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Drag Bit Cutting Characteristics Using Sintered Diamond Inserts

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UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm	centimeter
cm/min	centimeter per minute
cm/s	centimeter per second
cu ft	cubic foot
cu m	cubic meter
cu µm	cubic micrometer
cu µm/g	cubic micrometer per gram
ft	foot
g	gram
g/min	gram per minute
gal/min	gallon per minute
hp	horsepower
in	inch
in/min	inch per minute
in/s	inch per second
J/g	joule per gram
$J/g{\cdot}h^{-1}$	joule per gram, per hour
kg/sq cm	kilogram per square centimeter
m	meter
mg/cu m	milligram per cubic meter
mg/ton	milligram per short ton
min	minute
µm	micrometer
N	newton
pct	percent
psi	pound per square inch
rpm	revolution per minute

DRAG BIT CUTTING CHARACTERISTICS USING SINTERED DIAMOND INSERTS

By Wallace W. Roepke,[1] Bruce D. Hanson,[2] and Carl E. Longfellow[3]

ABSTRACT

The Bureau of Mines tested new designs of drag bit cutters with sintered diamond inserts instead of standard tungsten carbide tips. The bits were tested for orthogonal cutting forces, primary dust generation, and incendivity, with a standard plumb-bob type conical cutter (60° included tip angle) as the reference. Preliminary wear and impact-failure testing were also done. The results were mixed. Two new designs had forces similar to those of the reference bit, but one new design had about twice the normal force. This same design had almost twice the specific energy during shallow cutting but generated an equal or slightly lower amount of primary dust than did the reference bit. Incendivity was eliminated for two radial designs. One conical design had ignition only after more than 15 impacts, but the other conical design was incendive. Impact failure occurred, but not so quickly as anticipated. Over 7,500 impacts on a sandstone face, with a total cutting distance of more than 1,981.2 m, only scuffed the leading edge of the sintered diamond cutting face but put hairline cracks in the substrate mounting pad. Additional design and testing are needed to develop an optimum cutter, but prospects look good for this material.

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INTRODUCTION

The Federal Coal Mine Health and Safety Act of 1969, with revisions in 1977, was enacted to ensure more healthful and safer working conditions for miners. The Bureau of Mines coal-cutting research facility at Twin Cities (MN) is examining fundamental aspects of the cutting system, including primary dust generation, which affects pneumoconiosis rate in miners, and frictional impact ignition of methane by continuous mining machines (CMM's).

The regulation requiring that airborne respirable dust (ARD) not exceed 2 mg/cu m is intended to reduce the incidence of pneumoconiosis or "black lung" in coal miners. This legislation with its subsequent monitoring and enforcement by the Mine Safety and Health Administration requires that the Bureau of Mines and others in the mining community understand respirable dust generation and control better than they did in 1969. The Federal Government has paid over $11.7 billion to 470,000 miners and their survivors since 1970.[4] It is estimated by the same source that the present liability of the Federal disability trust funds "probably approaches $20 billion." This long-term burden on the miners themselves, the mining industry, and taxpayers merits correction. Long-term solutions are not immediately obvious, and a large effort has begun to establish the background knowledge and expertise necessary.

There are over 2,000 CMM's in use in the United States; they account for over half of our underground coal production. Studies have identified the continuous miner operator and helper as being at "high risk" for dust exposure in a continuous section. Reducing their exposure to acceptable levels will substantially reduce dust and improve the mine environment for thousands of miners. Reducing the dust hazard will also improve secondary controls and increase the usefulness and economic return of both continuous and longwall systems by adding to production potential and salable product at the preparation plant.

Previously it was thought that the only ways to reduce dust were secondary controls such as water sprays, ventilation, filtering, etc. Bureau research with conical bits has shown that as coal is cut deeper, the volume recovered increases faster than the ARD; thereby, less specific ARD is generated. This suggests that one approach to reducing the dust hazard is to modify the cutting technique. This Bureau research has resulted in several patents[5] on new cutting concepts, which would use new mining machine designs to maintain a constant depth of cut.

An alternative approach pursued by researchers at Sandia Laboratories (Albuquerque, NM) was to design bits that would maintain the new-bit condition longer, thus increasing their useful life. Under a U.S. Department of Energy program, Sandia Laboratories redesigned cutting tools to use new tip materials with better wear characteristics than those of tungsten carbide. These

[4] Newmeyer, G. E. Cost of the Black Lung Program. Min. Cong. J., v. 67, No. 11, November 1981, pp. 74-75.

[5] Roepke, W. W., D. P. Lindroth, and J. W. Rasmussen (assigned to U.S. Dep. Interior). Linear Cutting Rotary Head Continuous Mining Machine. U.S. Pat. 4,012,077, Mar. 15, 1977.

Roepke, W. W., K. C. Strebig, and B. V. Johnson (assigned to U.S. Dep. Interior). Method of Operating a Constant Depth Linear Cutting Head on a Retrofitted Continuous Mining Machine. U.S. Pat. 4,025,116, May 24, 1977.

Roepke, W. W., D. P. Lindroth, and R. J. Wilson (assigned to U.S. Dep. Interior). Automatic Face Transfer by Linear Cutting Rotary Head. U.S. Pat. 4,062,595, Dec. 13, 1977.

Roepke, W. W., and S. J. Anderson (assigned to U.S. Dep. Interior). Triangular Shaped Cutting Head for Use With a Longwall Mining Machine. U.S. Pat. 4,303,227, Dec. 1, 1981.

materials were used in both drill bit and drag bit cutter designs.[6] In September 1979, the Bureau and Sandia Laboratories entered into a cooperative agreement to evaluate new technology designed to replace traditional tungsten carbide bits with sintered synthetic diamond (Stratapax[7]) cutting faces.

Research on bit life involves testing for other parameters besides dust output. Impact failure and extended abrasive cutting are of paramount importance in bit life tests. Tests of these parameters are directly related to methane ignitions caused by frictional impact heating of bits or of the rock surfaces frequently found as inclusive material in continuous-miner sections.

Previous efforts have taken variables like dust generation or cutting-force measurements or incendivity out of context of the whole "cutting system," which is defined as the cutter-mineral interface with all its incident variables, e.g., dust, methane ignitions, forces, speed, cutter geometry, and wear. It has become apparent that no single parameter can be individually analyzed out of context. It has also become obvious that the cutting system directly impacts on the economics and design of the "total system," defined as all of the mining operation from the face to the preparation plant, which depend upon the only activity that produces a product--the cutting system. This report addresses all facets of the cutting system, which were evaluated by the Bureau for new long-life drag bit designs developed by Sandia Laboratories.

These bits were tested in coal to evaluate cutting forces and dust generation and in Berea sandstone to evaluate frictional impact ignitions in a 6.5 pct methane-air mixture. Preliminary testing for impact failure and bit wear is summarized.

ACKNOWLEDGMENTS

The authors express their appreciation of the meticulous care and expertise provided by Ted Myren, mining engineering technician, Twin Cities Research Center, who ran all of the cutting forces-dust measurement tests. The assistance of Carl Wingquist, physicist, and V. W. Dellorfano, mining engineering technician, both of Twin Cities, in testing for friction and wear, contributed significantly to the results. Wingquist also provided instrumentation design and support.

GENERAL DESCRIPTION OF TESTING

The two sections that follow report on separate tests involving the cutting system. Each section is self-contained, but the results are interrelated within the cutting system and mutually affect the total mining system. The two are separated for this report only because the experimental designs and sample needs varied. For instance, testing for ARD with orthogonal cutting forces in coal obviously required coal samples. Since coal does not cause bit wear, impact failures, or frictional ignitions in methane-rich atmospheres, however, all of the testing for those factors required cutting in coal-inclusive and/or top rock. All cutting in coal was done using Illinois No. 6, and the top rock was a Berea sandstone with more than 75 pct quartzite.

The bits supplied to the Bureau by Sandia Laboratories were modified designs, each with sintered, synthetic diamond Stratapax face material in place of the standard tungsten carbide tip inserts. Two basic design configurations, two conical round-body types (+3° rake face) and three radial types (+15°, +3°, and -17° rake faces), were provided. The round-body or conical-shaped bits are not

[6] Sandia drawing numbers S31119, T89751-000, T89751-001, and T89751-002.

[7] Reference to specific equipment (or trade names or manufacturers) does not imply endorsement by the Bureau of Mines.

equivalent to standard conical cutting tools of the plumb-bob type, however, but are conical only by virtue of their mounting configuration, i.e., 45° attack angle, and their round mounting shank. Since the so-called conical type has the same round, flat-face "Stratapax" insert as does the radial type, the tool cannot turn in the toolholder, but must be locked in place as the radial types are. Although they are more similar to radial bits by virtue of being locked in place, they will be referred to in this report as "conical type" to differentiate the attack angles between the two designs. The only difference between the two conical tools provided was in the thickness of the back mounting pad for the sintered insert material. Since this would have no effect on dust or forces, only one conical tool was used in those tests. Both conicals were tested for possible ignition differences, however. The radial bit types have a standard radial mounting configuration, but the mounting shank is larger than standard commercial radial types. For this work, the shanks were ground down to regular size so a standard radial mounting block could be used. The modified bits and the reference plumb bob are shown before testing in figure 1.

Different kinds of equipment were used for the various tests. Primary dust measurement depends on cutting at constant depth and low speed to eliminate fanning and secondary grinding of already fractured material. Methane ignition can be characterized realistically only with a single bit on a full-diameter drum section with variable speed capability. The impact failure-wear testing requires only that several controlled tests be done, but these may use either linear or rotary cuts. Each of these differences is described in detail in the relevant section.

SECTION 1. CUTTING FORCES AND DUST GENERATION

TEST FACILITY

The major equipment used for these tests consisted of a large, modified planer mill (fig. 2), a quartz crystal three-axis bit-dynamometer (figs. 3-4), an optical particle sizer, and a digital data acquisition system.

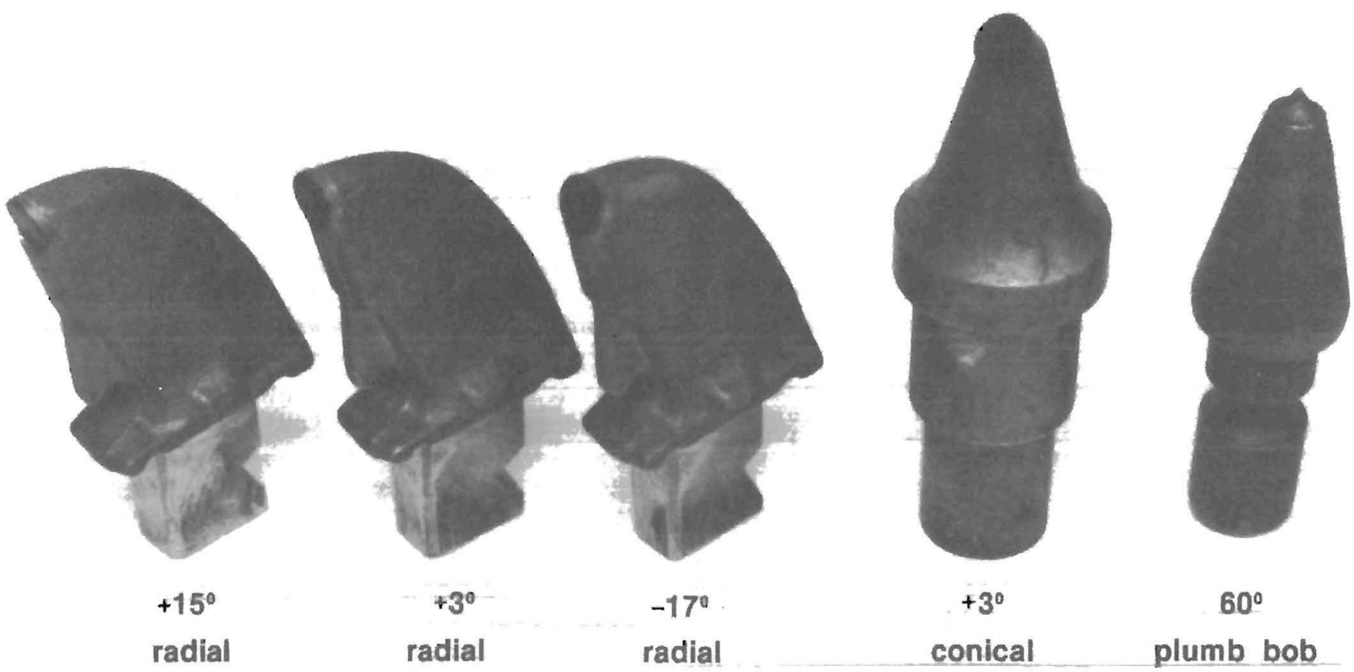

FIGURE 1. - Reference bit with test bits. 60° plumb bob is 4-7/8 in long

FIGURE 2. - Large planer-mill linear cutting facility.

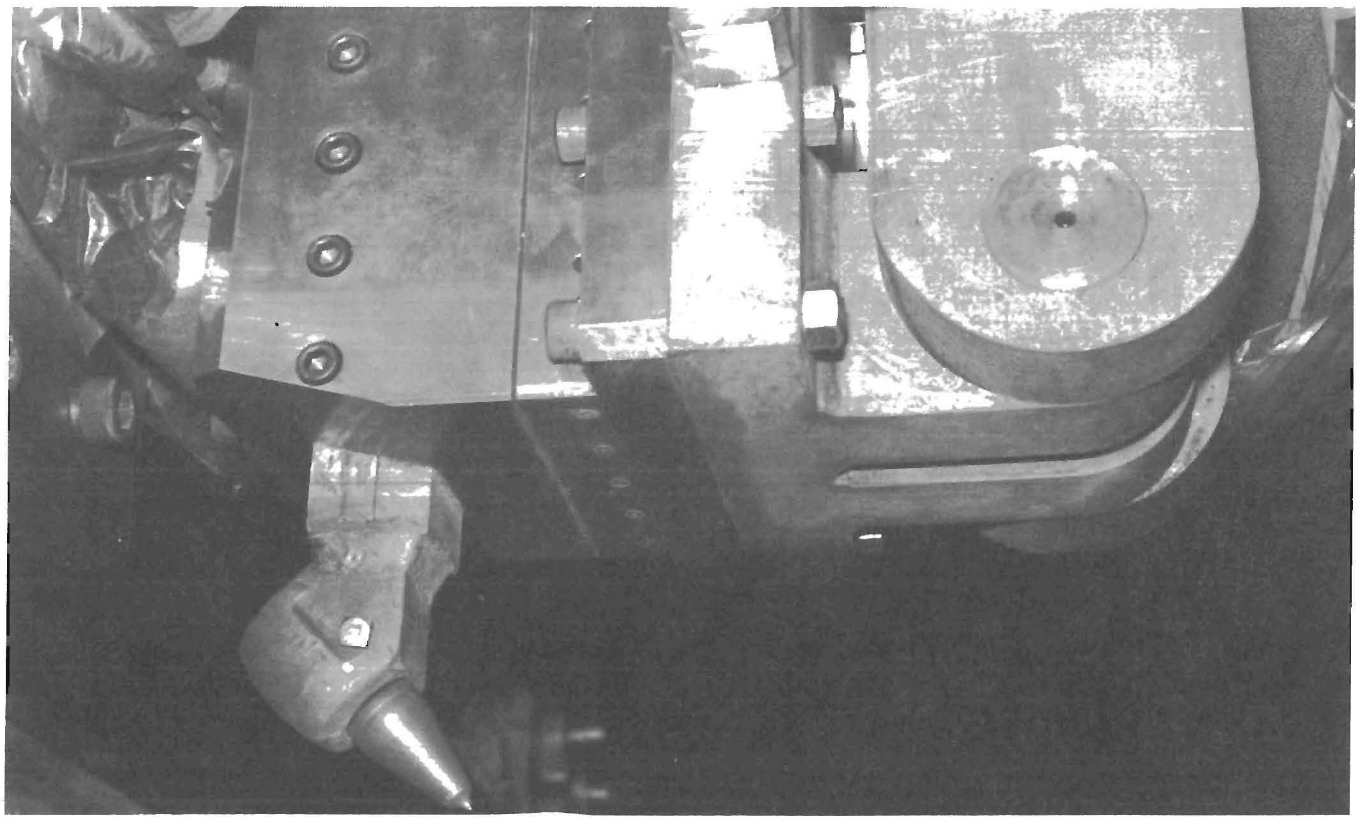

FIGURE 3. - Close view of bit-dynamometer.

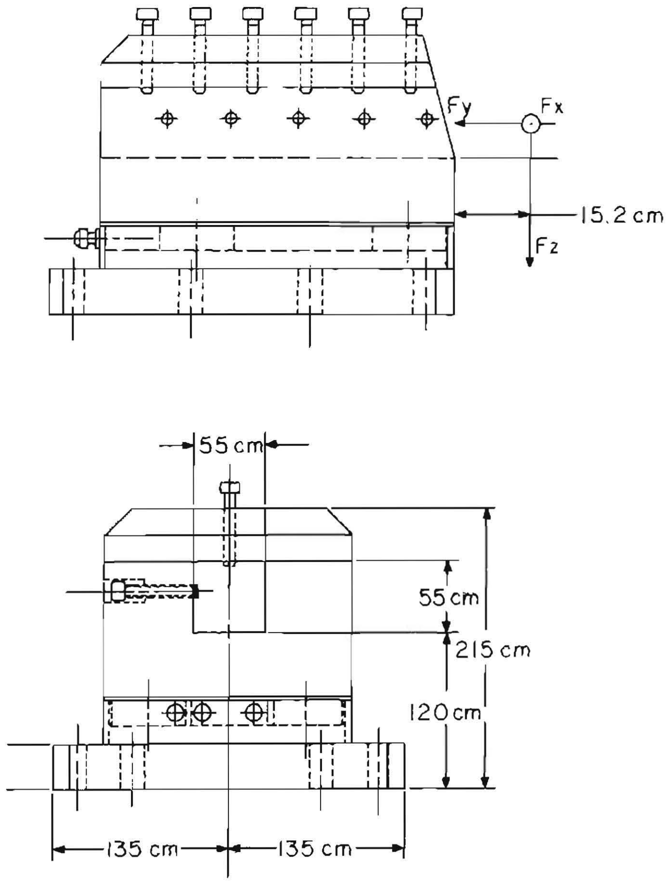

FIGURE 4. - Schematic of three-axis bit-dynamometer. (F_x = lateral force; F_y = axial force, F_z = normal force.)

The dynamometer shown in figures 3 and 4 is a commercial unit using piezo output from oriented quartz crystals to keep crosstalk at less than 5 pct between axes. The cutter bit being tested is mounted on a 5.08-cm (2-in) square post, 25.4-cm (10-in) long, which is clamped inside the dynamometer housing shown in the upper left half of figure 3. This in turn is bolted to the support system shown in the upper right half of the figure.

The large, double-sided planer mill was modified by removing the quill head and motor from the rail and replacing them on the overhead rail with a rigid mount to support the bit-dynamometer configuration. This overhead rail permits great flexibility in testing since the mounting may be translated laterally across the total open-throat distance of the table, or 167.64 cm (66 in), and the rail has a vertical displacement from 7.62 to 111.76 cm (3 to 44 in) above the table. The general configuration for testing is shown in figure 5. The top center of the figure shows the optical particle sampler with the sample collection tube coming up from the shrouded cutting area beneath it. The test sample at lower right, which has already been cut, is shown clamped to the traverse table with the backing supports in place. The large tube at top center brings clean air into the outer shroud, which excludes background dust during cutting. A smaller inner shroud surrounds the bit-coal test path. The optical particle sizer pickup, mounted near the cutting bit inside the inner shroud, is shown in figure 6 with the shrouds removed. The dust sampler covers a range from 0.2 to 8 µm in seven class intervals.

EXPERIMENTAL DESIGN

All tests were run in an identical manner, using a standard 60°-tip plumb-bob bit as the reference. The coal test samples locked in the holder were mounted rigidly on the machine bed. The bed and sample were moved under the bit, which had been previously adjusted for a predetermined depth of cut. Each bit mounted on the toolpost holder was held in the crystal dynamometer so the cutter tip intercepted the X-Y-Z calibration point of the dynamometer. The cutter area was surrounded by a plastic shroud to assist in dust sampling. Test conditions were--

1. Illinois No. 6 coal.

2. Attack angle of 45° for conical bits perpendicular to bedding planes.

3. Attack angle of 90° for radial bits perpendicular to bedding planes.

4. Minimum of 12 replications.

5. Speed of 4.921 cm/min (1.9375 in/min); total cut time is 2 min.

6. Constant spacing between bits.

Independent variables for these tests were--

FIGURE 5. - Sample test configuration.

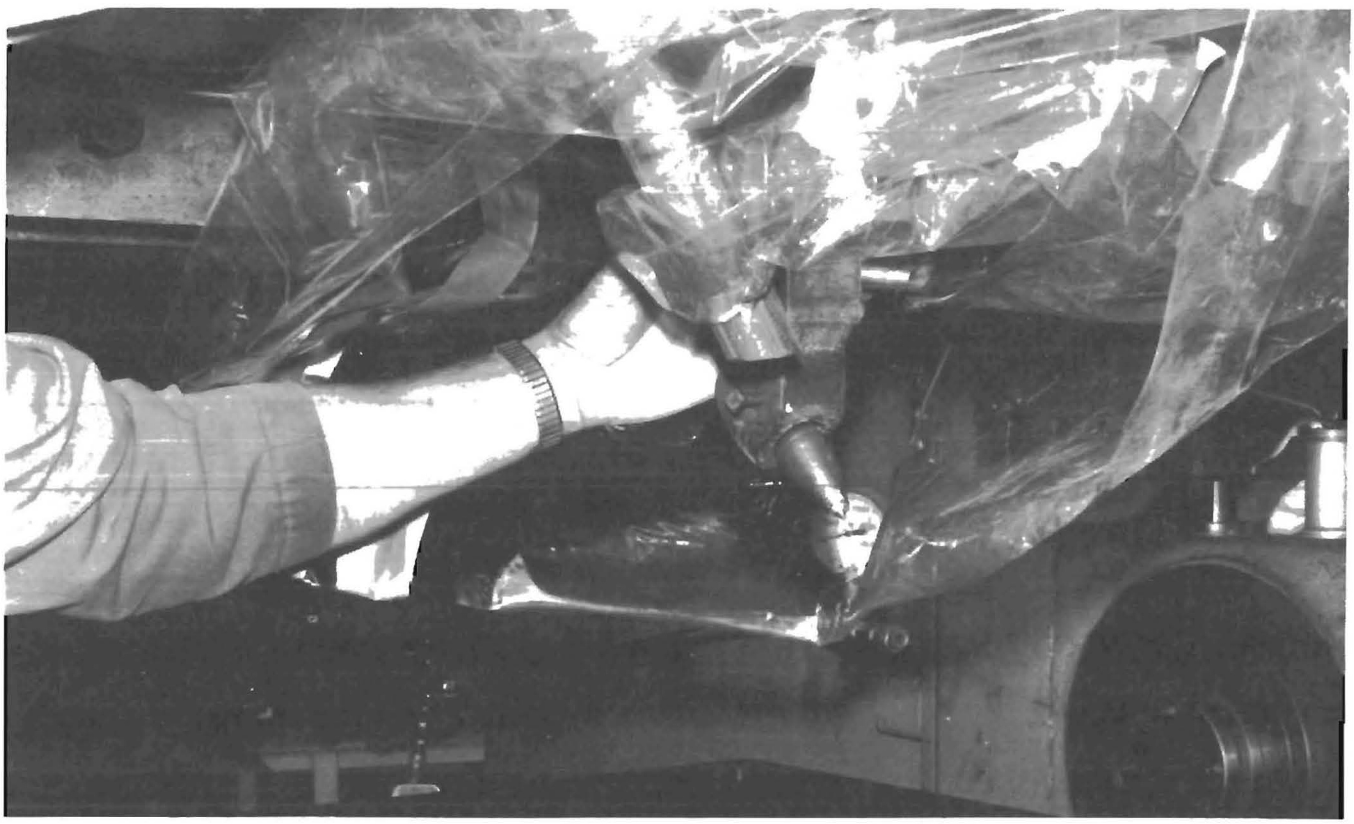

FIGURE 6. - Unshrouded view of bit-sampler configuration.

1. Four bit types.

2. Four depths of cut, 0.318 cm (1/8 in), 0.635 cm (1/4 in), 1.270 cm (1/2 in), and 2.540 cm (1 in).

Dependent variables for these tests were--

1. Mean and peak cutting forces.

2. Mean and peak normal forces.

3. Weight of coal removed.

4. Total ARD.

5. Specific ARD.

6. Milligram per ton calculated ARD (cu µm/g ARD × 1.163 × 10^{-3}).

7. Specific energy.

Compression tests made on this coal type are included to provide another basis for comparison with other research. The compression tests, performed on 2.54-cm (1.0-in) and 5.08-cm (2-in) cubes of coal, show a mean uniaxial compression strength of 281.228±24.607 kg/sq cm (4,000±350 psi) for the 5.08-cm (2-in) cubes, and 302.320±91.399 kg/sq cm (4,300±1,300 psi) for the 2.54-cm (1-in) cubes. The results show the expected increase with size demonstrated previously.

RESULTS AND DISCUSSION

The results were rather scattered, as is normal for this type of testing. In general, the modified bits had horizontal forces similar to those of the reference bit, but there were substantial differences among bits for normal forces. The greatest variations among cutters occurred in ARD generation, as can be seen in figures 7 and 8. One new bit design, the +3° rake conical cutter, produced less primary dust during cutting than did the reference cutter, for every depth tested. The negative-rake, -17° radial bit showed the greatest dust generation during shallow cutting, as was expected. It should be noted that the +15° radial, expected to be lowest overall in primary ARD generation, actually shared maximum ARD generation at maximum depth with the +3° radial bit. These differences may be seen more clearly when total dust is reviewed (fig. 8).

When the conical bit type is mounted at a 45° attack angle, its +3° rake face and the +3° rake face of the radial bit type cut coal at shallow depths in a similar manner, which would suggest similar dust generation. The difference in body shape

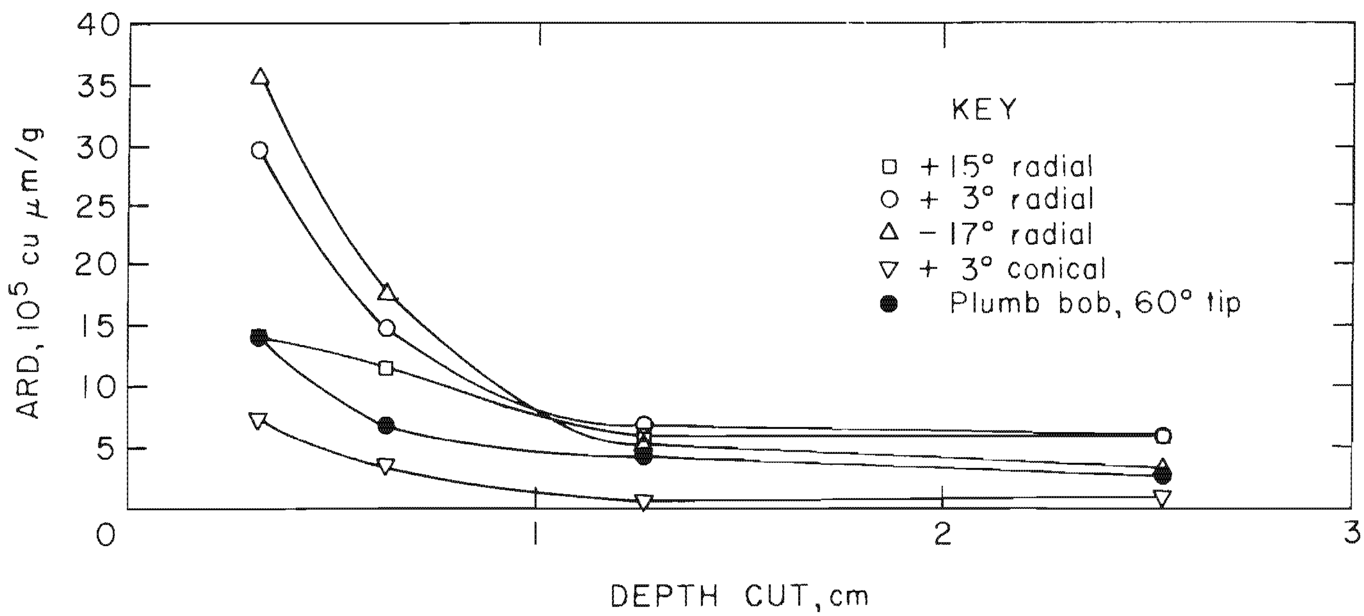

FIGURE 7 - Specific airborne respirable dust.

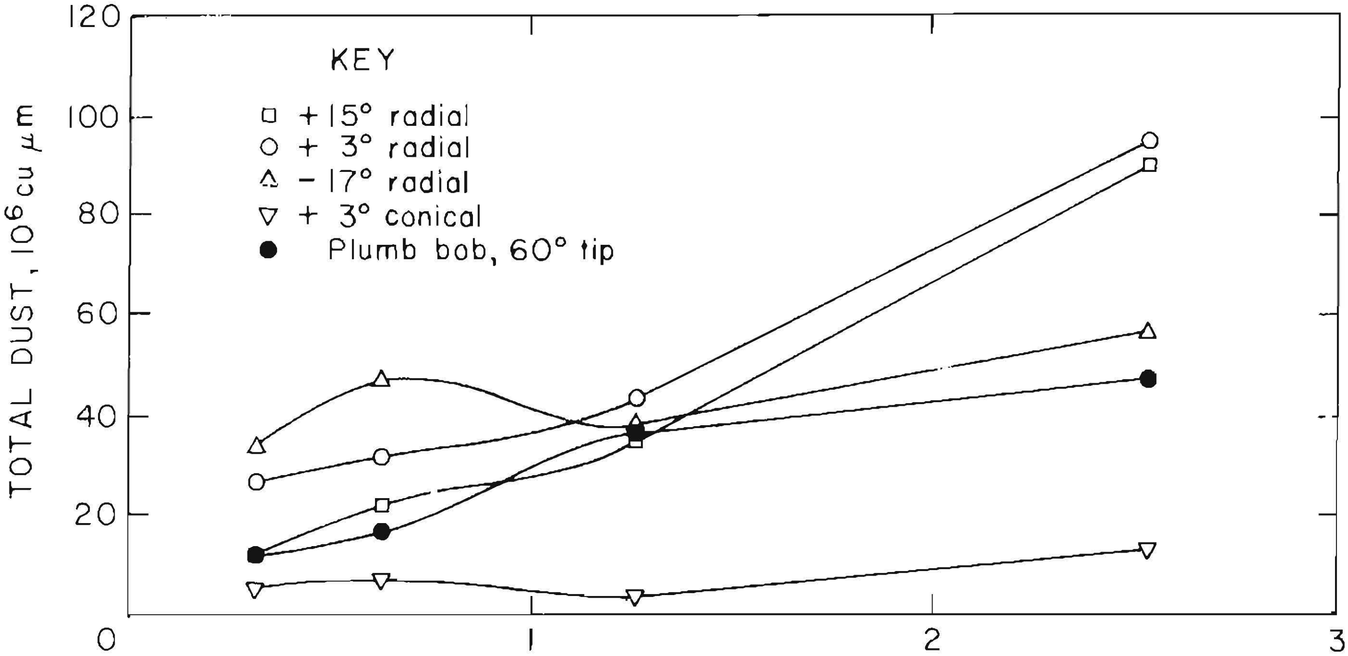

FIGURE 8. - Total airborne respirable dust.

between the radial and conical types, however, can be clearly seen in figure 1. As the tools cut deeper, it can be seen from figure 1 that the body steel of the conical tool should start to generate more dust by abrading the sides of the deep kerf, whereas the radial type advances the kerf without addition abrasion. However, results show that the +3° conical generated much less dust at all depths than did the +3° radial. At present, there are no explanations for the large difference in dust generation between these tool types.

This problem of scattered results becomes further compounded when specific energy (fig. 9) is reviewed. Previous research has shown that dust and energy are directly proportional for reference plumb-bob conical bits. The results obtained with these new bits do not follow a similar pattern. The +3° conical design, which produced the least specific ARD overall, and the +15° bit, which was near minimum ARD during shallow cutting but near maximum ARD during deep cutting, both used the most specific energy during shallow cutting. The +3° and -17° radial types used essentially the same specific energy as the reference plumb bob. It is unexpected that the -17° bit use the least specific energy during shallow cutting. There is at present no explanation for these inverse dust-energy relationship effects. The horizontal and normal average and peak forces are shown graphically in figures 10 through 13. A complete summary of these test results is presented in table 1. Appendix A provides mean values of forces and dust in this series. Appendix B provides a computer summary of the dust sampling data by class interval with a calculated value for milligram per ton.

SECTION 2. METHANE IGNITION BY FRICTIONAL HEATING

TEST FACILITY

The ignition test chamber used for these experiments is shown in figure 14. Major components of the facility are the full 86.36-cm (34-in) diam, narrow drum section, shown on the left, and the remote, automatic X-Y carriage with a

TABLE 1. - Summary of coal-cutting tests[1]

Cutting bit type[2]	Number of tests	Coal cut, g/min	Cutting forces, N: Hor. avg.	Cutting forces, N: Hor. peak	Cutting forces, N: Normal avg.	Cutting forces, N: Normal peak	Airborne dust: Total, cu µm	Airborne dust: Specific, cu µm/g	Airborne dust: Weight, mg/ton	Specific energy, J/g·h⁻¹
0.318-cm DEPTH										
+15° radial.....	6	8.4	411	1,436	563	1,787	1.249E+07	1.417E+06	1,648	4.91
+3° radial......	11	10.4	182	1,050	298	805	2.711E+07	2.971E+06	3,455	1.73
-17° radial.....	8	10.5	133	965	125	427	3.392E+07	3.581E+06	4,165	1.25
+3° conical.....	11	7.8	302	894	467	1,334	5.534E+06	7.466E+06	868	3.82
60° plumb bob...	20	9.2	213	731	187	624	1.231E+07	1.445E+06	1,681	2.41
0.635-cm DEPTH										
+15° radial.....	6	20.0	669	2,064	841	2,434	2.225E+07	1.147E+06	1,334	3.38
+3° radial......	11	23.0	400	1,939	431	1,103	3.158E+07	1.496E+06	1,740	1.71
-17° radial.....	6	26.1	423	1,997	254	930	4.658E+07	1.788E+06	2,080	1.59
+3° conical.....	12	23.0	792	2,077	1,094	2,478	7.127E+06	3.473E+05	404	3.39
60° plumb bob...	19	25.8	507	1,628	402	1,263	1.694E+07	6.840E+05	796	2.09
1.270-cm DEPTH										
+15° radial.....	6	59.0	1,291	3,770	1,351	3,145	3.502E+07	5.995E+05	697	2.18
+3° radial......	9	65.2	729	3,251	418	987	4.355E+07	6.824E+05	794	1.10
-17° radial.....	7	69.4	1,063	3,901	578	1,583	3.825E+07	5.316E+05	618	1.51
+3° conical.....	10	74.9	903	3,300	916	2,535	4.065E+07	5.456E+04	63	1.19
60° plumb bob...	20	88.3	1,067	2,921	621	1,697	3.651E+07	4.157E+05	483	1.27
2.540-cm DEPTH										
+15° radial.....	6	172.3	1,930	6,906	1,242	3,172	9.000E+07	5.971E+05	694	1.25
+3° radial......	10	176.1	1,165	5,649	547	1,237	9.526E+07	6.024E+05	701	.65
-17° radial.....	6	173.1	1,837	6.543	783	2,180	5.671E+07	3.232E+05	376	1.04
+3° conical.....	11	157.6	1,606	5,645	1,294	3,434	1.349E+07	8.742E+04	102	1.00
60° plumb bob...	17	185.1	2,043	5,996	1,026	2,461	4.709E+07	2.497E+05	290	1.11

[1] Illinois No. 6 coal; 5.08-cm (2-in) spacing; 4.291 cm/min (1-15/16 in/min).
[2] Only 1 conical bit was tested in coal since both cutters were geometrically similar.

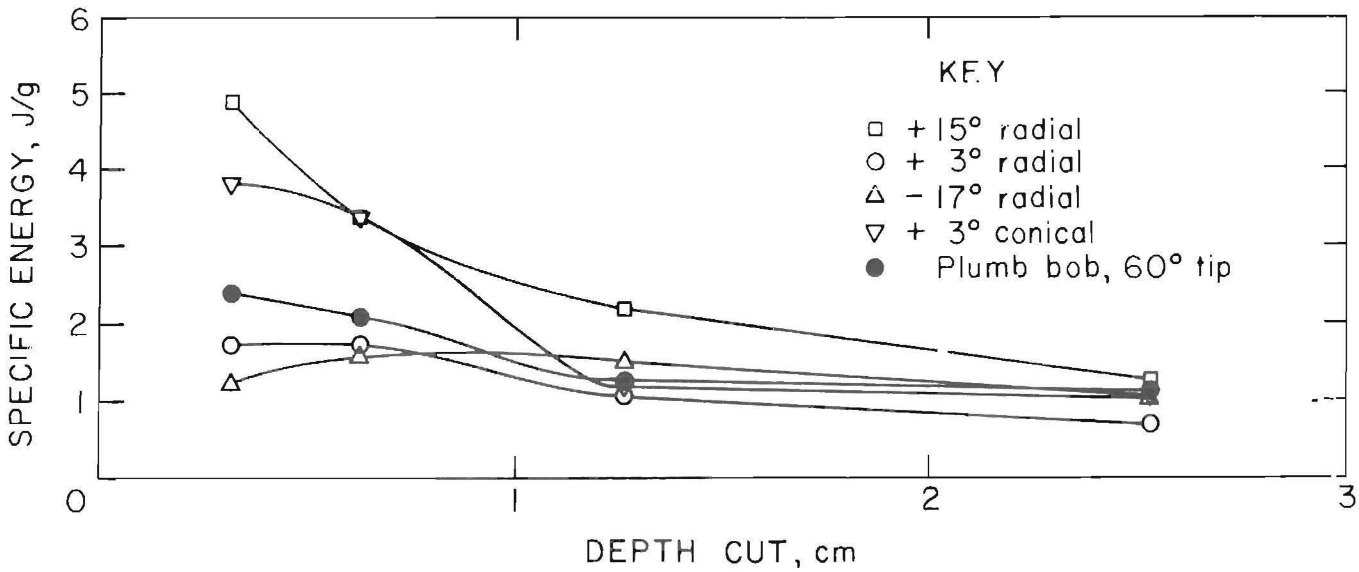

FIGURE 9. - Specific energy

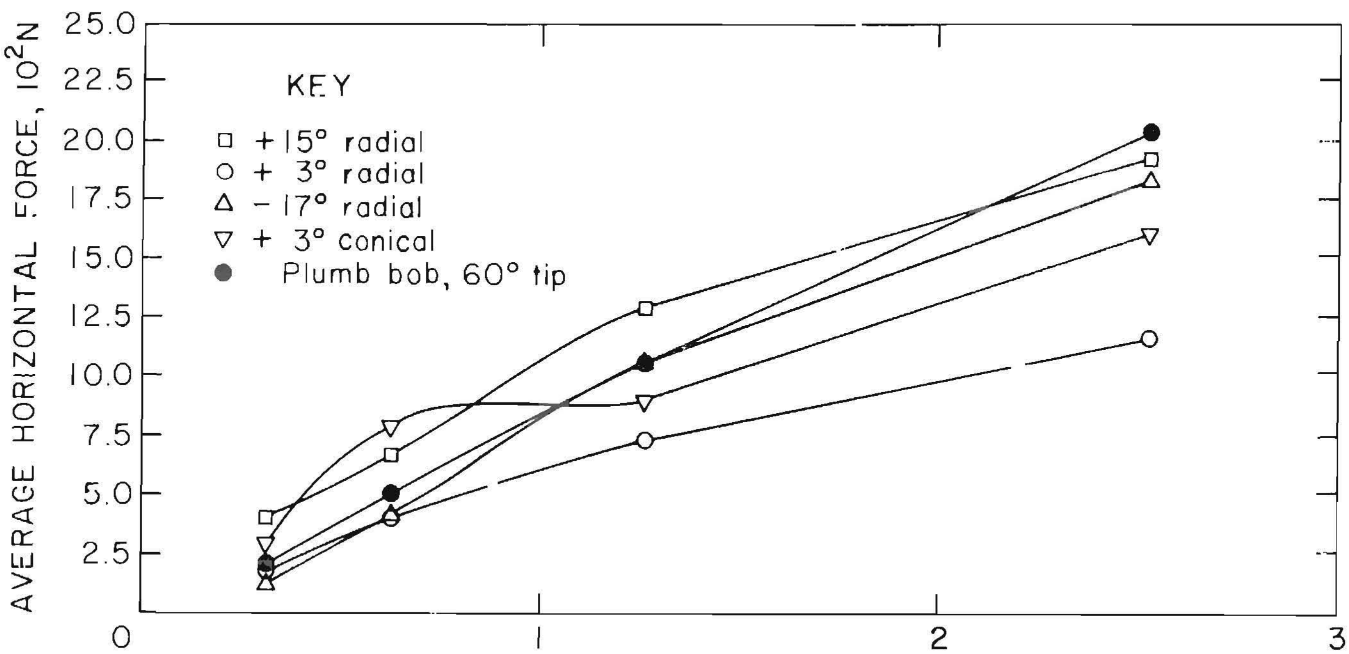

FIGURE 10. Average tangential cutting forces.

sample in place, shown on the right. The test facility has these capabilities:

1. A 100-hp, 130-gal/min pump and motor combination driving four Staufa motors on a 15.24-cm (6-in) wide, single bit row, the 86.36 cm (34-in) diam mining machine drum section fixed permanently to the test chamber base.

2. A 0- to 100-rpm infinitely variable drum speed.

3. Maximum sample size of 2,831.685 $\times 10^{-5}$ cu m (1 cu ft).

4. Sample mounted on X-Y base power-driven in each axis by remotely programed and operable stepping motors.

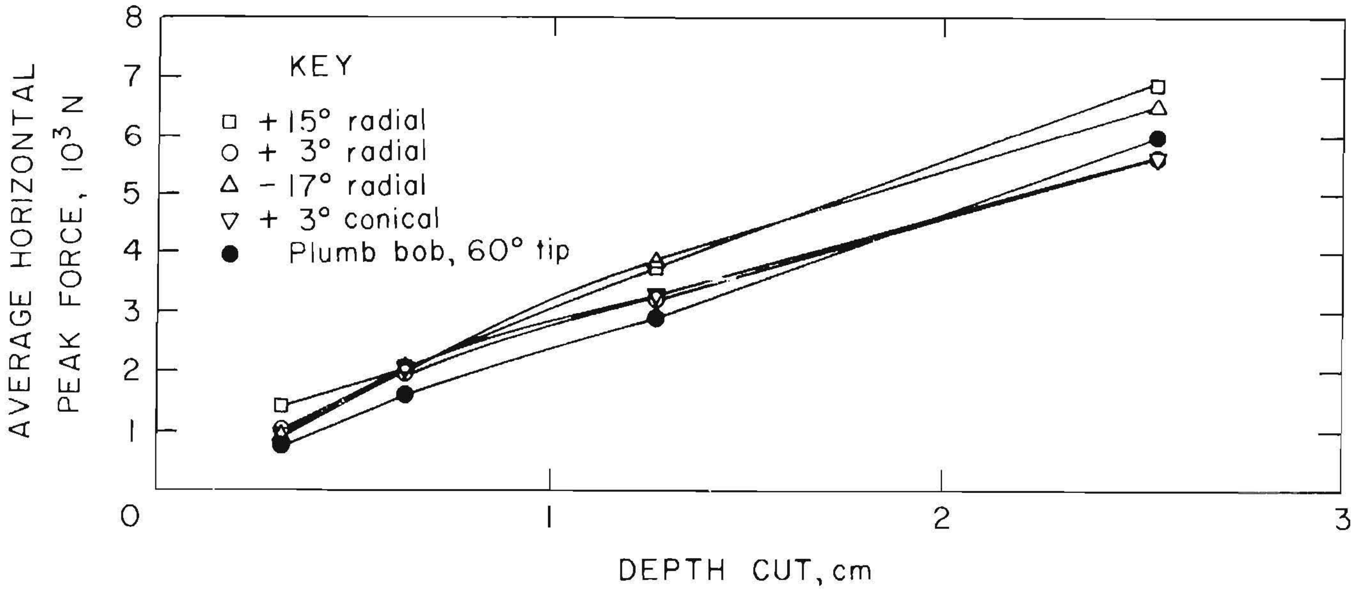

FIGURE 11. - Peak tangential cutting forces.

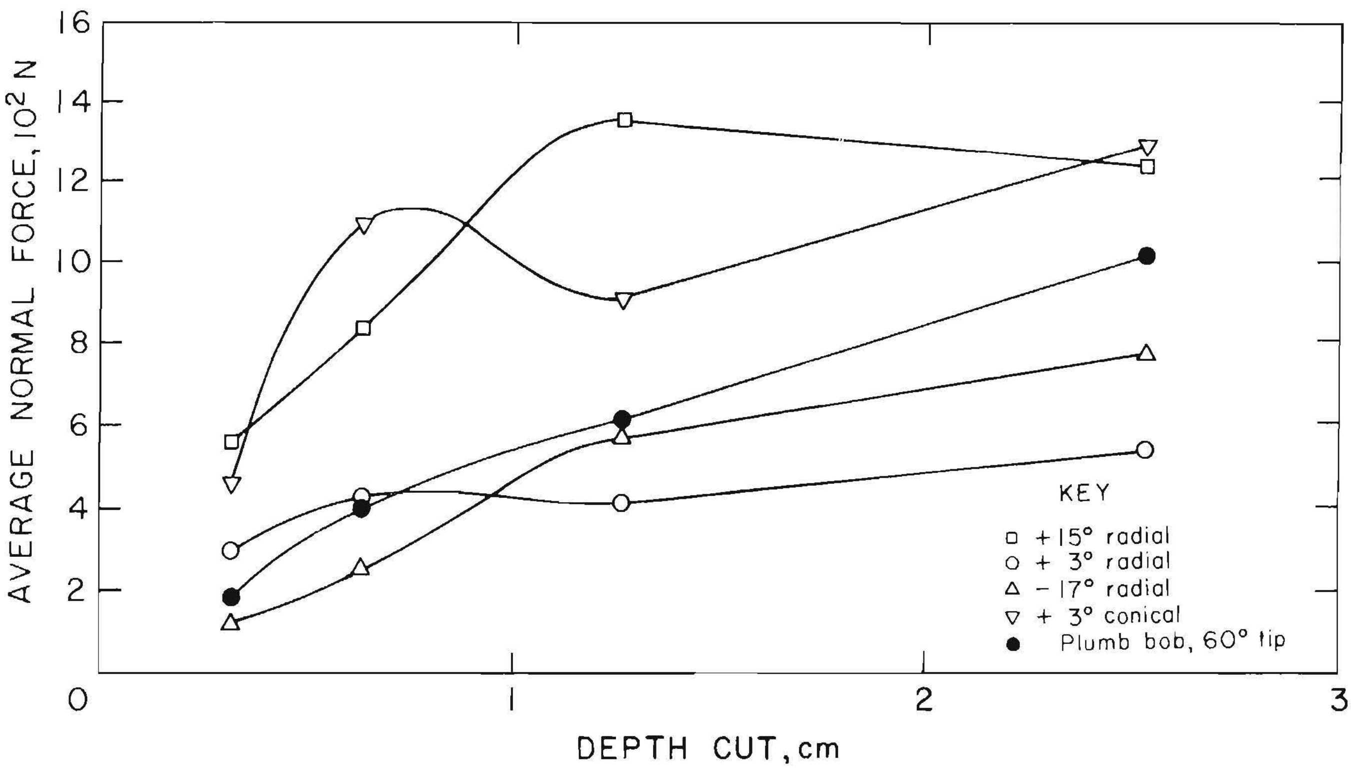

FIGURE 12. - Average bit normal forces.

5. A 0- to 0.925-cm/s (3/8-in/s) advance rate to move sample into the bit (Y-axis direction) for increasing arc length and/or kerf depth tests.

6. A 0- to 4.445-cm/s (1-3/4-in/s) lateral rate to translate the sample past the bit in the X-axis direction for constant arc length and/or kerf depth cuts.

During all frictional impact ignition testing, tangential cutting force, cutterhead revolutions per minute, work performed per impact, and percent methane

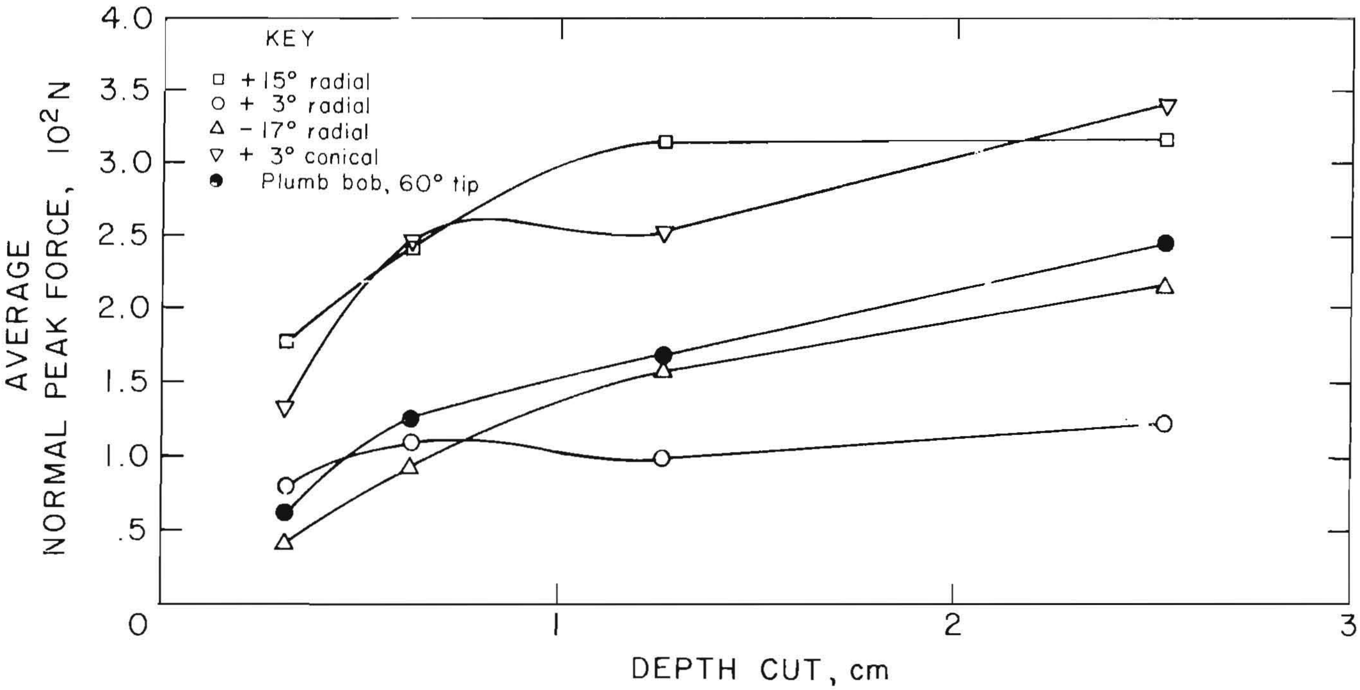

FIGURE 13. - Peak bit normal forces.

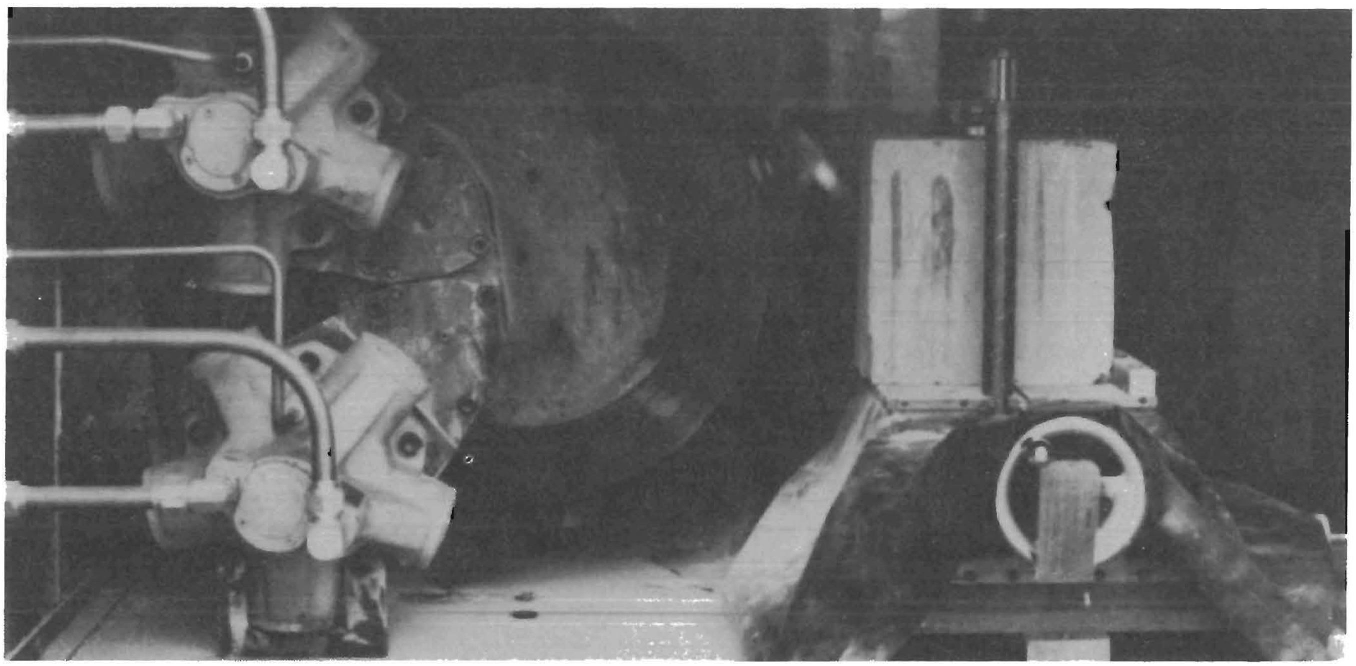

FIGURE 14. - Ignition test chamber.

were recorded on a multichannel strip chart. Cutting force was recorded from a differential pressure transducer connected across the hydraulic motors that drive the cutterhead. The relationship of pressure drop across the motors to the torque output at the cutterhead was established by static calibration with a load cell. The work performed, or energy absorbed, per impact was determined by electronically recording the time integral of the cutting force signal. The product of this integrated signal, the cutting radius, and the angular velocity of the cutterhead gives energy per impact. Angular velocity (revolutions per minute) was monitored by a proximity detector near a drive gear. The pulse output of the sensor drove a frequency-to-dc converter, which in turn drove a revolution-per-minute-scaled meter. A commercial methanometer continuously monitored methane concentration.

During any ignition test, the chamber was sealed with a polyethylene sheet before the 6.5 pct methane-air mixture was introduced and then continuously mixed by a fan to prevent layering. The cutting tool mounted on the drum section rotated at a set speed. The sample was then stepped into the cutter at a known rate for an increasing kerf depth (fig. 15) or set to a predetermined depth and stepped past the face of the drum for multipass, constant kerf depth cutting (fig. 16). Any test that did not produce an ignition was detonated electrically to verify the explosive mix. The sealed chamber milliseconds after ignition is shown in figure 17. The sample material for these tests was Berea sandstone with more than 75 pct quartzite. The mean for 10 compression tests on 2- by 4-in cores of this sandstone was 297.539 kg/sq cm (4,232 psi) with a standard deviation of 34.24 kg/sq cm (987 psi).

EXPERIMENTAL DESIGN

The five bit types were tested in both transverse and trenching cut modes. Since only a few bits with sintered diamond faces were available, limited ignition testing was done. The trenching cuts were made with a constant advancing depth to give an increasing kerf depth and length. The test sequence used drum speeds of 60, 40, and 20 rpm at advance rates of 0.0635 and 0.0381 cm (0.025 and 0.015 in). Each test was run to a total kerf depth of 1.27 cm (0.50 in) unless an igniton occurred. A trench cut at maximum kerf depth is shown on the left side

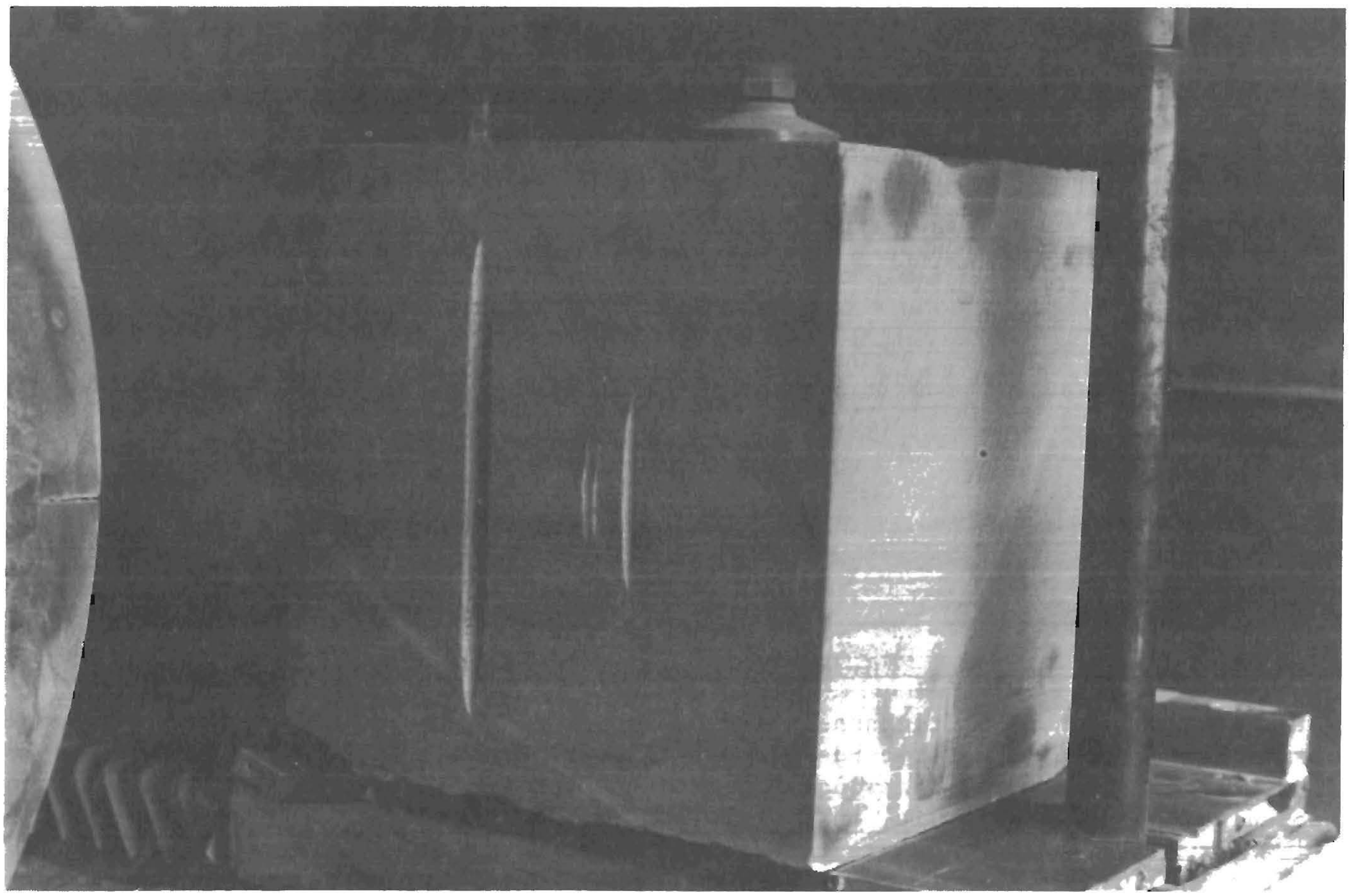

FIGURE 15 - Trench cutting, i.e., increasing kerf depth.

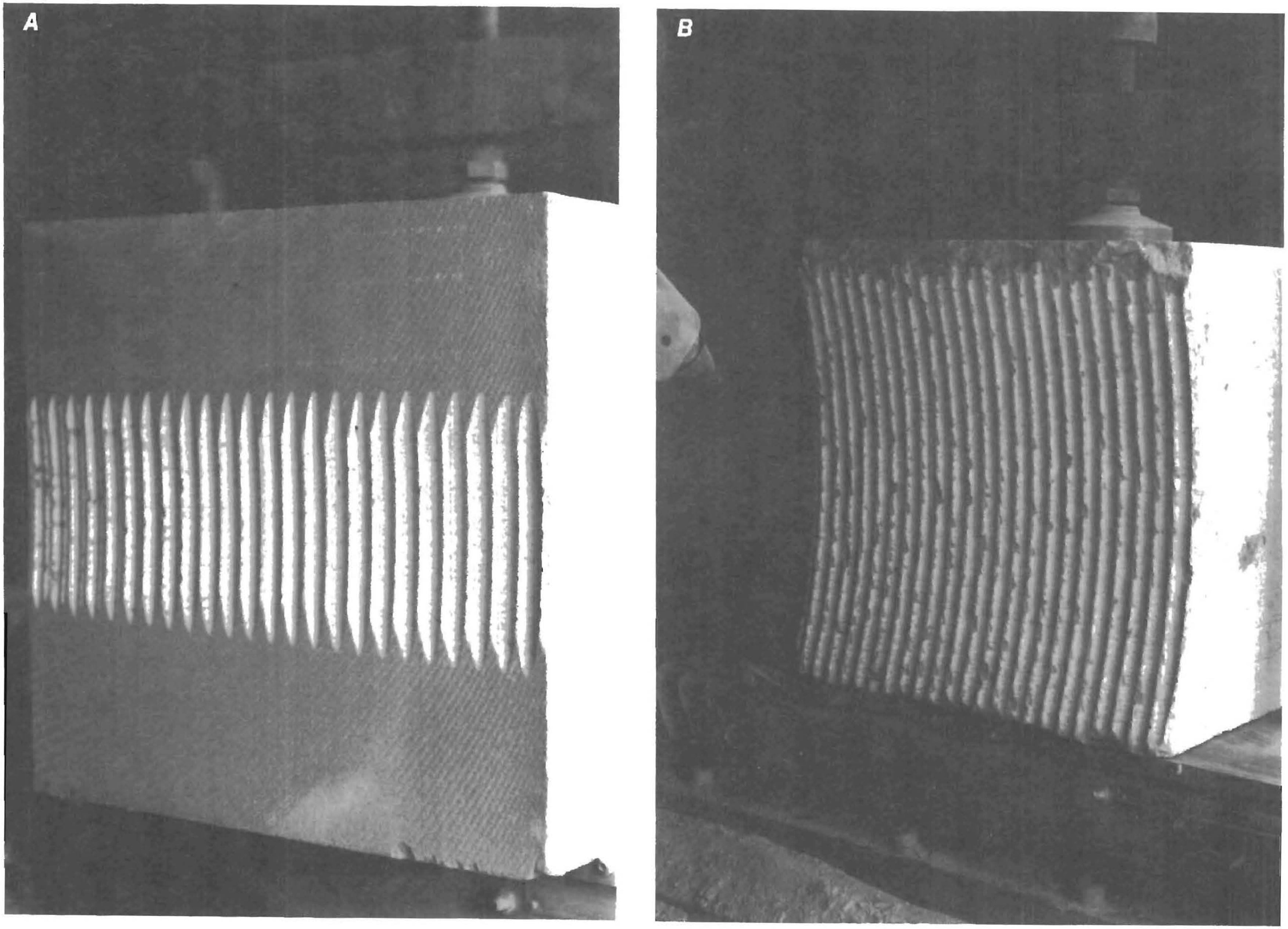

FIGURE 16. - Transverse cutting, i.e., constant kerf depth, on new block (*A*), used block (*B*).

FIGURE 17. - View of test chamber milliseconds after ignition.

of the sample in figure 15. The sequence was followed until two consecutive tests produced no ignition.

The transverse cutting tests at constant kerf depth and length were run in two layers on the sample face. The first layer was made across an initially flat face as shown in figure 16*A*. This layer produced minimum kerf length since the sample block was not yet aligned to the drum-bit contour. If no ignition occurred, the sample block was advanced for a second layer with a slightly longer kerf length. The effect of additional cuts is shown in figure 16*B*.

RESULTS AND DISCUSSION

Ignition test results are shown in table 2 for trenching cuts and in table 3 for transverse cuts. These data show that the thin-backed conical bit was easily the most incendive tool of the four types tested. In trenching cuts with this type, ignitions occurred at 40 and 60 rpm with advance rates of 0.0635 cm (0.025 in). No ignitions occurred when the advance rate was reduced to 0.0381 cm (0.015 in) at the same speeds. In the transverse mode, 0.254-cm (0.100-in) and 0.381-cm (0.150-in) cuts were used to determine if the face material adequately protected the body steel from abrasive contact with the sandstone. Ignitions occurred after three or fewer impacts with the thin-backed bit during each test. The cutting element does not adequately protect the body steel from abrading on the sandstone. Neither the +3° or -17° rake-face radial type bits produced a transverse or trench cut ignition. The thick-backed conical type produced an ignition in the trenching cut after 17 impacts, at 60 rpm and 0.0635 cm (0.025 in), but the test was repeated with no ignition. This bit did not produce ignitions during multiple cuts in the transverse mode.

TABLE 2. - Ignition tests with trench cuts, i.e., increasing kerf depth

Bit type	Advance rate, per impact		Impacts to ignition[1] at		
	cm	in	60 rpm	40 rpm	20 rpm
Conical:					
Thin-backed..	0.0635	0.025	7	3	(20)
	.0381	.015	33	(33)	NR
Thick-backed.	.0635	.025	17, (20)	NR	NR
Radial:					
+3° rake.....	.0635	.025	(20),(20)	NR	NR
-17° rake....	.0635	.025	(20),(20)	NR	NR

NR No test run.

[1]Number of impacts to ignition. Numbers in parentheses indicate impacts with no ignition.

TABLE 3. - Ignition tests with transverse cuts, i.e. constant kerf depth

Bit type	First pass			Second pass		
	Depth of cut		Number of impacts[1]	Depth of cut		Number of impacts[1]
	cm	in		cm	in	
Conical:						
Thin-backed..	0.381	0.150	2	0.254	0.100	3
Thick-backed.	.254	.100	(22)	.381	.150	(23)
Radial:						
+3° rake.....	.254	.100	(22)	.381	.150	(22)
-17° rake....	.381	.150	(21)	.381	.150	(22)

[1]Number of impacts to ignition. Numbers in parentheses indicate impacts with no ignition.

Although orthogonal cutting forces could not be determined, the tangential cutting force was obtained from the differential pressure transducer connected across the hydraulic motors that drove the cutting head. The cutting forces in sandstone for the new bit designs are shown in table 4, with the plumb-bob forces for comparison. The percent differences between the forces of the new bits and the reference bit are also shown in the table for the 0.0635-cm (0.025-in) depth of cut. Except for the new +3° conical type, all of the new cutter types had lower forces than the reference bit. It was expected that the negative-rake -17° bit would have the highest cutting force, but data in table 4 show that this did not occur. The new +3° conical bit needed the highest force of all, exceeding even the reference bit, except at 20 rpm. The two radial type bits (+3° and -17°) were substantially lower in horizontal force than the 60° reference at comparable depth. It should be remembered that these results are substantially different from those obtained for cutting in coal. The condensed summary of tangential forces in coal (table 5)[8] shows appreciably fewer differences in cutting forces among the various types. Only the +3° radial bit appears to be significantly different from the reference bit at maximum depth.

The results of these ignition tests suggest that it may be possible to design a long-life bit with no incendivity and to substantially reduce cutting forces. That reduction should be directly related to the economics of the total mineral recovery system, since lower forces use

[8]Data from section 1, table 1.

TABLE 4. - Summary results of horizontal cutting forces in sandstone

Bit type	Advance rate, per impact		60 rpm		40 rpm		20 rpm	
	cm	in	Force, N[1]	Diff., pct[2]	Force, N[1]	Diff., pct[2]	Force, N[1]	Diff., pct[2]
+3° radial.......	0.0635	0.025	1,824	-74	1,156	-78	890	-87
	.1270	.050	1,601	NAp	1,512	NAp	1,290	NAp
	.2540	.100	2,758	NAp	2,135	NAp	1,975	NAp
-17° radial......	.0635	.025	1,334	-81	1,156	-72	845	-87
	.1270	.050	2,669	NAp	1,868	NAp	1,201	NAp
	.2540	.100	4,448	NAp	3,380	NAp	2,224	NAp
+3° conical......	.0381	.015	6,049	NAp	6,405	NAp	NA	NAp
	.0635	.025	8,896	+25	7,117	+33	6,227	-8
Plumb bob........	.0635	.025	7,117	NAp	5,338	NAp	6,761	NAp

NA Not available. NAp Not applicable.
[1]Newtons × 0.2248 = pounds force.
[2]Percentage indicates difference from reference plumb-bob bit at 0.0635 cm.

less energy and lower reactive mass in the mining machine, which means reduced capital cost.

A subjective observation, made by touching the bits with the fingers, indicated that after one pass across the rock face (22 cuts), a plumb-bob bit was too hot to touch whereas the new cutters' face material was cool. Additional research will be done with these new cutters to quantify face temperature during extended cutting, which will be substantiated with a remote sensing radiometer, as part of the expanded wear program.

TABLE 5. Summary of average linear horizontal cutting forces in coal, newtons

Depth of cut		60° plumb bob	+3° radial	-17° radial	+3° conical
cm	in				
0.318	0.125	213	182	133	302
.635	.25	507	400	423	792
1.270	.50	1,067	729	1,116	903
2.540	1.00	2,043	1,165	1,837	1,606

NOTE.--The +15° radial is not included in this summary since it was received too late for the ignition tests.

SUMMARY AND CONCLUSIONS

The results showed these preliminary bit designs to be as good as or slightly better than standard plumb-bob type bits for cutting force and primary airborne respirable dust (ARD) generation in coal. The specific energy, however, was anomalous for one of the new bits, which produced the least ARD but showed the highest specific energy at shallow depths. In the new radial bits, incendivity was eliminated. The new conical designs were not so reliable, since one indicated incendivity after 16 cuts and the other after only 2 cuts.

Preliminary results for impact failure and wear were not good for three of the four new designs, but the fourth, a radial type, took 7,500 impacts on Berea sandstone with a total cutting length of 1,981.2 m (6,500 ft) before it showed incipient cracking along the edge of the carbide mounting pad that supports the sintered diamond face. The sintered diamond never did fail but showed only slight scuffing of the leading edge. Additional impact failure and wear testing is in process and will be reported at a later date.

Results of these tests are fully documented in this report. To assist other researchers, appendixes containing all raw data are included.

APPENDIX A.--MEAN VALUES FOR EACH TEST

Tables A-1 through A-5 give the mean values for each test of bits with sintered diamond inserts and include weight of coal cut, horizontal, normal, and resultant forces, total respirable dust, specific energy, and respirable dust per gram cut. Dust data presented are for sixth class interval. There are minor differences in some cases between appendix A and appendix B data owing to truncating error in computer used to list appendix B.

TABLE A-1. - TEST RESULTS FOR 60° PLUMB BOB

BLOCK	CUT WEIGHT, G	CUTTING FORCES, N						AIRBORNE DUST		SPECIFIC ENERGY, J/G
		HOR. AVG.	HOR. PEAK	NORMAL AVG.	NORMAL PEAK	RES. AVG.	RES. PEAK	TOTAL, CU µM	SPECIFIC, CU µM/G	
					0.318-CM DEPTH					
1PA......	7.4	116	494	71	298	136	577	7.511E+06	1.015E+06	1.54
2PA......	7.1	98	903	62	396	116	986	8.144E+06	1.147E+06	1.36
3PA......	6.6	227	681	169	645	283	939	3.717E+06	5.632E+05	3.38
4PA......	11.5	173	716	120	676	211	985	3.591E+07	3.123E+06	1.48
5PA......	4.3	62	427	27	169	68	459	9.989E+06	2.323E+06	1.43
6PA......	4.6	138	552	120	463	183	720	7.001E+06	1.522E+06	2.95
3B.......	8.7	240	854	222	792	327	1165	1.159E+07	1.332E+06	2.72
	9.1	222	787	227	734	318	1076	5.833E+06	6.410E+05	2.41
	8.7	431	939	400	867	589	1278	1.922E+06	2.209E+05	4.88
	19.7	116	369	102	262	154	453	2.987E+06	1.516E+05	.58
	9.1	259	890	151	365	299	961	2.194E+07	2.411E+06	2.79
5B.......	7.3	262	981	267	1072	374	1387	3.861E+07	5.289E+06	3.54
	8.5	240	796	218	676	324	1045	2.455E+07	2.888E+06	2.78
	11.1	307	956	325	916	447	1324	4.417E+06	3.979E+05	2.72
	13.5	178	529	160	547	239	761	2.206E+07	1.634E+06	1.30
	8.9	151	560	129	338	199	655	2.151E+07	2.417E+06	1.67
6B.......	8.5	205	605	178	467	271	764	2.980E+06	3.506E+05	2.37
	9.8	209	743	196	712	286	1029	7.291E+06	7.440E+05	2.10
	8.6	329	1063	342	1192	475	1597	8.324E+05	9.679E+04	3.77
	11.6	294	867	258	898	391	1249	7.313E+06	6.304E+05	2.49
AVERAGE..	9.2	213	731	187	624	285	970	1.231E+07	1.445E+06	2.41
STD. DEV.	3.3	89	195	97	281	130	313	1.121E+07	1.308E+06	1.02
					0.635-CM DEPTH					
1PB......	18.4	365	1023	289	907	465	1367	5.882E+06	3.197E+05	1.95
2PB......	19.7	543	3189	414	2509	682	4058	8.973E+06	4.555E+05	2.71
3PB......	20.7	365	1695	334	1677	494	2384	1.812E+07	8.755E+05	1.73
4PB......	16.8	356	1139	280	1041	453	1543	3.882E+06	2.311E+05	2.08
5PB......	14.4	427	1686	387	1637	576	2350	3.902E+07	2.710E+06	2.92
6PB......	20.5	725	1850	681	1926	994	2671	9.934E+06	4.846E+05	3.48
3B.......	22.9	583	2131	445	1793	733	2784	7.374E+06	3.220E+05	2.50
	16.2	592	2073	556	1486	812	2550	6.888E+06	4.252E+05	3.59
	20.9	556	1263	405	854	688	1525	1.041E+07	4.981E+05	2.62
	31.7	378	1695	236	992	446	1964	6.467E+07	2.040E+06	1.17
	20.8	414	1174	334	974	531	1526	2.852E+06	1.371E+05	1.96
5B.......	40.5	525	1446	440	1446	685	2044	2.760E+07	6.816E+05	1.28
	26.8	565	1868	476	890	739	2063	1.485E+07	5.540E+05	2.07
	36.0	600	1374	400	832	722	1607	1.682E+07	4.673E+05	1.64
	27.6	378	1397	347	1379	513	1963	3.795E+07	1.375E+06	1.35
6B.......	34.1	534	1552	334	738	629	1719	6.585E+06	1.931E+05	1.54
	34.2	516	1303	351	979	624	1630	2.154E+07	6.298E+05	1.48
	30.1	756	1739	592	1068	960	2041	1.616E+07	5.370E+05	2.47
	37.9	449	1343	347	867	568	1599	2.258E+06	5.957E+04	1.17
AVERAGE..	25.8	507	1628	402	1263	648	2073	1.694E+07	6.840E+05	2.09
STD. DEV.	8.1	119	489	112	475	158	640	1.583E+07	6.724E+05	.74

TABLE A-1. - TEST RESULTS FOR 60° PLUMB BOB--CONTINUED

BLOCK	CUT WEIGHT, G	CUTTING FORCES, N: HOR. AVG.	HOR. PEAK	NORMAL AVG.	NORMAL PEAK	RES. AVG.	RES. PEAK	AIRBORNE DUST: TOTAL, CU µM	SPECIFIC, CU µM/G	SPECIFIC ENERGY, J/G
					1.270-CM DEPTH					
1PC......	65.2	996	3852	632	1917	1180	4303	5.757E+07	8.829E+05	1.50
2PC......	69.6	1201	3652	729	2540	1405	4448	3.537E+07	5.082E+05	1.70
3PC......	78.4	1210	4435	770	2758	1434	5222	3.878E+07	4.946E+05	1.52
4PC......	56.8	1245	4604	712	3501	1434	5783	2.299E+07	4.047E+05	2.16
5PC......	75.1	1308	4822	934	2833	1607	5593	1.041E+08	1.386E+06	1.71
6PC......	82.9	1072	2900	609	2695	1233	3959	3.815E+07	4.602E+05	1.27
3B.......	77.2	1797	3483	925	1988	2021	4010	3.488E+06	4.518E+04	2.29
	104.0	987	2513	587	1183	1149	2778	7.019E+06	6.749E+04	.93
	105.2	921	2251	356	676	987	2350	4.371E+07	4.155E+05	.86
	82.7	1085	2291	596	1081	1238	2533	1.357E+07	1.641E+05	1.29
	103.2	1054	2095	494	823	1164	2251	1.047E+07	1.015E+05	1.01
5B.......	126.6	596	2059	276	1050	657	2312	2.109E+07	1.666E+05	.46
	81.0	1401	3025	703	1788	1567	3514	4.371E+07	5.396E+05	1.70
	90.1	445	1414	285	894	528	1673	1.671E+07	1.855E+05	.49
	131.2	930	2135	707	1423	1168	2566	1.796E+08	1.369E+06	.70
	79.8	1543	3585	903	1557	1788	3909	5.900E+07	7.394E+05	1.90
6B.......	95.9	907	2117	681	1450	1134	2566	3.089E+06	3.221E+04	.93
	87.6	681	2104	485	1499	836	2583	5.821E+06	6.645E+04	.76
	74.4	943	2504	592	1210	1113	2781	6.151E+06	8.267E+04	1.25
	98.9	1014	2571	440	1072	1106	2785	1.990E+07	2.012E+05	1.01
AVERAGE..	88.3	1067	2921	621	1697	1237	3396	3.651E+07	4.157E+05	1.27
STD. DEV.	19.0	312	969	192	790	355	1197	4.189E+07	4.083E+05	.53
					2.540-CM DEPTH					
1PD......	211.5	2945	9252	1317	3790	3226	9998	4.797E+07	2.268E+05	1.37
2PD......	176.7	3234	11129	1432	3425	3537	11644	3.382E+07	1.914E+05	1.80
3PD......	283.6	2629	6716	1192	3389	2886	7523	7.705E+07	2.717E+05	.91
4PD......	177.3	2389	8571	1317	4012	2727	9464	4.706E+07	2.654E+05	1.33
5PD......	193.2	3180	12365	1268	3990	3424	12993	2.096E+08	1.085E+06	1.62
6PD......	176.2	2700	10809	1877	4315	3288	11638	1.394E+08	7.913E+05	1.51
3B.......	156.0	2046	5355	1076	2322	2312	5837	1.170E+07	7.499E+04	1.29
	125.6	1953	5218	810	1695	2114	5486	1.624E+07	1.293E+05	1.53
	193.9	1975	4061	818	1406	2138	4297	1.311E+07	6.762E+04	1.00
	208.0	1570	4163	614	1672	1686	4487	1.739E+07	8.360E+04	.74
	176.8	1299	3763	538	1290	1406	3978	1.738E+07	9.832E+04	.72
5B.......	136.8	1134	3576	489	1254	1235	3790	3.918E+07	2.864E+05	.82
	212.1	1526	3225	605	1285	1641	3472	6.645E+07	3.133E+05	.71
6B.......	213.8	907	2869	636	1495	1108	3235	3.201E+06	1.497E+04	.42
	156.5	1357	3296	1045	2446	1713	4105	3.388E+06	2.165E+04	.85
	160.2	2055	3972	1312	2175	2438	4529	1.823E+07	1.138E+05	1.26
	187.7	1841	3598	1090	1868	2140	4054	3.930E+07	2.094E+05	.97
AVERAGE..	185.1	2043	5996	1026	2461	2295	6502	4.709E+07	2.497E+05	1.11
STD. DEV.	36.3	712	3176	383	1108	781	3322	5.379E+07	2.803E+05	.39

TABLE A-2. - TEST RESULTS FOR +15° RADIAL

BLOCK	CUT WEIGHT, G	CUTTING FORCES, N: HOR. AVG.	HOR. PEAK	NORMAL AVG.	NORMAL PEAK	RES. AVG.	RES. PEAK	AIRBORNE DUST: TOTAL, CU UM	SPECIFIC, CU UM/G	SPECIFIC ENERGY, J/G
					0.318-CM DEPTH					
1RA......	7.0	400	2411	565	2598	692	3544	1.446E+07	2.066E+06	5.63
2RA......	10.7	409	1570	560	1810	694	2396	2.923E+07	2.732E+06	3.76
3RA......	6.6	289	939	374	1085	472	1435	3.751E+06	5.683E+05	4.31
4RA......	9.3	351	863	480	1130	595	1422	1.610E+07	1.731E+06	3.72
5RA......	8.6	409	1277	547	1975	683	2352	7.120E+05	8.278E+04	4.68
6RA......	8.1	605	1557	854	2122	1047	2632	1.069E+07	1.320E+06	7.35
AVERAGE..	8.4	411	1436	563	1787	697	2297	1.249E+07	1.417E+06	4.91
STD. DEV.	1.5	106	563	160	588	191	799	1.015E+07	9.756E+05	1.39
					0.635-CM DEPTH					
1RB......	19.4	734	2700	850	2953	1123	4002	6.786E+07	3.498E+06	3.72
2RB......	25.6	645	2073	792	2206	1021	3027	1.743E+07	6.808E+05	2.48
3RB......	17.3	765	1979	1050	2651	1299	3308	2.602E+06	1.504E+05	4.35
4RB......	17.0	529	1486	663	2091	848	2565	3.029E+07	1.782E+06	3.06
5RB......	21.8	489	1850	547	2010	734	2732	5.832E+06	2.675E+05	2.21
6RB......	18.8	854	2295	1148	2691	1430	3537	9.481E+06	5.043E+05	4.47
AVERAGE..	20.0	669	2064	841	2434	1076	3195	2.225E+07	1.147E+06	3.38
STD. DEV.	3.2	141	411	227	383	264	533	2.444E+07	1.291E+06	.95
					1.270-CM DEPTH					
1RC......	60.1	1495	6476	1277	3874	1966	7547	2.000E+07	3.328E+05	2.45
2RC......	52.5	1530	4074	1712	3185	2296	5171	2.622E+07	4.995E+05	2.87
3RC......	75.5	1632	4025	1717	3848	2369	5568	2.155E+07	2.854E+05	2.13
4RC......	56.2	1019	2411	1103	2286	1501	3323	5.139E+07	9.144E+05	1.78
5RC......	48.2	1174	2544	1414	2451	1838	3533	1.798E+07	3.730E+05	2.40
6RC......	61.2	898	3087	885	3225	1261	4464	7.295E+07	1.192E+06	1.45
AVERAGE..	59.0	1291	3770	1351	3145	1872	4934	3.502E+07	5.995E+05	2.18
STD. DEV.	9.4	302	1503	332	671	435	1553	2.228E+07	3.691E+05	.51
					2.540-CM DEPTH					
1RD......	101.6	2228	8322	1361	3336	2611	8966	8.113E+07	7.985E+05	2.16
2RD......	278.2	2353	8104	1388	3332	2732	8762	1.834E+08	6.592E+05	.83
3RD......	119.5	2277	7268	1886	4426	2957	8510	2.016E+08	1.687E+06	1.88
4RD......	184.3	1326	3910	823	2220	1560	4496	1.331E+07	7.220E+04	.71
5RD......	158.7	1944	7984	1308	3154	2343	8584	4.582E+07	2.887E+05	1.21
6RD......	191.3	1450	5849	685	2566	1604	6387	1.473E+07	7.699E+04	.75
AVERAGE..	172.3	1930	6906	1242	3172	2301	7618	9.000E+07	5.971E+05	1.25
STD. DEV.	62.8	444	1722	434	761	591	1795	8.337E+07	6.121E+05	.62

TABLE A-3. - TEST RESULTS FOR +3° RADIAL

BLOCK	CUT WEIGHT, G	CUTTING FORCES, N: HOR. AVG.	HOR. PEAK	NORMAL AVG.	NORMAL PEAK	RES. AVG.	RES. PEAK	AIRBORNE DUST: TOTAL, CU ΜM	SPECIFIC, CU ΜM/G	SPECIFIC ENERGY, J/G
					0.318-CM DEPTH					
1A.......	13.5	236	1788	196	1099	306	2099	5.129E+07	3.799E+06	1.72
	10.9	222	952	267	898	347	1309	8.788E+06	8.062E+05	2.01
	18.8	138	930	80	200	159	951	3.914E+07	2.082E+06	.72
4A.......	11.0	240	1250	480	979	537	1587	2.978E+06	2.707E+05	2.15
	8.8	302	1250	538	1219	617	1746	1.804E+07	2.050E+06	3.38
	13.1	200	992	405	827	452	1292	2.856E+06	2.180E+05	1.50
	9.1	160	1072	280	854	323	1371	2.120E+07	2.330E+06	1.73
	7.5	227	867	458	1032	511	1348	1.110E+07	1.480E+06	2.98
5A.......	7.1	80	894	125	396	148	978	5.423E+07	7.638E+06	1.11
	7.4	120	814	271	734	297	1096	7.896E+07	1.067E+07	1.60
	7.2	93	729	187	605	209	948	9.598E+06	1.333E+06	1.28
AVERAGE..	10.4	184	1049	299	804	355	1338	2.711E+07	2.971E+06	1.83
STD. DEV.	3.6	70	295	152	305	157	361	2.518E+07	3.290E+06	.78
					0.635-CM DEPTH					
1A.......	20.7	360	1535	209	489	417	1611	1.290E+07	6.233E+05	1.71
	27.3	418	2215	222	685	474	2319	1.505E+06	5.511E+04	1.51
4A.......	19.4	703	2553	805	1668	1069	3050	1.147E+08	5.910E+06	3.57
	26.0	485	2615	574	1793	751	3171	1.729E+07	6.650E+05	1.84
	29.2	427	2117	547	1552	694	2625	1.833E+07	6.290E+05	1.44
	22.8	569	2064	685	1343	891	2463	4.970E+06	2.180E+05	2.46
	26.0	471	2197	592	1446	756	2630	2.163E+07	8.320E+05	1.78
5A.......	19.8	227	1059	351	867	418	1369	1.775E+07	8.964E+05	1.13
	20.5	262	2086	325	1005	417	2316	5.264E+07	2.568E+06	1.26
	20.3	254	1361	187	574	315	1477	2.570E+06	1.266E+05	1.23
	21.1	231	1530	271	698	357	1682	8.305E+07	3.936E+06	1.08
AVERAGE..	23.0	401	1939	433	1102	596	2246	3.158E+07	1.496E+06	1.73
STD. DEV.	3.5	153	499	214	472	248	627	3.671E+07	1.876E+06	.73
					1.270-CM DEPTH					
1A.......	78.8	703	2211	254	525	747	2272	2.941E+07	3.732E+05	.88
	61.8	756	3060	236	547	792	3109	1.648E+07	2.667E+05	1.20
4A.......	72.2	961	4186	543	1397	1103	4412	1.412E+07	1.955E+05	1.31
	56.1	1085	3723	672	1334	1276	3955	9.632E+06	1.717E+05	1.90
	75.3	947	3354	507	1032	1075	3509	1.166E+08	1.548E+06	1.24
	65.9	578	2931	351	1219	677	3175	2.725E+07	4.135E+05	.86
	63.6	912	4946	636	1486	1112	5164	2.801E+07	4.404E+05	1.41
5A.......	53.7	414	3630	342	729	537	3702	1.130E+08	2.105E+06	.76
	59.6	218	1241	231	632	318	1392	3.742E+07	6.279E+05	.36
AVERAGE..	65.2	730	3253	419	989	849	3410	4.355E+07	6.824E+05	1.10
STD. DEV.	8.6	284	1083	173	386	314	1117	4.131E+07	6.776E+05	.45
					2.540-CM DEPTH					
1A.......	212.8	1539	7410	1032	2357	1853	7776	1.718E+07	8.071E+04	.71
	250.3	1561	7691	729	1334	1723	7806	7.429E+06	2.968E+04	.61
4A.......	177.5	916	3585	396	898	998	3696	1.086E+07	6.119E+04	.51
	162.7	1588	5547	454	898	1651	5619	8.911E+06	5.477E+04	.96
	141.7	1094	3803	654	1197	1275	3987	5.382E+06	3.798E+04	.76
5A.......	133.7	876	4386	400	1130	963	4529	8.112E+07	6.067E+05	.65
	158.0	2028	9101	707	1561	2148	9234	3.321E+08	2.102E+06	1.26
	198.3	436	5591	258	787	507	5646	5.612E+07	2.830E+05	.22
	155.1	734	6236	414	1165	842	6344	3.888E+08	2.507E+06	.47
	171.0	890	3131	427	1032	987	3297	4.467E+07	2.612E+05	.51
AVERAGE..	176.1	1166	5648	547	1236	1295	5793	9.526E+07	6.024E+05	.67
STD. DEV.	35.4	490	1976	230	455	524	1991	1.426E+08	9.193E+05	.29

TABLE A-4. - TEST RESULTS FOR -17° RADIAL

BLOCK	CUT WEIGHT, G	CUTTING FORCES, N: HOR. AVG.	HOR. PEAK	NORMAL AVG.	NORMAL PEAK	RES. AVG.	RES. PEAK	AIRBORNE DUST: TOTAL, CU UM	SPECIFIC, CU UM/G	SPECIFIC ENERGY, J/G
0.318-CM DEPTH										
1B.......	12.5	151	1059	125	400	196	1132	4.281E+07	3.428E+06	1.19
	12.2	209	974	169	507	269	1098	9.141E+06	7.493E+05	1.69
	8.2	111	881	125	427	167	979	5.363E+07	6.540E+06	1.33
2A.......	7.4	107	872	120	414	161	965	4.332E+07	5.854E+06	1.42
3A.......	9.5	102	614	111	258	151	666	5.971E+07	6.285E+06	1.06
	14.0	151	1254	125	494	196	1348	2.044E+07	1.460E+06	1.06
	9.5	138	1032	125	476	186	1136	3.268E+07	3.440E+06	1.43
	10.8	107	1032	107	427	151	1117	9.655E+06	8.940E+05	.97
AVERAGE..	10.5	135	965	126	425	185	1055	3.392E+07	3.581E+06	1.27
STD. DEV.	2.3	36	185	19	78	39	196	1.930E+07	2.421E+06	.24
0.635-CM DEPTH										
1B.......	26.4	512	2647	316	1232	601	2919	1.615E+07	6.116E+05	1.91
	22.3	489	2380	267	1063	557	2606	7.332E+07	3.288E+06	2.16
2A.......	26.6	369	1615	231	916	436	1857	2.498E+07	9.390E+05	1.37
3A.......	24.9	454	2188	280	1014	533	2412	2.029E+07	8.150E+05	1.79
	28.7	409	1472	231	654	470	1611	1.170E+08	4.075E+06	1.40
	27.8	311	1672	182	685	361	1807	2.772E+07	9.970E+05	1.10
AVERAGE..	26.1	424	1996	251	927	493	2202	4.658E+07	1.788E+06	1.62
STD. DEV.	2.3	76	476	46	225	88	519	4.028E+07	1.494E+06	.40
1.270-CM DEPTH										
1B.......	94.0	1735	5302	774	1930	1900	5643	9.340E+07	9.936E+05	1.82
	79.4	1561	5177	796	2242	1753	5642	2.025E+07	2.551E+05	1.94
2A.......	47.1	778	3323	467	1566	908	3673	5.935E+07	1.260E+06	1.63
	61.5	796	2313	494	979	937	2511	1.304E+07	2.120E+05	1.27
3A.......	59.4	858	3029	552	1401	1020	3337	6.742E+06	1.135E+05	1.42
	85.4	1041	4363	552	1797	1178	4719	7.315E+07	8.566E+05	1.20
	59.1	685	3785	405	1183	796	3966	1.812E+06	3.066E+04	1.14
AVERAGE..	69.4	1065	3899	577	1585	1213	4213	3.825E+07	5.316E+05	1.49
STD. DEV.	17.0	416	1113	151	440	437	1180	3.648E+07	4.923E+05	.31
2.540-CM DEPTH										
1B.......	195.0	3461	9915	1134	2522	3642	10230	1.383E+08	7.093E+05	1.75
2A.......	195.1	2304	8402	1023	2300	2521	8711	1.120E+08	5.740E+05	1.16
	111.5	961	4408	569	2135	1117	4898	4.827E+07	4.329E+05	.85
3A.......	159.4	1588	5346	712	2228	1740	5792	5.365E+06	3.366E+04	.98
	195.8	1290	7477	583	2033	1415	7748	2.686E+07	1.372E+05	.65
	181.9	1406	3710	672	1846	1558	4144	9.475E+06	5.209E+04	.76
AVERAGE..	173.1	1835	6543	782	2177	1999	6921	5.671E+07	3.232E+05	1.02
STD. DEV.	33.3	913	2438	238	232	933	2363	5.576E+07	2.884E+05	.40

TABLE A-5. - TEST RESULTS FOR +3° CONICAL

BLOCK	CUT WEIGHT, G	CUTTING FORCES, N						AIRBORNE DUST		SPECIFIC ENERGY, J/G
		HOR. AVG.	HOR. PEAK	NORMAL AVG.	NORMAL PEAK	RES. AVG.	RES. PEAK	TOTAL, CU µM	SPECIFIC, CU µM/G	
					0.318-CM DEPTH					
2B.......	6.6	129	747	156	761	202	1066	2.740E+06	4.152E+05	1.92
	8.5	476	1192	752	2046	890	2368	1.663E+07	1.956E+06	5.51
	6.2	320	881	480	1148	577	1447	5.876E+06	9.478E+05	5.08
4B.......	10.5	298	832	463	1272	550	1520	4.858E+06	4.627E+05	2.79
	6.8	360	925	552	1308	659	1602	5.417E+06	7.966E+05	5.21
	6.1	160	681	191	658	249	947	1.127E+07	1.848E+06	2.38
	9.2	245	658	365	1139	439	1315	2.916E+06	3.170E+05	2.62
6A.......	9.2	280	863	431	1423	514	1665	3.479E+05	3.781E+04	3.00
	7.5	294	1023	436	1414	526	1746	6.443E+06	8.590E+05	3.85
	7.6	520	1072	939	2006	1073	2274	3.954E+06	5.203E+05	6.74
	8.0	227	947	360	1512	426	1785	4.187E+05	5.234E+04	2.79
AVERAGE..	7.8	301	893	466	1335	555	1612	5.534E+06	7.466E+05	3.83
STD. DEV.	1.4	119	164	225	432	253	439	4.771E+06	6.436E+05	1.56
					0.635-CM DEPTH					
2B.......	33.5	400	1343	467	1446	615	1973	5.249E+06	1.567E+05	1.18
	18.5	983	2353	1352	2824	1672	3676	5.023E+06	2.715E+05	5.23
	25.2	876	2678	1076	2402	1388	3597	1.337E+06	5.307E+04	3.42
4B.......	19.1	498	1624	565	1632	753	2302	5.037E+06	2.637E+05	2.57
	23.6	961	2673	1268	2740	1591	3828	1.446E+06	6.129E+04	4.01
	28.6	627	1686	823	2108	1035	2699	4.313E+06	1.508E+05	2.16
	27.1	787	2669	1019	3594	1287	4477	2.673E+06	9.865E+04	2.86
	19.1	1103	2553	1637	3807	1974	4584	3.104E+07	1.625E+06	5.68
6A.......	22.5	565	1170	823	1410	998	1832	3.308E+06	1.470E+05	2.47
	19.1	891	1864	1303	2033	1573	2758	8.500E+06	4.450E+05	4.54
	20.1	939	1864	1401	2282	1686	2946	1.912E+06	9.513E+04	4.60
	19.6	885	2464	1397	3438	1654	4230	1.568E+07	7.998E+05	4.45
AVERAGE..	23.0	792	2078	1094	2476	1352	3242	7.127E+06	3.473E+05	3.60
STD. DEV.	4.8	219	550	363	822	419	956	8.499E+06	4.541E+05	1.37
					1.270-CM DEPTH					
2B.......	69.8	912	4577	867	2522	1258	5226	1.002E+07	1.435E+05	1.29
	67.7	1321	5293	1197	2936	1782	6053	5.381E+06	7.948E+04	1.92
	65.5	863	3434	743	1944	1139	3946	3.944E+06	6.021E+04	1.30
4B.......	75.3	1036	3323	836	2091	1332	3926	6.876E+05	9.132E+03	1.35
	64.9	845	3968	845	3067	1195	5027	1.506E+06	2.320E+04	1.28
	63.1	1014	3683	1139	3149	1525	4846	2.084E+06	3.302E+04	1.58
6A.......	98.5	663	2451	814	2451	1050	3466	5.469E+06	5.552E+04	.66
	75.4	632	1379	663	1833	916	2293	1.238E+06	1.642E+04	.82
	87.2	774	1744	810	1944	1120	2611	1.492E+06	1.711E+04	.87
	81.7	987	3171	1259	3407	1600	4655	8.824E+06	1.080E+05	1.19
AVERAGE..	74.9	905	3302	917	2536	1292	4205	4.065E+06	5.456E+04	1.23
STD. DEV.	11.4	201	1205	204	577	270	1185	3.305E+06	4.446E+04	.37
					2.540-CM DEPTH					
2B.......	152.7	1317	6908	1463	3812	2412	7890	1.326E+07	8.681E+04	1.24
	136.8	1348	7753	854	2228	1596	8067	1.122E+07	8.204E+04	.97
	179.9	1557	5440	712	2389	1712	5941	1.714E+07	9.530E+04	.85
4B.......	149.7	2202	7459	1913	5431	2916	9227	2.199E+06	1.469E+04	1.45
	184.1	1521	4217	903	3243	1769	5319	7.990E+06	4.340E+04	.81
	150.7	1655	6992	1148	3656	2014	7890	1.108E+07	7.352E+04	1.08
	195.6	1628	6490	1241	4132	2047	7694	1.833E+07	9.370E+04	.82
6A.......	137.3	1361	3394	1343	2691	1912	4331	4.123E+07	3.003E+05	.98
	177.7	1334	4457	1076	2869	1714	5300	1.039E+07	5.848E+04	.74
	163.0	1268	4168	1428	3065	1909	5173	1.024E+07	6.280E+04	.77
	106.0	1877	4795	2162	4279	2863	6427	5.358E+06	5.055E+04	1.74
AVERAGE..	157.6	1606	5643	1295	3436	2079	6660	1.349E+07	8.742E+04	1.04
STD. DEV.	25.9	292	1527	441	947	457	1566	1.030E+07	7.461E+04	.32

APPENDIX B.--SUMMARY OF AIRBORNE RESPIRABLE DUST BY CLASS INTERVAL, WITH CALCULATED MILLIGRAMS PER TON

TABLE B-1. - Airborne respirable dust by class interval

Bit type	Cut avg. wt, g	DP, µm	Number	Cum. number	Volume, cu µm		Weight, mg/ton	
					Int. vol	Cum. vol.	Int. wt.	Cum. wt.
0.318-cm (1/8-in) DEPTH								
+3° radial.	10.4	0.94	23,135	23,135	1.0061E+04	1.0061E+04	11.7	11.7
		1.83	13,122	36,257	4.2107E+04	5.2168E+04	49.0	60.7
		2.62	9,064	45,321	8.5353E+04	1.3752E+05	99.4	160.1
		3.63	12,334	57,655	3.0890E+05	4.4642E+05	359.6	519.7
		5.06	10,386	68,041	7.0455E+05	1.1510E+05	820.2	1,339.9
		6.86	10,875	78,916	1.8383E+06	2.9893E+06	2,140.0	3,479.8
		8.51	64,442	85,360	2.0794E+06	5.0686E+06	2,420.6	5,900.4
0.635-cm (1/4-in) DEPTH								
+3° radial.	23.0091	0.94	10,930	10,930	4.7533E+03	4.7533E+03	5.5	5.5
		1.83	6,471	17,401	2.0764E+04	2.5517E+04	24.2	29.7
		2.62	4,444	21,845	4.1852E+04	6.7369E+04	48.7	78.4
		3.63	6,148	27,993	1.5398E+05	2.2135E+05	179.3	257.7
		5.06	5,038	33,031	3.4176E+05	5.6311E+05	397.8	655.5
		6.86	5,671	38,702	9.5851E+05	1.5216E+06	1,115.8	1,771.3
		8.51	3,470	42,172	1.1197E+06	2.6413E+06	1,303.4	3,074.7
1.27-cm (1/2-in) DEPTH								
+3° radial.	65.2222	0.94	4,475	4,475	1.9462E+03	1.9462E+03	2.3	2.3
		1.83	2,758	7,233	8.8507E+03	1.0797E+04	10.3	12.6
		2.62	1,927	9,161	1.8149E+04	2.8946E+04	21.1	33.7
		3.63	2,583	11,743	6.4683E+04	9.3629E+04	75.3	109.0
		5.06	2,310	14,053	1.5669E+05	2.5032E+05	182.4	291.4
		6.86	2,557	16,610	4.3222E+05	6.8253E+05	503.1	794.5
		8.51	1,702	18,312	5.4910E+05	1.2316E+06	639.2	1,433.8
2.54-cm (1.0-in) DEPTH								
+3° radial.	176.11	0.94	4,007	4,007	1.7427E+03	1.7427E+03	2.0	2.0
		1.83	2,321	6,328	7.4469E+03	9.1896E+03	8.7	10.7
		2.62	1,711	8,039	1.6116E+04	2.5306E+04	18.8	29.5
		3.63	2,169	10,208	5.4312E+04	7.9617E+04	63.2	92.7
		5.06	2,028	12,236	1.3757E+05	2.1719E+05	160.1	252.8
		6.86	2,286	14,522	3.8639E+05	6.0358E+05	449.8	702.6
		8.51	1,532	16,054	4.9433E+05	1.0979E+06	575.4	1,278.1
0.31-cm (1/8-in) DEPTH								
-17° radial.	10.5125	0.94	35,689	35,689	1.5521E+04	1.5521E+04	18.1	18.1
		1.83	18,376	54,065	5.8967E+04	7.4488E+04	68.6	89.7
		2.62	12,414	66,480	1.1690E+05	1.9139E+05	136.1	222.8
		3.63	15,040	81,520	3.7668E+05	5.6807E+05	438.5	661.3
		5.06	12,212	93,732	8.2387E+05	1.3964E+06	964.3	1,625.6
		6.86	12,922	106,653	2.1842E+06	3.5807E+06	2,542.6	4,168.2
		8.51	5,858	112,511	1.8903E+06	5.4709E+06	2,200.4	6,368.7
0.635-cm (1/4-in) DEPTH								
-17° radial.	26.1167	0.94	16,304	16,304	7.0903E+03	7.0903E+03	8.3	8.3
		1.83	9,192	25,496	2.9497E+04	3.6587E+04	34.3	42.6
		2.62	6,234	31,730	5.8708E+04	9.5295E+04	68.3	110.9
		3.63	7,579	39,309	1.8982E+05	2.8512E+05	221.0	331.9
		5.06	6,315	45,625	4.2840E+05	7.1352E+05	498.7	830.6
		6.86	6,598	52,223	1.1153E+06	1.8288E+06	1,298.3	2,128.9
		8.51	3,249	55,472	1.0486E+06	2.8774E+06	1,220.6	3,349.5

See explanatory notes at end of table.

TABLE B-1. - Airborne respirable dust by class interval--Continued

Bit type	Cut avg. wt, g	DP, µm	Number	Cum. number	Volume, cu µm		Weight, mg/ton	
					Int. vol.	Cum. vol.	Int. wt.	Cum. wt.
1.27-cm (1/2-in) DEPTH								
-17° radial.	66.7	0.94	15,202	15,202	6.6883E+03	6.6113E+03	7.7	7.7
		1.83	10,170	25,372	3.6233E+04	3.9244E+04	38.0	45.7
		2.62	7,800	33,171	7.3448E+04	1.1269E+05	85.5	131.2
		3.63	10,879	44,051	2.7247E+05	3.8516E+05	317.2	448.4
		5.06	10,308	54,359	6.9926E+05	1.0844E+06	814.0	1262.4
		6.86	11,082	65,441	1.8731E+06	2.9576E+06	2,180.5	3,442.9
		8.51	6,780	72,220	2.1877E+06	5.1453E+06	2,546.7	5,989.6
2.54-cm (1-in) DEPTH								
-17° radial.	173.1171	0.94	2,722	2,722	1.1839E+03	1.1839E+03	1.4	1.4
		1.83	1,488	42,111	4.7757E+03	5.9596E+03	5.6	6.9
		2.62	1,003	5,214	9.4494E+03	1.5409E+04	11.0	17.9
		3.63	1,257	6,471	3.1471E+04	4.6880E+04	36.6	54.6
		5.06	1,086	7,557	7.3667E+04	1.2055E+05	85.8	140.3
		6.86	1,229	8,785	2.0769E+05	3.2824E+05	241.8	382.1
		8.51	5,480	9,333	1.7690E+05	5.0514E+05	205.9	588.0
1.27-cm (1/8-in) DEPTH								
Conical.	7.83636	0.94	8,719	8,719	3.7927E+03	3.7917E+03	4.4	4.4
		1.83	4,875	13,704	1.5997E+04	1.9788E+04	18.6	23.0
		2.62	2,844	16,548	2.6780E+04	4.6568E+04	31.2	54.2
		3.63	3,403	19,951	8.5225E+04	1.3179E+05	99.2	153.4
		5.06	2,527	22,478	1.7145E+05	3.0324E+05	199.6	353.0
		6.86	2,624	25,102	4.4351E+05	7.4675E+05	516.3	869.3
		8.51	1,233	26,335	3.9782E+05	1.1446E+06	463.1	1,332.4
2.54-cm (1/4-in) DEPTH								
Conical.	23	0.94	2,996	29,967	1.30299+03	1.3029E+03	1.5	1.5
		1.83	2,321	6,328	5.4022E+03	9.1896E+03	8.7	10.7
		2.62	1,711	8,039	1.6116E+04	2.5306E+04	18.8	29.5
		3.63	2,169	10,208	5.4312E+04	7.9617E+04	63.2	92.7
		5.06	2,028	12,236	1.3757E+05	2.1719E+05	160.1	252.8
		6.86	2,286	14,522	3.8639E+05	6.0358E+05	449.8	702.6
		8.51	1,532	16,054	4.9433E+05	1.0979E+06	575.4	1,278.1
1.27-cm (1/2-in) DEPTH								
Conical.	74.91	0.94	509	509	2.2114E+02	2.2114E+02	0.3	0.3
		1.83	279	788	8.9068E+02	1.1180E+03	1.0	1.3
		2.62	199	987	1.8759E+03	2.9939E+03	2.2	3.5
		3.63	245	1,232	6.1392+035	9.1331E+03	7.1	10.6
		5.06	203	1,436	1.3794E+04	2.2927E+04	16.1	26.7
		6.86	187	1,623	3.1646E+04	5.4573E+04	36.8	63.5
		8.51	98	1,721	3.1578E+04	8.6151E+04	36.8	100.3
2.54-cm (1-in) DEPTH								
Conical.	157.591	0.94	697	697	3.0296E+02	3.0296E+02	0.4	0.4
		1.83	385	1,082	1.2368E+03	1.5397E+03	1.4	1.8
		2.62	284	1,366	2.6767E+03	4.2164E+03	3.1	4.9
		3.63	349	1,715	8.7391E+03	1.2956E+04	10.2	15.1
		5.06	268	1,983	1.8197E+04	3.1153E+04	21.2	36.3
		6.86	336	2,320	5.6848E+04	8.8001E+04	66.2	102.4
		8.51	152	2,472	4.8974E+04	1.3697E+05	57.0	159.5

See explanatory notes at end of table.

TABLE B-1. - Airborne respirable dust by class interval--Continued

Bit type	Cut avg. wt, g	DP, µm	Number	Cum. number	Volume, cu µm Int. vol.	Cum vol	Weight, mg/ton Int. wt.	Cum. wt.
0.318-cm (1/8-in) DEPTH								
Plumb bob	9.23	0.94	13,082	13,082	5.6893E+03	5.6893E+03	6.6	6.6
		1.83	6,906	19,988	2.2159E+04	2.7848E+04	25.8	32.4
		2.62	4,309	24,296	4.0574E+04	6.8423E+04	47.2	79.7
		3.63	5,648	29,945	1.4146E+05	2.0988E+05	164.7	244.3
		5.06	34,622	34,622	3.1732E+05	5.2720E+06	369.4	613.7
		6.86	5,427	40,049	9.1733E+05	1.4445E+06	1,067.9	1,681.6
		8.51	2,923	42,973	9.4331E+05	2.3878E+06	1,098.1	2,779.7
0.635-cm (1/4-in) DEPTH								
Plumb bob	25.8	0.94	5,409	5,409	2.3525E+03	2.3525E+03	2.7	2.7
		1.83	2,918	8,328	9.3642E+03	1.1717E+04	10.9	13.6
		2.62	2,030	10,357	1.9112E+04	3.0829E+04	22.2	35.9
		3.63	2,407	12,764	6.0285E+04	9.1114E+04	70.2	106.1
		5.06	2,136	14,901	1.4492E+05	2.3603E+05	168.7	274.8
		6.86	2,638	17,539	4.4597E+05	6.8201E+05	519.2	793.9
		8.51	1,306	18,845	4.2140E+05	1.10343+06	490.6	1,284.5
1.27-cm (1/2-in) DEPTH								
Plumb bob	88.29	0.94	2,406	2,406	1.0466E+03	1.0466E+03	1.2	1.2
		1.83	1,466	3,873	4.7055E+03	5.7520E+03	5.5	6.7
		2.62	1,057	4,930	9.9535E+03	1.5706E+04	11.6	18.3
		3.63	1,143	6,373	3.6140E+04	5.1846E+04	42.1	60.4
		5.06	1,223	7,596	8.2959E+04	1.3481E+05	96.6	156.9
		6.86	1,677	9,273	2.8348E+05	4.1829E+05	330.0	486.9
		8.51	833	10,106	2.6884E+06	6.8713E+05	313.0	799.9
2.54-cm (1-in) DEPTH								
Plumb bob	185.053	0.94	1,240	1,240	5.39449+02	5.3944E+02	0.6	0.6
		1.83	802	2,043	2.5743E+03	3.1137E+03	3.0	3.6
		2.62	581	2,624	5.4756E+03	8.5893E+03	6.4	10.0
		3.63	831	3,455	2.0815E+04	2.9404E+04	24.2	34.2
		5.06	731	4,186	4.9559E+06	7.8964E+04	57.7	91.9
		6.86	1,013	5,199	1.7122E+05	2.5019E+05	199.3	291.2
		8.51	532	5,731	1.7169E+05	4.2188E+05	199.9	491.1
0.317-cm (1/8-in) DEPTH								
+15° radial.	8.38333	0.94	9,007	9,007	3.9171E+03	3.9171E+03	4.6	4.6
		1.83	5,088	14,095	1.6326E+04	2.0243E+04	19.0	23.6
		2.62	3,489	17,584	3.2860E+04	3.2860E+04	38.3	61.8
		3.63	3,998	21,582	1.0012E+05	1.5322E+05	116.6	178.4
		5.06	3,590	25,172	2.4355E+05	3.9677E+05	283.5	461.9
		6.86	6,036	31,209	1.0204E+06	1.0204E+06	1,187.8	1,649.7
		8.51	2,487	33,696	8.0264E+05	2.2198E+06	934.44	2,584.0
0.635-cm (1/4-in) DEPTH								
+15° radial.	19.9833	0.94	5,561	5,561	2.4185E+03	2.4185E+03	2.8	2.8
		1.83	2,757	8,318	8.8457E+03	1.1264E+04	10.3	13.1
		2.62	2,428	10,746	2.2861E+04	3.4125E+04	26.6	39.7
		3.63	3,114	13,860	7.8002E+04	1.1213E+05	90.8	130.5
		5.06	3,231	17,983	1.8197E+04	3.1153E+04	21.2	36.3
		6.86	4,828	21,919	8.1603E+05	1.14735+06	959.9	1,335.6
		8.51	3,806	25,725	1.2282E+06	2.3756E+06	1,429.8	2,765.4

See explanatory notes at end of table.

TABLE B-1.--Airborne respirable dust by class interval--Continued

Bit type	Cut avg. wt, g	DP, µm	Number	Cum. number	Volume, cu µm		Weight, mg/ton	
					Int. vol.	Cum. vol.	Int. vol.	Cum. wt.
1.27-cm (1/2-in) DEPTH								
+15 radial.	9.23	0.94	3,015	3,015	1.3111E+03	1.3222E+03	1.5	1.5
		1.83	1,671	4,686	5.3615E+03	6.6726E+03	6.2	7.8
		2.62	1,142	5,828	1.0754E+04	1.7427E+04	12.5	20.3
		3.63	1,608	7,436	4.0273E+04	5.7699E+04	46.9	67.2
		5.06	1,627	9,063	1.1040E+05	1.6810E+05	128.5	195.7
		6.86	2,553	11,616	4.3159E+05	5.9968E+05	502.4	698.1
		8.51	1,981	13,508	6.3912E+05	1.2388E+06	744.0	1,442.1
2.54-cm (1-in) DEPTH								
+15 radial.	25.8	0.94	1,961	1,961	8.5268E+02	8.5268E+02	1.0	1.0
		1.83	1,188	3,149	3.8120E+03	4.6647E+03	4.4	5.4
		2.62	970	4,119	9.1378E+03	1.3803E+04	10.6	16.1
		3.63	1,409	5,528	3.5382E+04	4.9085E+04	41.1	57.1
		5.06	1,480	7,008	1.0043E+05	1.4951E+05	116.9	174.0
		6.86	2,647	9,656	4.4751E+05	5.9702E+05	520.9	695.0
		8.51	2,105	11,761	6.7942E+05	1.27643+06	790.9	1,485.9

Column descriptions:

DP = Mean size value for each class interval.

Number = Number of particle counts in class interval.
Cum. number = Cumulative particle count.

Int. vol. = Volume of airborne respirable dust in class interval.
Cum. vol. = Cumulative volume of all sizes of respirable dust.

Weight = Calculated weight of dust per short ton coal, using 80-lb/cu ft density.

Int. wt. = Weight of dust per class interval.
Cum. wt. = Cumulative weight of dust per ton.

APPENDIX C.--STUDENT'S T-VALUES OF PAIRED DATA[1]

$$T = \frac{(\bar{y}_2 - \bar{y}_1) - D_o}{\sqrt{\frac{(n_2 - 1)\, s_2^2 + (n_1 - 1)\, s_1^2}{(n_2 + n_1 - 2)} \times \frac{1}{n_2} + \frac{1}{n_1}}},$$

where T = calculated paired Student's t-value indicating statistically significant differences between two given arithmetic average comparisons if this calculated t-value is not less than the handbook t-value for the same paired degrees of freedom at a given percent confidence level;

D_o = null hypothesis set to zero for computing Student's t-value under the conditions described above;

$\bar{y}$ = arithmetic average of given column of data; subscripts 1 and 2 indicate the first and second data columns being compared;

n = number of digits in a given data column;

$(n_2 + n_1 - 2)$ = degrees of freedom of a given pair of data columns;

and s = standard deviation for a given data column:

$$s = \sqrt{\frac{\Sigma xi^2 - (\Sigma xi)^2 n}{n - 1}},$$

where Σxi^2 = result of squaring each digit, then totaling up values;

and $(\Sigma xi)^2$ = result of totaling up all digits, then squaring the sum.

[1]Mendenhall, W. Introduction to Linear Models and the Designs and Analysis of Experiments. Wadsworth Pub. Co., Inc., Belmont, CA, 1968, pp. 26-27.

Weast, R. C. Handbook of Chemistry and Physics. Chemical Rubber Co., Cleveland, OH, 48th ed., 1967-68, p. A-161.

TABLE C-1. - Student's t-values of significance of paired specific energy averages

Depth of cut....	0.318 cm (1/8 in)	0.635 cm (1/4 in)	1.270 cm (1/2 in)	2.540 cm (1 in)
+15RD, PB60.....	4.850[a]	3.485[a]	3.717[a]	0.647
+3RD, PB60......	-1.636[b]	-1.290[c]	-.834	-3.091[a]
+3RD, -17RD.....	1.951[a]	.339	-1.954[a]	-2.032[a]
+15RD, -17RD....	7.360[a]	4.182[a]	3.002[a]	.764
PB60, -17RD.....	3.094[a]	1.474[b]	-1.030	.483
+15RD, +3RD.....	5.924[a]	4.014[a]	4.323[a]	2.568[a]
PB60, +3CO......	-3.067[a]	-3 993[a]	.213	.496
+15RD, +3CO.....	1.414[b]	-.351	4.325[a]	.934
+3RD, +3CO......	-3.803[a]	-4.028[a]	-.691	-2.766[a]
+3CO, -17RD.....	4.567[a]	3.420[a]	-1.519[b]	.113

[a]≥90-pct confidence level. [b]≥80-pct confidence level. [c]≥70-pct confidence level.

NOTE.-- +3CO.....+3° conical -17RD.....-17° radial
+3RD.....+3° radial PB60.....60° plumb-bob bit
+15RD.....+15° radial

TABLE C-2. - Student's t-values of significance of paired specific dust averages

Depth of cut....	0.318 cm (1/8 in)	0.635 cm (1/4 in)	1.270 cm (1/2 in)	2.540 cm (1 in)
+15RD, PB60.....	-0.048	1.169[c]	0.986	1.895[a]
+3RD, PB60......	1.845[a]	1.723[a]	1.320[b]	1.486[b]
+3RD, -17RD.....	-.443	-.327	.494	.714
+15RD, -17RD....	-2.051[a]	-.795	.277	.992
PB60, -17RD.....	-3.036[a]	-2.574[a]	-.614	-.548
+15RD, +3RD.....	-1.116[c]	-.404	-.272	-.012
PB60, +3CO......	1.655[b]	1.524[b]	2.764[a]	1.867[a]
+15RD, +3CO.....	1.715[b]	1.965[a]	4.722[a]	2.801[a]
+3RD, +3CO......	2.201[a]	2.060[a]	2.932[a]	1.856[a]
+3CO, -17RD.....	-3.742[a]	-3.145[a]	-3.090[a]	-2.621[a]

[a]≥90-pct confidence level. [b]≥80-pct confidence level. [c]≥70-pct confidence level.

NOTE.-- +3CO.....+3° conical -17RD.....-17° radial
+3RD.....+3° radial PB60.....60° plumb-bob bit
+15RD.....+15° radial

TABLE C-3. - Student's t-values of significance of paired tangential force averages

Depth of cut....	0.318 cm (1/8 in)	0.635 cm (1/4 in)	1.270 cm (1/2 in)	2.540 cm (1 in)
+15RD, PB60.....	4.584[a]	2.787[a]	1.553[b]	-0.362
+3RD, PB60......	-.931	-2.177[a]	-2.762[a]	-3.433[a]
+3RD, -17RD.....	1.804[a]	-.342	-1.917[a]	-1.927[a]
+15RD, -17RD....	6.930[a]	3.747[a]	1.102[c]	.229
PB60, -17RD.....	2.380[a]	1.596[b]	.013	.573
+15RD, +3RD.....	5.341[a]	3.541[a]	3.657[a]	3.121[a]
PB60, +3CO......	-2.336[a]	-4.705[a]	1.488[b]	1.923[a]
+15RD, +3CO.....	1.887[a]	-1.243[c]	3.089[a]	1.824[a]
+3RD, +3CO......	-2.811[a]	-4.918[a]	-1.563[b]	-2.529[a]
+3CO, -17RD.....	3.795[a]	3.947[a]	-1.062	-.780

[a]≥90-pct confidence level. [b]≥80-pct confidence level. [c]≥70-pct confidence level.

NOTE.-- +3CO.....+3° conical -17RD.....-17° radial
+3RD.....+3° radial PB60.....60° plumb-bob bit
+15RD.....+15° radial

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