 8....................	308	396	57.7	2.2E+5	1.3E+7
$\bar{X}$ (mean).................	331	427	62.0	5.7E+5	3.4E+7
Std dev..................	65.4	120.5	10.2	5.0E+5	2.9E+7

TABLE A-3. - Cutting forces for dry versus wet (3,000 psi) blocks C and D, pounds

(Illinois coal; spacing, 2 in; table speed, 48.5 in/min)

Cut	Dry				Wet (3,000 psi)			
	Horizontal		Normal		Horizontal		Normal	
	Peak	Av	Peak	Av	Peak	Av	Peak	Av
1/4-IN DEPTH OF CUT								
1C	447	200	649	249	543	118	505	102
2C	838	228	1,023	287	754	137	563	117
3C	1,012	241	1,023	271	544	122	369	100
1D	380	144	452	171	285	91	222	65
2D	468	147	552	190	511	83	260	49
3D	486	124	373	131	243	77	199	49
1/2-IN DEPTH OF CUT								
4C	1,281	500	872	360	1,184	467	450	213
5C	1,125	346	752	316	1,406	561	635	282
6C	1,121	492	1,140	561	861	335	534	193
4D	1,014	399	802	318	530	174	190	63
5D	1,064	329	681	274	764	325	265	123
6D	1,109	441	916	312	555	219	344	108
1-IN DEPTH OF CUT								
7C	2,007	826	1,085	437	1,470	776	637	220
8C	2,135	600	652	138	1,540	526	435	155
9C[1]	1,292	183	470	98	1,657	437	277	71
7D	1,210	478	667	292	802	244	135	46
8D	2,015	578	747	226	895	267	385	87
9D	1,630	503	505	207	1,242	389	662	199

[1] For dry block, chunk broke out at end, and bit coasted.

TABLE A-4. - Cutting forces for dry versus wet (5,000 psi) blocks E, F, and G, pounds

(Illinois coal; spacing, 2 in; table speed, 48.5 in/min)

Cut	Dry				Wet (5,000 psi)			
	Horizontal		Normal		Horizontal		Normal	
	Peak	Av	Peak	Av	Peak	Av	Peak	Av
	1/4-IN DEPTH OF CUT							
1E	668	217	679	263	------Plugged------			
2E	734	183	813	173	1,024	109	377	47
3E	1,024	205	656	161	1,073	207	415	129
1F	718	148	538	163	468	152	267	121
2F	552	221	532	234	481	88	218	52
3F	513	143	397	133	470	211	304	154
1G	373	80	264	58	432	80	338	65
2G[1]	454	86	478	83	453	31	96	19
3G	395	136	326	126	446	87	361	76
	1/2-IN DEPTH OF CUT							
4E	2,431	424	1,196	321	1,606	313	294	85
5E	1,907	425	571	180	1,649	432	579	274
6E	2,482	541	1,110	472	2,272	490	594	237
4F	1,525	390	1,097	313	1,024	511	440	160
5F	1,607	522	951	437	859	341	672	149
6F	1,496	531	935	357	1,101	418	605	248
4G	1,260	259	919	275	637	164	291	78
5G	1,114	336	727	168	771	168	232	42
6G	955	311	677	240	542	141	236	86
	1-IN DEPTH OF CUT							
7E	3,097	742	1,155	483	2,162	441	257	91
8E	2,715	650	802	393	2,225	665	355	144
9E	2,985	953	1,325	677	1,635	464	300	96
7F	2,247	729	1,007	302	1,602	482	237	135
8F	2,505	812	857	376	1,785	775	797	209
9F	2,147	833	722	354	1,475	612	372	150
7G	1,287	360	877	244	875	271	185	55
8G	1,947	565	897	420	1,030	506	325	82
9G	1,855	786	920	546	1,342	476	385	147

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[1] Shallow cut for wet block.

TABLE A-5. - Cutting forces for wet (3,000 psi) versus wet (5,000 psi) blocks H and J, pounds

(Illinois coal; spacing, 2 in; table speed, 48.5 in/min)

Cut	Wet (3,000 psi)				Wet (5,000 psi)			
	Horizontal		Normal		Horizontal		Normal	
	Peak	Av	Peak	Av	Peak	Av	Peak	Av
	1/4-IN DEPTH OF CUT							
1H	177	51	147	41	191	50	84	28
2H	198	57	146	46	218	54	135	29
3H	258	60	176	52	221	59	131	34
1J	227	67	178	59	315	70	175	59
2J	258	78	175	70	195	38	143	23
3J	316	85	204	70	289	36	105	26
	1/2-IN DEPTH OF CUT							
4H	563	270	284	113	786	331	309	146
5H	597	237	296	101	904	413	360	150
6H	614	235	197	84	844	302	355	129
4J	780	291	360	141	809	302	350	109
5J	938	322	395	168	776	148	276	59
6J	1,207	456	614	300	751	261	324	135
	1-IN DEPTH OF CUT							
7H	730	203	340	110	917	371	522	185
8H	1,055	432	465	224	1,117	467	247	96
9H	1,110	496	502	275	1,410	449	275	91
7J	1,217	433	382	221	915	190	242	70
8J	1,787	561	555	273	1,542	337	435	144
9J	1,695	812	595	301	1,342	513	427	200

APPENDIX B

A complete analysis was not used because the variances were unequal. Therefore, a modified Student's t analysis was performed. A summary of the technique for a one-tailed distribution is as follows:

$$t = \frac{\overline{X} - \overline{Y}}{\sqrt{S_X{}^2/N_X + S_Y{}^2/N_Y}}$$

The Student's t value is then evaluated using the appropriate table for V degrees of freedom when

$$V = \frac{(S_X{}^2/N_X + S_Y{}^2N_Y)^2}{\frac{(S_X{}^2/N_X)^2}{N_X + 1} + \frac{(S_Y{}^2/N_Y)^2}{N_Y + 1}} - 2$$

where $S_X{}^2$, $S_Y{}^2$ = sample variance,

$\overline{X}$, $\overline{Y}$ = sample means,

and N_X, N_Y = number of tests.

For a complete description of the method used, consult Lipson and Sheth (7),[1] or any other publication on experimental statistics.

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[1] Underlined numbers in parentheses refer to items in the list of references preceding the appendixes.

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