RI 8801

Bureau of Mines Report of Investigations/1983

Testing Modified Coal-Cutting Bit Designs for Reduced Energy, Dust, and Incendivity

By Wallace W. Roepke and Bruce D. Hanson

UNITED STATES DEPARTMENT OF THE INTERIOR

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Library of Congress Cataloging in Publication Data:

Roepke, Wallace W

Testing modified coal-cutting bit designs for reduced energy, dust, and incendivity.

(Report of investigations / United States Department of the Interior, Bureau of Mines ; 8801)

Includes bibliographical references.

Supt. of Docs. no.: I 28.23:8801.

1. Coal-cutting bits—Testing. I. Hanson, Bruce D. II. Title. III. Series: Report of investigations (United States. Bureau of Mines) ; 8801.

TN23.U43 [TN813] 622s [622'.3382'028] 83-600223

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm	centimeter	in/s	inch per second
cm/min	centimeter per minute	J/g	joule per gram
cu µm	cubic micrometer	lb	pound
cu µm/g	cubic micrometer per gram	lb/cu ft	pound per cubic foot
ft	foot	~~mg/ton~~	~~milligram~~ per short ton
ft/min	foot per minute	µm	micrometer
g	gram	N	newton
g/ton	gram per short ton	pct	percent
gal/min	gallon per minute	psi	pound per square inch
in	inch	rpm	revolution per minute
in/min	inch per minute		

TESTING MODIFIED COAL-CUTTING BIT DESIGNS FOR REDUCED ENERGY, DUST, AND INCENDIVITY

By Wallace W. Roepke[1] and Bruce D. Hanson[2]

ABSTRACT

Four bit designs, two conical and two radial, were tested in coal against a 60° conical reference bit to obtain data on orthogonal cutting forces and primary respirable dust generation. One conical and one radial design were modified by the Bureau of Mines for these tests. Results were mixed: One radial bit used substantially lower overall cutting forces and specific energy than the other bits and was the only cutter lower on energy and most forces than the standard 60° bit. However, it generated more specific and total dust than any other bit.

The four bits were also tested for incendivity, with a 90° plumb-bob bit as the reference. The frictional ignition tests were designed to simulate both trimming top rock and cutting such rock during advance on-sump. Results of these tests were also mixed. The radial bits were substantially less incendive than the reference bit and caused no ignitions in either top trimming or sump modes. Only the modified mushroom-tipped conical bit caused ignitions. Bits similar to this modified design should not be used on drum-type miners in gassy mine areas; instead, the other types of bits tested should be used to reduce ignition potential to a minimum.

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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. Because of the nature of the dust problem and the varying mining conditions complicating its control (e.g., geology and seam characteristics), a long-term research commitment is required to develop basic solutions that are more generic and of greater benefit to a large segment of the mining and minerals industry than those resulting from previous efforts. This research seeks a basic understanding of the formation of dust during the cutting cycle. The results should provide knowledge that can help minimize the primary generation of dust and speed development of cost-effective cutting equipment. Improved cutting concepts will help manufacturers to improve overall machine efficiency, resulting in increased product recovery with reduced dust generation, ignition potential, cutting-force requirements, and energy consumption.

The Bureau of Mines coal-cutting research facility at Twin Cities (MN) is examining the fundamental aspects of the cutting system that affect dust generation and frictional-impact ignition of methane. The cutting system is defined as the cutter-mineral interface area with all its variables, i.e., forces, speed, cutter geometry, and wear. The evidence has been established over the past several years that cutting directly affects the economics and design of the "total system," which is defined as all areas of the mining operation, from the face to the preparation plant, which support mineral recovery by the cutting tools.

Over 2,000 continuous mining machines in use in the United States today account for well over half of our underground coal production. Studies have identified continuous miner operators and helpers as those in "high risk" occupations for dust exposure on continuous sections. The coal mining industry also considers respirable dust to be the greatest obstacle to achieving the full-production potential of longwall mining using double-drum shearers.

The dust problem is a continuing burden on the miners, the mining industry, and taxpayers, which merits correction. Since 1970, the Federal Government has paid over $11.7 billion to more than 470,000 miners with black lung disease and their survivors.[3] Six percent of coal miners now working show symptoms of the disease. Reducing the individual's exposure to below the mandated level by controlling primary dust generation during cutting will substantially reduce the incidence of black lung and other respiratory diseases. These efforts will help the industry ensure the health and well-being of its work force, while producing coal and other critical and important nonfuel minerals most efficiently.

This report covers one of an ongoing series of basic studies that seek better understanding of the fundamental use and design of coal cutters so that primary dust production can be limited while economic return is increased.

This report reviews testing of a modified conical mushroom-type bit, a modified radial bit, and generic designs including the 60° conical reference bit, the 90° conical reference bit, and the commercial radial bit. The tests compared their orthogonal cutting forces, specific energy, and dust generation, including specific airborne respirable dust (ARD) and total dust. Frictional ignition tests were also run.

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

ACKNOWLEDGMENTS

The authors thank Ted Myren, mining engineering technician, Twin Cities Research Center, for his usual excellent efforts in obtaining all of the coal dust and forces data. The assistance of V. William Dellorfano, mining engineering technician, Twin Cities, in obtaining the ignition data is also gratefully recognized.

We also thank Lung Cheng, mechanical engineer, Pittsburgh Research Center, for supplying the modified bits for testing and for providing technical consultation early in the testing.

BIT SPECIFICATIONS

New designs of both conical and radial bits using modified tungsten carbide inserts were tested for orthogonal cutting forces, primary respirable dust generation, and incendivity. Such design changes should have a clear, positive health and safety impact on the cutting systems, and the economics of the total system through the preparation plant should also be improved.

The bits tested are shown in figure 1. On the left is the standard reference plumb-bob type with a 60° included tip angle (PB-60), as used for coal cutting. (Not shown, but having the same body style as PB-60 is the plumb-bob bit with a 90° tip (PB-90R) used as the reference bit for ignition testing.) Although both conicals tested (PB-90, PB-90M) have 90° included tip angles, the latter has been modified with a carbide insert that covers the end of the body completely like a mushroom cap. The intent is to reduce incendivity by preventing contact of body steel with any inclusive rock during cutting. As may be seen in figure 2, both 90° conicals have cutting tips

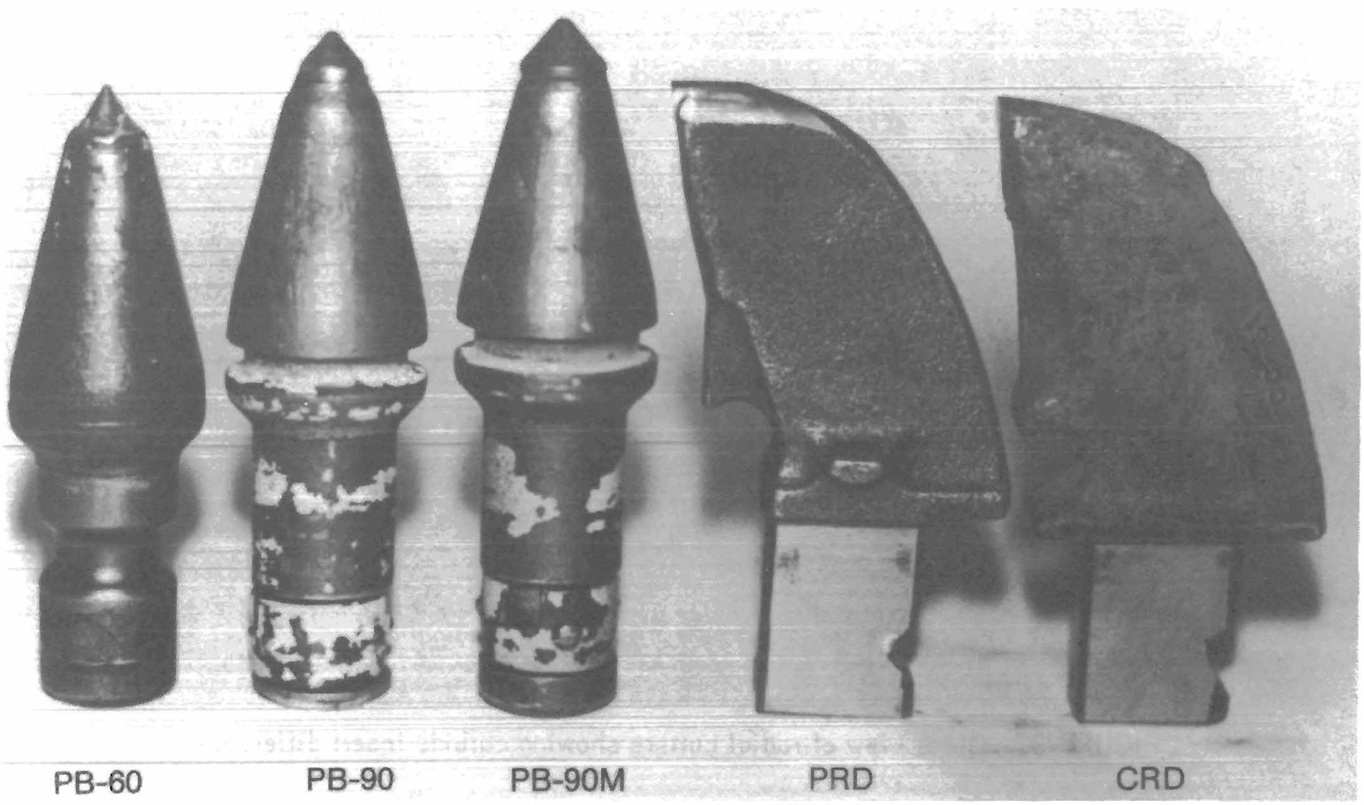

FIGURE 1. - Bits tested. PB-60 reference bit is 4-7/8 in long.

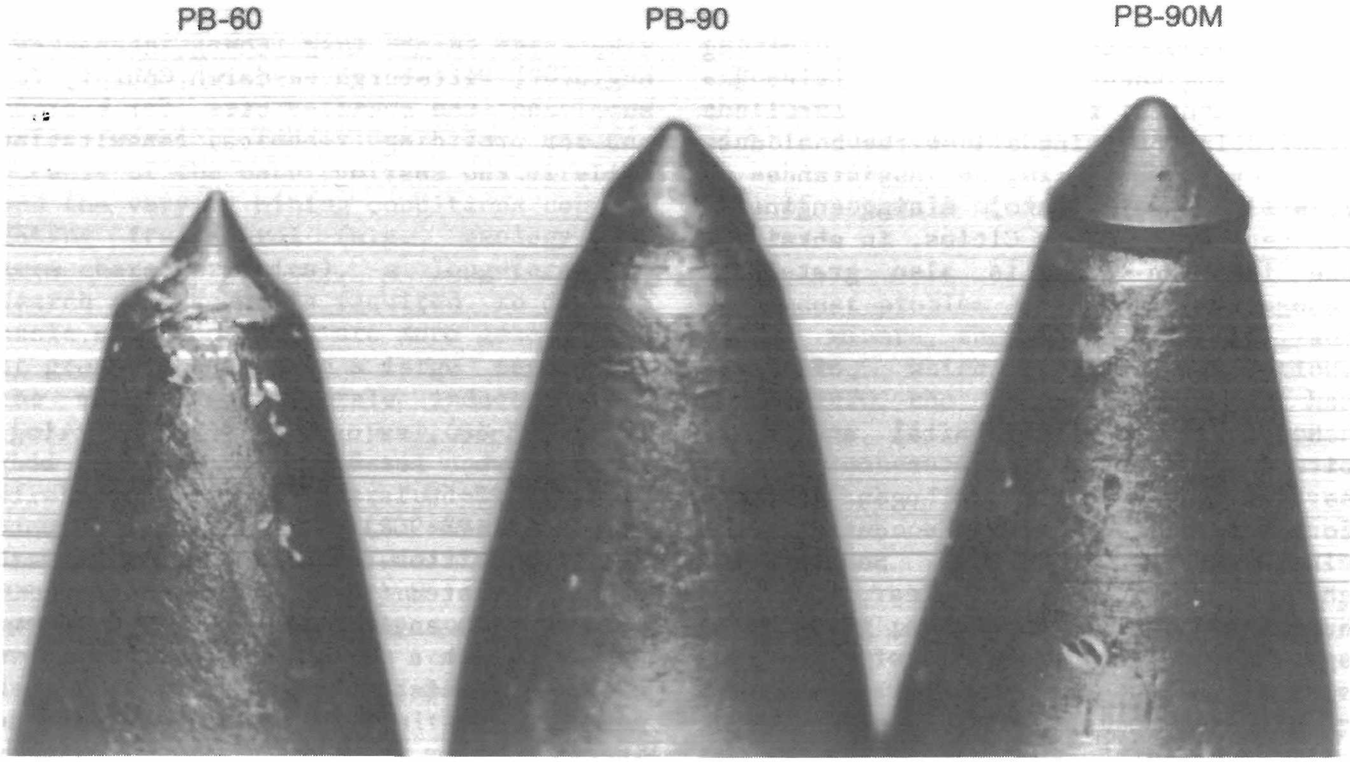

FIGURE 2. - Close view of conical cutters for comparison with reference bit.

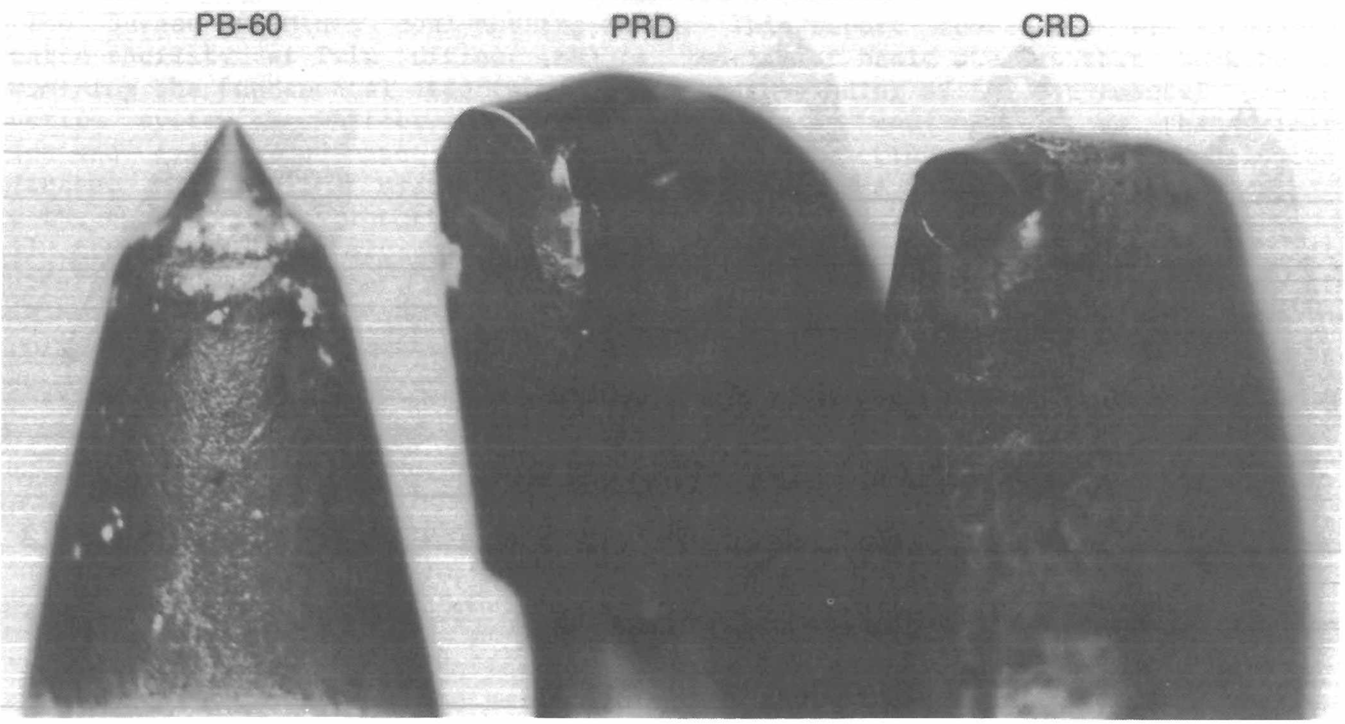

FIGURE 3. - Close view of radial cutters showing carbide insert difference.

larger than the standard reference bit, but both have a standard conical geometry and standard cobalt-bonded tip material.

The modified radial bit (PRD) and the commercial radial bit (CRD) both have standard geometry. Both radial inserts have standard cobalt-bonded tip material, but the PRD has been modified to provide a carbide area along the back or clearance side (fig. 3). No attempt was made to modify the shoulder area of the body steel, which supports the carbide on the sides. The PRD radial bit has less than +1° clearance with a +2° rake on the face and a +10° rake in the body area below the carbide insert. The CRD radial bit has +6° clearance with a +5-1/2 rake on the face and a +7° rake in the body area below the carbide insert.

PRIMARY RESPIRABLE DUST AND CUTTING FORCES IN COAL

TEST EQUIPMENT FOR COAL CUTTING

The major equipment used to obtain data on orthogonal cutting forces and primary respirable dust consisted of a large modified planer mill, a three-axis quartz crystal dynamometer, an optical particle sizer, and a digital data acquisition system. The planer mill (fig. 4) has been modified by removing the quill head and motor from the crossrail and replacing them with a rigid mount to support the bit-dynamometer configuration. This arrangement permits great flexibility in

FIGURE 4. - Large deep-cutting test facility.

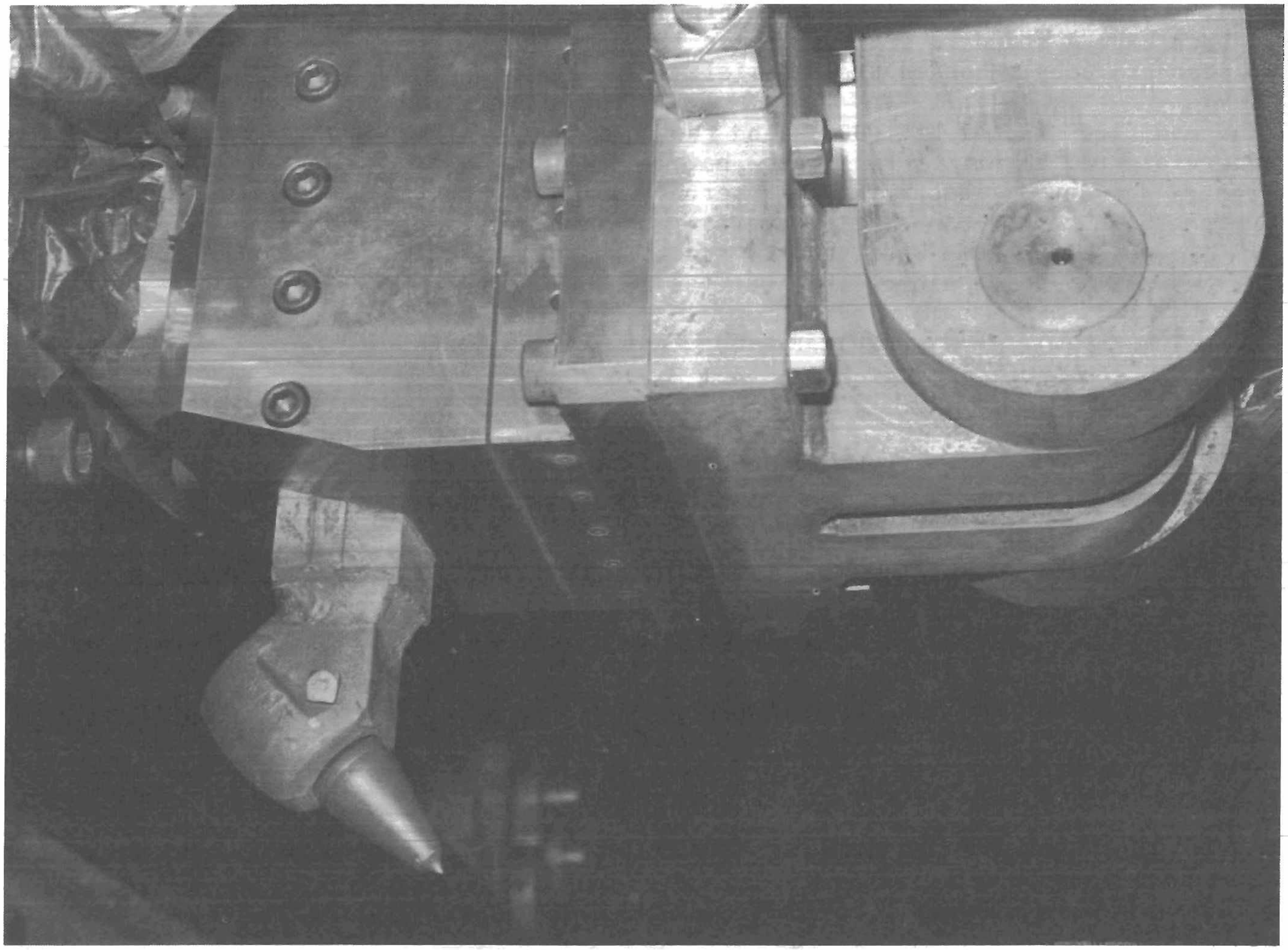

FIGURE 5. - Bit-dynamometer configuration.

testing since the new mount may be translated laterally across the full 66-in distance of the open throat of the machine. Since the rail has a vertical displacement of 44 in, a variety of sample sizes may be accommodated. A test bit mounted on the dynamometer is shown in figure 5 with the shroud and dust-sample tube removed for clarity. The test facility with the dust sampler and sample holder clamped to the traverse table and with the backing supports in place is shown in figure 6. The large tube at the top center brings clean air into an outer shroud to exclude background dust during cutting. A smaller, inner shroud surrounds the bit-coal test and the inlet to the dust sampler, which is mounted just above the bit. The cutter-sampler area is shown in figure 7 with both inner and outer shrouds folded up for clarity. The optical particle sizer is shown just to the left of the clean air duct at the top center of figure 6.

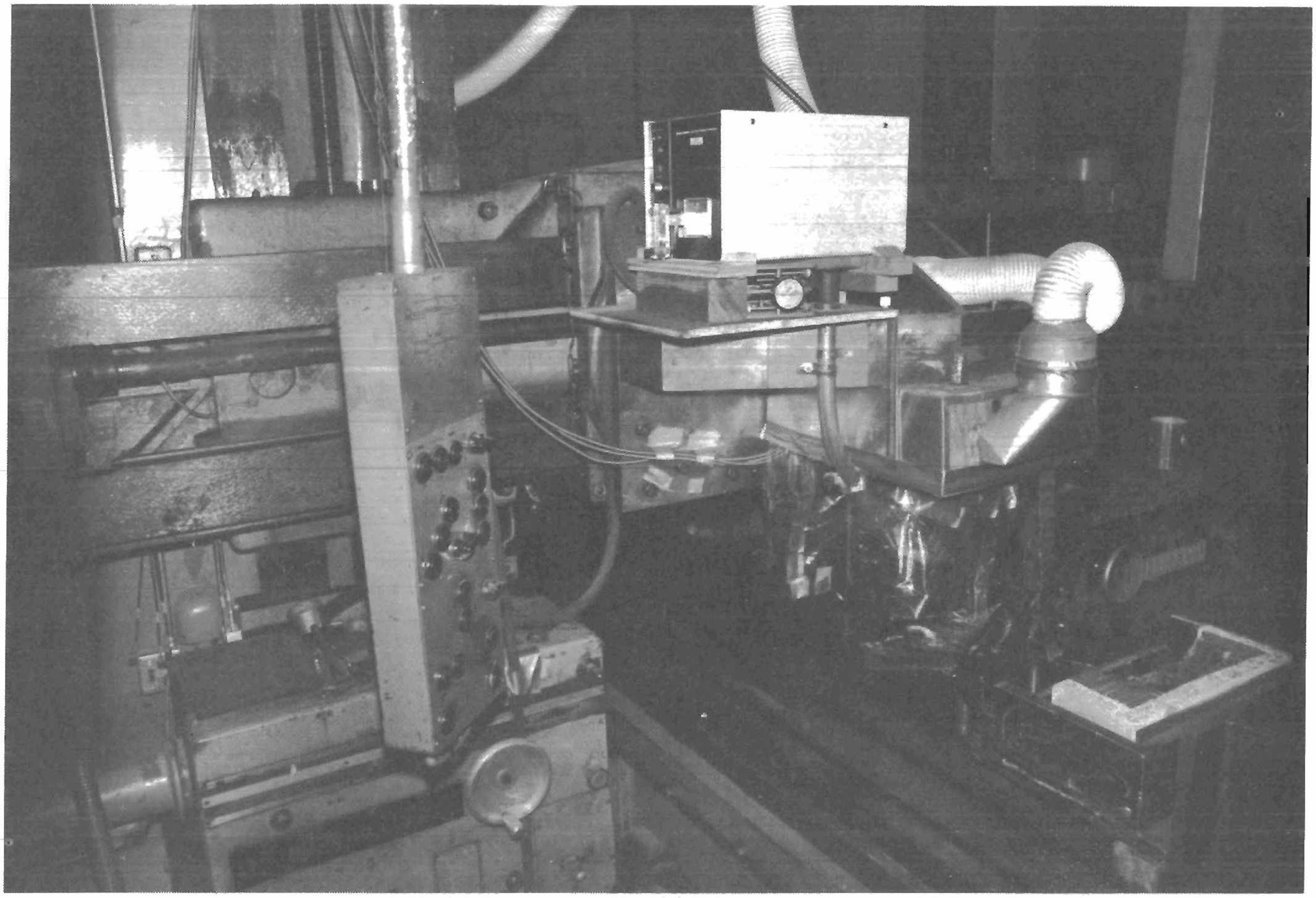

FIGURE 6. - General test configuration.

EXPERIMENTAL TECHNIQUE FOR COAL CUTTING

All tests were run in an identical manner, using the 60° plumb-bob bit as the reference. Each bit was rigidly mounted on a toolpost holder locked in the dynamometer, so that the cutter tip intercepted the X-Y-Z calibration point of the dynamometer. The coal samples were locked to the bed of the planer mill so they could be moved under the bit, which was adjusted for a set depth of cut.

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. A 4.921-cm/min (1.9375-in/min) cutting speed.

5. Constant spacing between bits of 5.08 cm (2 in).

6. A 2-min cutting time, making a 9.8425-cm (3.875-in) kerf in all tests.

Independent variables for these tests were--

1. Three conical and two radial bit types.

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

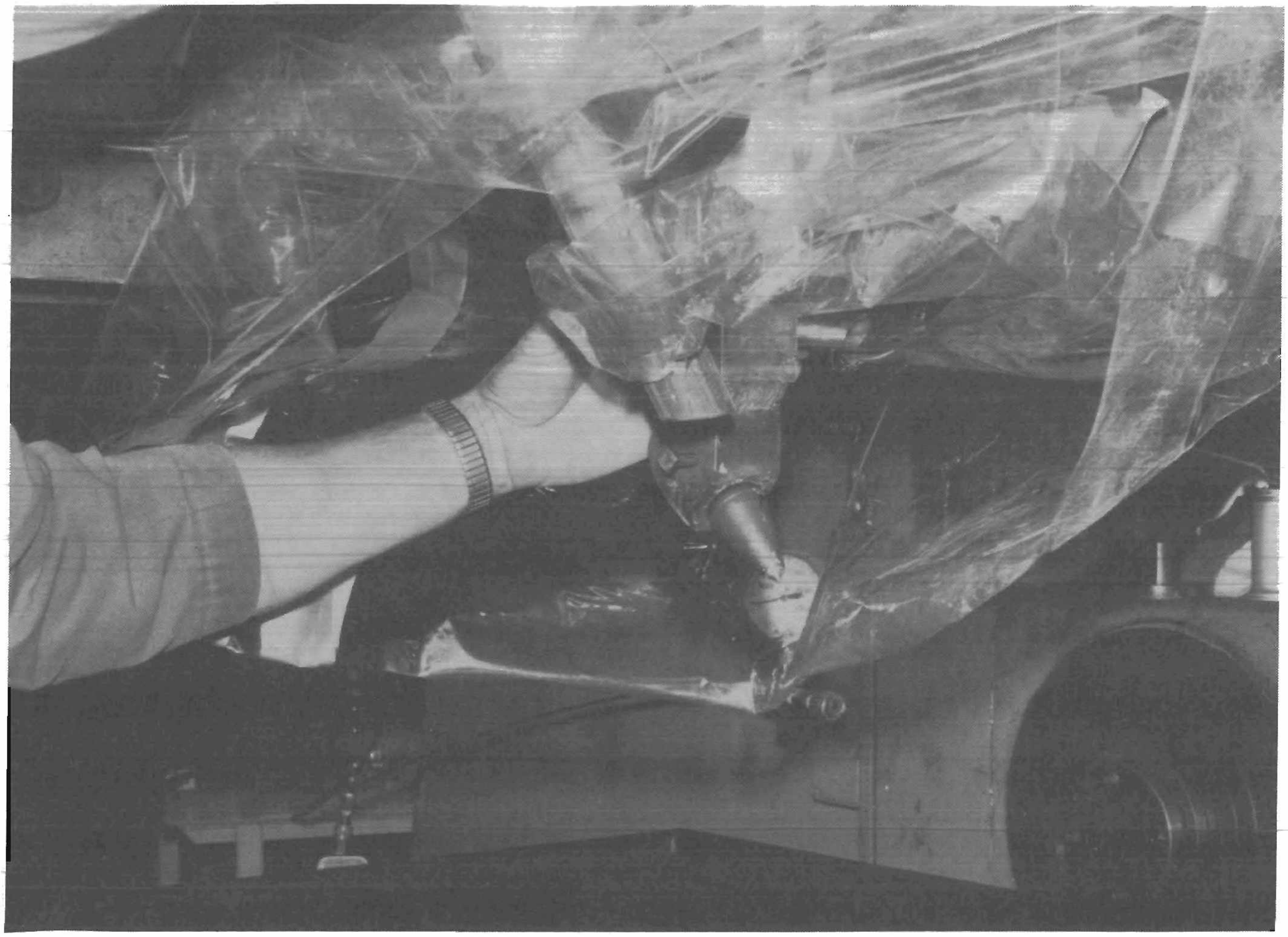

FIGURE 7. - Cutter-sampler configuration.

Dependent variables were--

1. Mean and peak cutting forces.

2. Mean and normal peak normal forces.

3. Weight of coal removed.

4. Total primary airborne respirable dust (ARD).

5. Specific primary ARD.

6. Calculated milligrams ARD per short ton coal.

7. Specific energy.

Compression tests are included to provide another basis for comparison with other research. These tests, made on 1- and 2-in cubes of Illinois No. 6 coal, show a mean uniaxial compression strength of 4,000±350 psi for the 2-in cubes and 4,300±13 psi for the 1-in cubes. The results have the expected direction of change with size reported previously by others.

RESULTS AND CONCLUSIONS OF COAL CUTTING

The mixed test results (figs. 8-14) make arrival at specific conclusions difficult. However, the CRD was observed to use the lowest specific energy, average horizontal force, average normal, and average normal peak force (figs. 8-9, 11-12), while it produced the largest volume of primary ARD (fig. 13) and total dust (fig. 14). The other bits, including the 60° reference bit, all used substantially higher specific energy during shallow cutting; but at the 2.540-cm (1-in) depth there was little difference, since specific energy values for all bits declined and converged as cutting depth increased. This same general distribution was apparent for the dust data, although the pattern was less consistent. A broad distribution may be seen for the total dust curves (fig. 14), which appear to be nearly flat and may even decrease

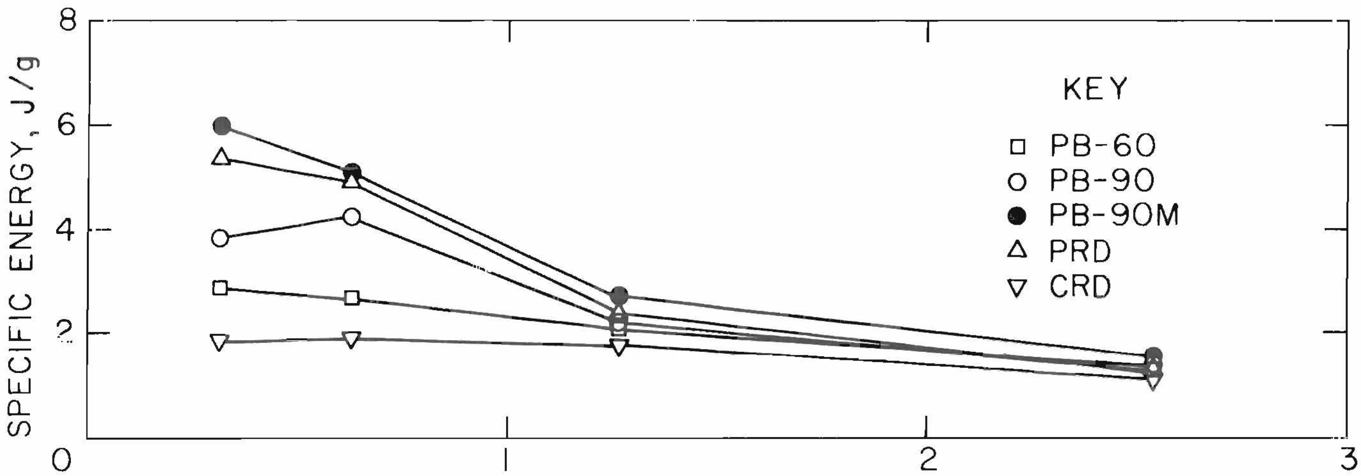

FIGURE 8. - Specific energy.

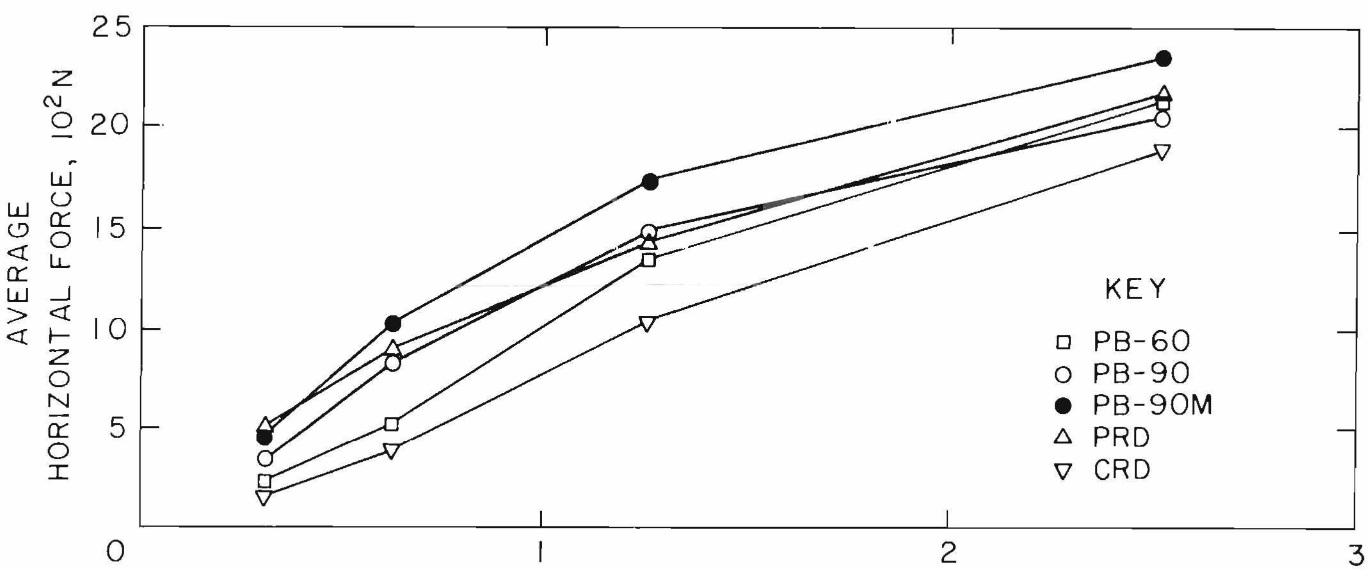

FIGURE 9. - Average horizontal forces.

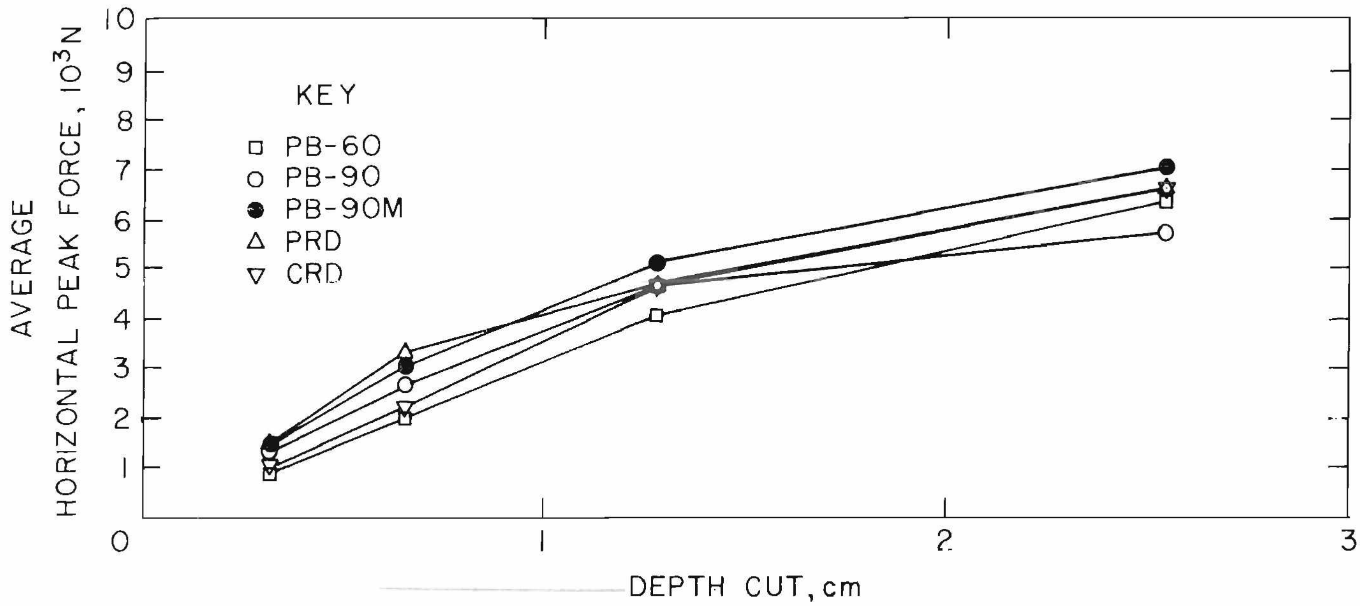

FIGURE 10. - Peak average horizontal forces.

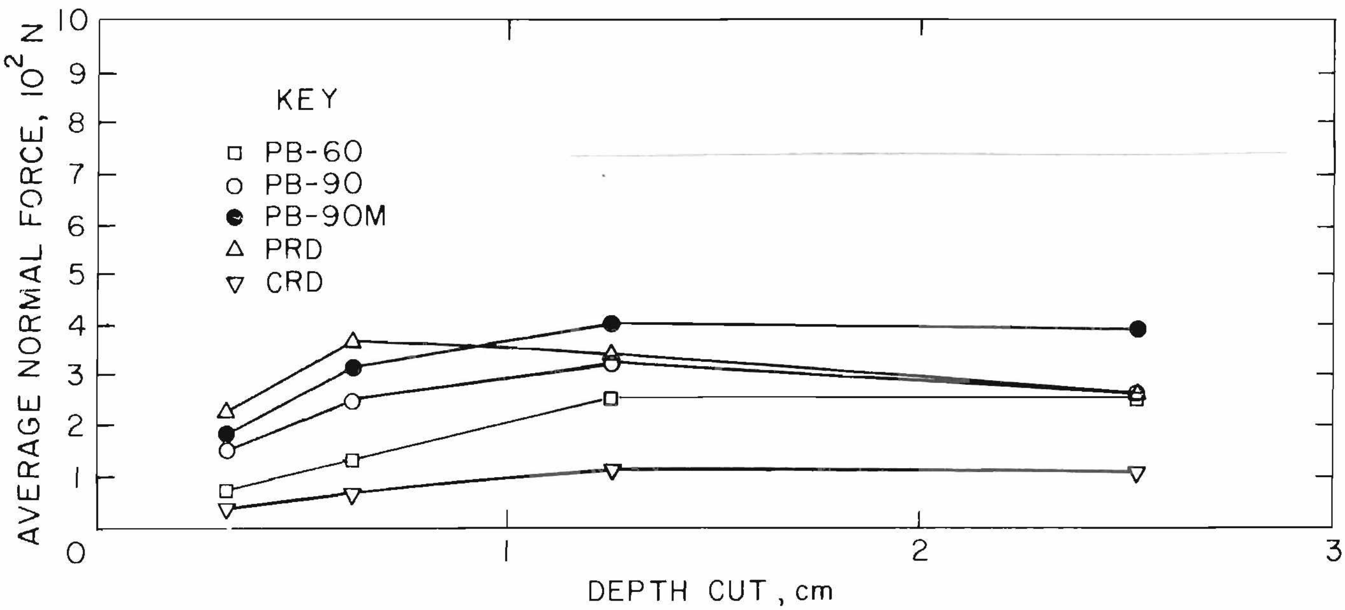

FIGURE 11. - Average normal forces.

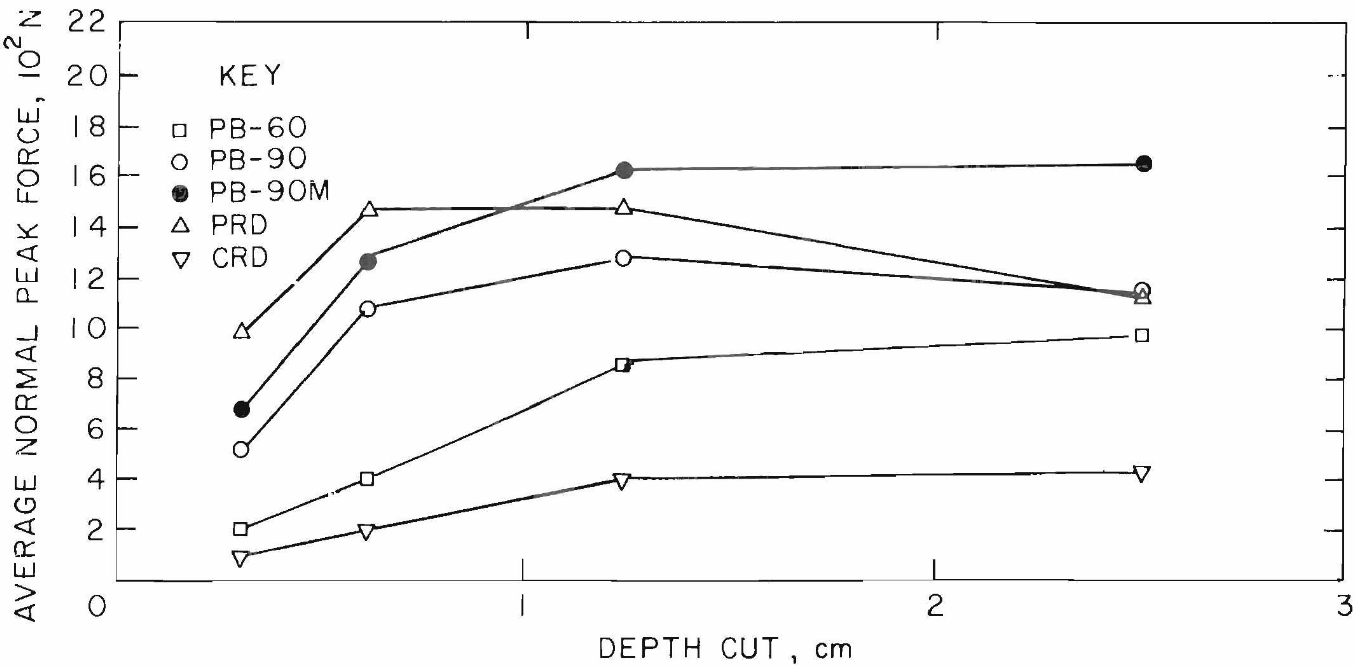

FIGURE 12. - Peak average normal forces.

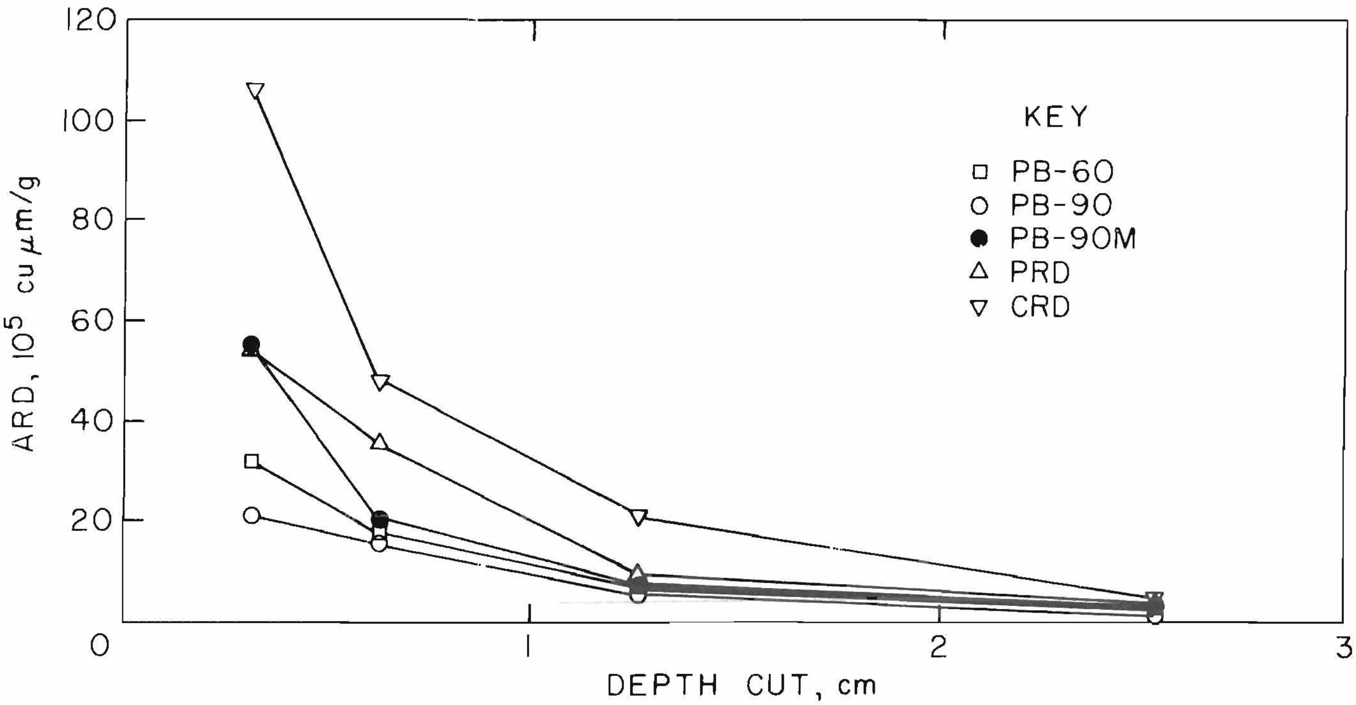

FIGURE 13. - Specific primary airborne respirable dust (ARD).

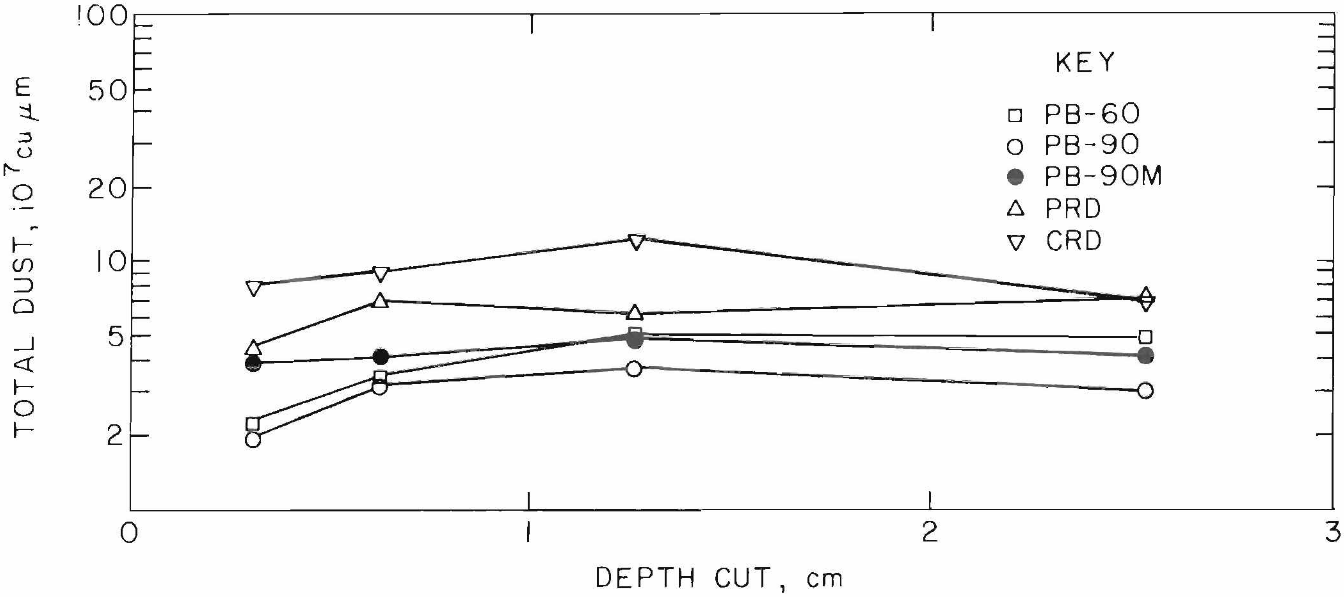

FIGURE 14. - Total primary airborne respirable dust.

slightly beyond a 1-cm depth of cut. The data for normal forces are also distributed broadly at all depths of cut. As would be expected, both types of horizontal forces increased nearly linearly with depth (figs. 9-10). The peak horizontal force increased at a higher rate than the corresponding average force. This condition diminishes the design advantage of deep-cutting equipment since horizontal peak loading is a primary design criterion. The distributions of average and peak normal forces (figs. 11-12) were nearly identical, but the peak normal force traces were higher than the respective average normal force traces. Both average and peak normal forces stabilized with depth, which supports equipment design for deeper cutting, although the design advantage is weakened to the extent that peak normal forces are high, exceeding peak horizontal forces for several bits.

A summary of all test results is given in table 1. All of the data are based on direct measurements except for specific energy, which is calculated as follows:

$$\text{Specific energy} = \frac{F_{\bar{x}H} \times C \times 9.999 \times 10^{-3}}{\bar{x}\ \text{g cut}} = \text{joules per gram coal cut},[4]$$

where $F_{\bar{x}H}$ = average horizonatal cutting force, in N;[5]

C = distance cut, 9.8425 cm for all tests;

and $\bar{x}$ g cut = average grams of coal cut.

[4]Joules per gram coal cut × 334.6 = foot pounds per pound coal cut.
[5]Newtons × 0.2248 = pounds force.

Milligrams ARD per short ton coal were also calculated, as shown below. The calculated values are given in appendix B.

$$\text{ARD (mg/ton)} = \frac{\text{sp. ARD} \times \text{g/ton}}{K} = \text{sp. ARD} \times 1.163 \times 10^{-3},$$

or

$$\frac{\text{sp. ARD} \times \text{coal density}^{6} \times \text{g/ton}}{f},$$

where sp. ARD = average specific airborne respirable dust, in cu µm/g of coal cut;

g/ton = 907,185;

f = volume-to-mass conversion factor for ARD, in cu µm, that is 6.24×10^{10}, allowing insertion of required coal density, in lb/cu ft;

and K = volume-to-mass conversion factor for ARD, in cu µm, that is 7.80×10^{8}, using coal density of 80 lb/cu ft only.

The results shown in table 1 provide more of an insight into the variability of this type of testing than specific

[6]Coal density refers to solid material, not bulk density.

TABLE 1. - Summary of experimental data averages

Bit type	Coal cut, g	Cutting forces, N						Airborne dust		Specific energy, J/g
		Hor. avg.	Hor. peak	Normal avg.	Normal peak	Resultant avg.	Resultant peak	Total, cu µm	Specific, cu µm/g	
					0.318-cm DEPTH					
PB-60..	8.0	235	914	200	734	309	1,185	2.299E+07	3.215E+06	2.92
PB-90..	9.1	347	1,340	515	1,516	622	2,026	1.993E+07	2.150E+06	3.84
PB-90M.	7.8	473	1,516	677	1,804	826	2,365	3.954E+07	5.465E+06	6.03
PRD....	9.5	518	1,507	981	2,256	1,114	2,757	4.646E+07	5.441E+06	5.33
CRD....	9.0	163	1,068	100	391	192	1,144	8.151E+07	1.064E+07	1.87
					0.635-cm DEPTH					
PB-60..	19.8	530	1,956	403	1,331	667	2,379	3.450E+07	1.752E+06	2.69
PB-90..	19.8	829	2,594	1,082	2,533	1,366	3,634	3.165E+07	1.602E+06	4.25
PB-90M.	20.5	1,026	3,044	1,279	3,148	1,641	4,385	4.094E+07	2.063E+06	5.05
PRD....	18.5	898	3,290	1,468	3,687	1,735	5,036	6.970E+07	3.569E+06	4.90
CRD....	20.3	381	2,155	206	718	435	2,285	9.050E+07	4.812E+06	1.92
					1.270-cm DEPTH					
PB-60..	67.4	1,343	4,037	862	2,572	1,607	4,845	4.996E+07	7.746E+05	2.11
PB-90..	66.3	1,486	4,637	1,279	3,241	1,966	5,711	3.699E+07	5.773E+05	2.28
PB-90M.	67.2	1,744	5,097	1,625	4,034	2,388	6,528	4.855E+07	7.606E+05	2.72
PRD....	63.8	1,434	4,709	1,478	3,387	2,083	5,855	6.040E+07	9.720E+05	2.39
CRD....	60.1	1,057	4,632	395	1,155	1,130	4,779	1.237E+08	2.135E+06	1.79
					2.540-cm DEPTH					
PB-60..	168.5	2,136	6,335	965	2,520	2,348	6,842	4.821E+07	3.227E+05	1.41
PB-90..	161.5	2,058	5,701	1,134	2,607	2,356	6,294	2.960E+07	1.804E+05	1.28
PB-90M.	150.4	2,357	7,049	1,641	3,902	2,880	8,097	4.059E+07	2.470E+05	1.56
PRD....	176.9	2,177	6,626	1,115	2,637	2,482	7,201	7.041E+07	3.906E+05	1.26
CRD....	167.8	1,894	6,636	423	1,089	1,944	6,732	6.875E+07	4.749E+05	1.15

answers. It is essential that each variable be reviewed in context of the total mining system, rather than cutting alone. Normal force is particularly important since it affects to a large extent the total system's economics. High normal forces require high horsepower on the mainframe for greater tractive effort and a larger mass of the mainframe to prevent backout. Additionally, a high normal force will affect the dust control by requiring shallower depths of cut. Reduced depth of cut will increase the dust load on all secondary suppression and control systems, which will need to be larger and more expensive and will cause greater maintenance problems. However, focusing only on normal force precludes an overall perspective. It can quickly be seen from these data that, while a bit may have unusually low normal force, it may conversely produce a higher than usual amount of respirable dust. What must be achieved is a redesign of the cutters that melds the best characteristics of each into a single unit. This has not yet been attained.

All raw data from the tests in coal are presented in appendix A. In appendix B there is a class-interval summary for all of the primary ARD between 0.2 and 10.0 µm.

FRICTIONAL BIT IGNITION OF METHANE

TEST EQUIPMENT FOR FRICTIONAL IGNITIONS

The test chamber (fig. 15) is 3- by 4-1/2- by 6-ft and is constructed of 1/8-in-thick steelplate. The front side of the chamber is open. A 21- by 27-in opening on the back side provides access for equipment maintenance. The cutting drum is powered by four hydraulic motors driven by a 130-gal/min pump. The drum can deliver a maximum force of 5,200 lb, and the rotational speed can be varied from 0 to 100 rpm. The maximum bit

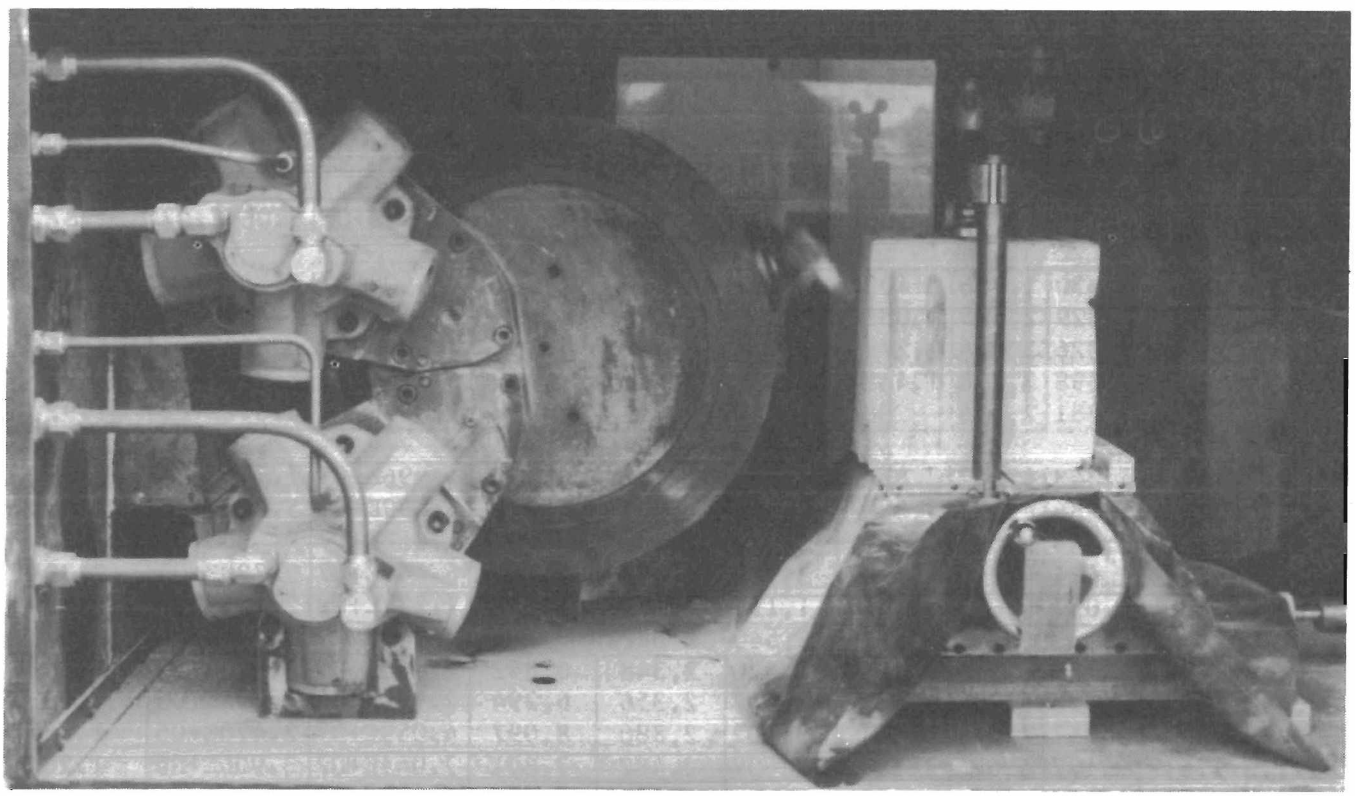

FIGURE 15. - Ignition test chamber.

tip circle diameter is 34 in. The rock sample is mounted on a powered table that has two directions of motion. The rock sample can either be translated across the drum, simulating the cutting of roof rock, or advanced into the drum, simulating the cutting of inclusive material. The table is driven by two dc stepping motors that are programmable and remotely controlled. The table can be translated past the drum at an infinitely variable rate between 0 and 3/4 in/s and advanced toward the drum at a rate between 0 and 3/8 in/s. The open side of the chamber is sealed using 2-mil polyethylene sheet. Flaps are positioned to vent the explosion to the outside.

EXPERIMENTAL TECHNIQUE FOR IGNITION TESTS

During all frictional-impact ignition testing, tangential cutting force, cutterhead revolutions per minute, work performed per impact, and percent methane were recorded on a multichannel strip chart. Cutting force was recorded from a differential pressure transducer connected across the hydraulic motors driving 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 the integrated cutting force 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 methane was introduced. A 6.5 pct methane-air mixture was continuously mixed by a fan in the chamber to prevent layering. The drum section with the cutting tool mounted on it rotated at a predetermined speed. The sample was then stepped into the cutter at a predetermined rate of advance for an increasing kerf depth or set to a predetermined cutting depth and stepped past the drum face for multipass, constant kerf depth cutting. Any test that did not produce an ignition was detonated electrically to verify the explosive mix. The sample material for these tests was Berea sandstone with more than 75 pct quartzite. The mean for 10 compression tests was 4,232±487 psi.

The four bit types were tested only in the transverse cut mode. Since few bits were available, only limited testing could be done before bit wear became a factor.

RESULTS AND CONCLUSIONS OF IGNITION TESTING

Test results are shown in tables 2 and 3 for the four bits tested and for a reference plumb-bob bit similar to the PB-60, but with a 90° tip (PB-90R). The reference bit was not tested at the same time as the others, but all criteria were identical. A standard mounting configuration of 0° skew with a 45° attack angle was used for all conical bits. The radials were also mounted in the normal configuration, i.e., with bit axis normal to the rock face at cutting point.

Two sets of ignition test were run. The first evaluated the two radial bits at maximum anticipated depths for cutting top rock on-sump with a constant kerf length. The worst case ignition condition, 60 rpm at a 0.635-cm (0.25-in) advance rate, i.e., maximum depth of cut per pass, was the condition for the first tests. The 0.50-in spacing between cuts resulted in 24 cuts of identical kerf length per layer of rock. The data in table 2 show that four replications were made with 24 cuts per replication for each bit type, with no ignitions. Twenty-four cuts at 0.635-cm (0.25-in) depth represent the number of cuts taken per bit in top rock during sump. This simulates cutting on the top inside corner of the face area, where the greatest potential for ignitions exists.

TABLE 2. - Ignition tests with transverse cuts across sample face at constant kerf depth and length

(60 rpm)

Bit type	Depth of cut, cm	Number of tests	Cuts per test
PRD........	0.635	4	24N
CRD........	.635	4	24N
PB-90R[1]....	.381	11	[2]2-13
	.381	1	24N

N No ignition.
[1]Reference bit.
[2]Impacts for ignition; mean $\bar{x}$ = 4+.

Previous research has shown that shallower cuts reduce ignition potential. Therefore, the plumb-bob test that set the reference for these tests was run at 60 rpm with 0.381-cm (0.15-in) advance rate. It was also assumed that the bit would be new, but nonrotating, i.e., the same conditions as in the radial tests. The data in table 2 show that the first 11 plumb-bob tests had ignition between 2 and 13 impacts. The mean of less than 5 indicates a very dangerous situation on-sumping at the top in a gassy mine, even with new bits. Only in one case, test 12, was the set completed without ignition. These results suggest that radial bits are substantially less incendive than the standard conical plumb bobs.

The second series of tests (table 3) evaluated all four bit types. The initial test conditions were a drum speed of 60 rpm and a cut depth of 0.508 cm (0.20 in). If any of the bits produced an ignition, those bits were tested again at a reduced depth of cut. This process continued until no ignitions resulted from the test conditions. An individual test consisted of four layers, i.e., four passes across the face. The 0.75-in spacing between cuts resulted in 16 cuts per layer. The kerf length increased with each additional layer. These tests simulate trimming a top by lifting the drum into the roof during repeated cuts. The average tangential force for each of the ignition tests is shown in appendix C.

TABLE 3. - Ignition tests with layered transverse cuts across sample face at constant kerf depth but increasing cut length per layer

(60 rpm)

Bit type	Depth of cut, cm	Number of tests	Cuts per test
PB-90......	0.508	2	64N
PB-90M.....	.254	2	64N
	.381	1	40
	.381	1	64N
	.508	1	22
	.508	1	36
PRD........	.508	2	64N
CRD........	.508	2	64N

N No ignition.

Although compression tests of the Berea sandstone gave a mean of 4,232±487 psi, no visible impact failure could be detected from any bit. The impacts per pass were always oblique since the bit path followed a crescent shape. Thus, no impact-failure testing was performed, since the shallow crescent cuts start at zero depth and simulate sumping or trimming of the roof or floor. Specific impact failures will be tested at a later date, on material that simulates inclusive layers in midseam, where the cuts will strike the top face of a sample at some initial depth.

The conical bits tested, PB-90 and PB-90M, were both substantially less incendive than the PB-90R reference. The mushroom-capped bit, PB-90M, was actually more incendive, however, than the large-tip conical, PB-90. Apparently, even a new bit with only tungsten carbide striking the inclusive material may be incendive.

Since the modified plumb-bob bit with the large carbide cap, PB-90M, was still ignition prone, a series of tests was designed to better define this problem. The intent of the tests was to clearly establish the mechanics of the bit-mineral interface causing frictional ignitions. It was decided that the large 90° included tip angle of PB-90M might be a significant contributing factor. An experiment was therefore designed to test the effect of clearance angle on ignitions. To do this, two test materials were chosen, 4340 body steel and cobalt-bonded tungsten carbide. Rectangles 3/8 in thick by 3/4 in wide by 1-1/4 in long were made of each material. The mounting block configuration was such that if a 3/4-in face were mounted with the block in one direction the test piece would have a positive 3° clearance, and if the block were turned around for mounting, the test piece would have a negative 3° clearance.

The tests clearly showed that body steel is not incendive in every case as originally believed (table 4). When the 4340 test piece had positive clearance, no ignitions occurred in five multiple-impact tests with cut depth ranging from 0.0127 to 0.0381 cm (0.005 to 0.015 in). With negative clearance, ignitions occurred in every test.

The tests with tungsten carbide were run at 60 rpm using 0.0635-cm (0.025-in) depth of cut. In every test with positive clearance no ignitions occurred, but in every test with negative clearance ignition did occur (table 5).

The mechanics of frictional impact ignitions appear to be primarily controlled by the back clearance angle. This is a condition affected by such considerations as initial bit geometry, mounting angle, metallurgical properties, wear, and style of use. All of these considerations will also affect primary dust generation, so that great care must be taken to evaluate these aspects within the context of the cutting system.

TABLE 4. - 4340 body steel incendivity tests

Negative clearance				Positive clearance			
Speed, ft/min	Depth of cut, cm	Impacts to ignition	Avg. force, lb	Speed, ft/min	Depth of cut, cm	Impacts without ignition	Avg. force, lb
470...	0.0127	18	1,051	470...	0.0127	83	407
	.0127	22	793		.0127	88	413
	.0127	16	893		.0127	69	380
	.0127	10	820		.0127	59	453
	.0254	7	1,120		.0381	26	400
	.0254	7	1,170				
	.0381	5	NA				
500...	.0381	31	1,080				
400...	.0381	17	1,080				
300...	.0381	20	987				
200...	.0127	12	800				

NA Not available.

TABLE 5. - Tungsten carbide incendivity tests

Negative clearance			Positive clearance		
Impacts to ignition	Avg. force, lb	Average energy	Impacts without ignition	Avg. force, lb	Average energy
19	504	0.587	64	309	0.205
18	332	.121	68	317	.281
19	523	.777	68	308	.308
18	292	.141	68	309	.353

NOTE.--60 rpm (470 ft/min) at 0.0635-cm depth of cut.

SUMMARY AND CONCLUSIONS

These tests with both standard and modified conical and radial bits have demonstrated how critical it is to examine all aspects of cutting tools in their context. Evaluating only one or two criteria will not allow judgments on safety or health factors. Cutter economics, i.e., initial bit cost, is probably the least desirable evaluation standard. The results presented in this report clearly show substantial differences in primary dust generation, normal forces, specific energy, and incendivity among the test bits and also between the test bits and reference bits. The commercial radial bit (CRD) is clearly superior to all others for lowest specific energy and normal force. Unfortunately, it also generates the most primary respirable dust.

The modified mushroom-tipped conical bit is more incendive than the modified radial bit, but both bits are clearly less incendive than the reference bit. It is strongly recommended that the reference-type plumb-bob bits no longer be used on drum-type continuous mining machines in gassy mine areas. In these areas, the kinds of bits tested for this report will minimize ignition potential. It must be remembered that even a carbide will become incendive when the clearance goes negative owing to wear.

These results should not be considered absolutes, but are a good representation of trends. That is, given the same criteria and test conditions in another coal type and/or inclusive material, the relative rankings among bits should be the same.

APPENDIX A.--MEAN VALUES FOR EACH TEST

Tables A-1 through A-5 give the mean values for each test with standard and modified conical and radial bits and include horizontal, normal, and resultant forces, weight of coal cut, respirable dust per gram cut, and total respirable dust.

TABLE A-1. - TEST RESULTS FOR PB-60

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										
1PA......	7.2	111	485	93	396	145	626	2.394E+07	3.325E+06	1.52
2PA......	7.4	156	689	138	471	208	835	1.678E+07	2.268E+06	2.07
3PA......	6.7	76	498	85	520	113	720	5.771E+06	8.613E+05	1.11
4PA......	9.8	169	796	133	471	215	925	1.581E+07	1.613E+06	1.70
5PA......	6.9	178	1001	129	334	220	1055	2.403E+07	3.482E+06	2.54
6PA......	7.5	262	930	227	858	347	1265	3.869E+07	5.158E+06	3.44
7PA......	6.7	276	1019	218	538	352	1152	2.754E+07	4.110E+06	4.05
8PA......	6.9	334	1254	271	1023	430	1619	9.067E+06	1.314E+06	4.76
9PA......	7.3	391	996	351	1219	526	1574	5.706E+07	7.816E+06	5.28
10PA.....	8.5	160	654	142	423	214	779	4.471E+07	5.267E+06	1.85
11PA.....	4.2	209	658	214	796	299	1033	3.289E+07	7.831E+06	4.90
12PA.....	4.4	98	600	102	738	142	952	1.504E+07	3.418E+06	2.19
1PAB.....	8.2	178	738	138	552	225	922	4.123E+06	5.028E+05	2.14
2PAB.....	6.7	196	663	160	556	253	865	2.945E+07	4.395E+06	2.88
3PAB.....	16.0	445	1423	369	1259	578	1900	7.238E+06	4.524E+05	2.74
1PAC.....	8.8	320	1468	316	1410	450	2035	2.241E+07	2.547E+06	3.58
2PAC.....	8.1	169	738	120	427	207	853	1.102E+07	1.361E+06	2.05
3PAC.....	13.1	498	1846	400	1223	639	2214	2.822E+07	2.154E+06	3.74
AVERAGE..	8.0	235	914	200	734	309	1185	2.299E+07	3.215E+06	2.92
STD. DEV.	2.8	120	372	101	348	156	479	1.427E+07	2.241E+06	1.24
0.635-CM DEPTH										
1PB......	15.9	311	1112	227	983	385	1484	1.615E+07	1.016E+06	1.93
2PB......	16.3	712	2317	614	1966	940	3039	1.710E+07	1.049E+06	4.30
3PB......	26.3	663	1775	494	1321	826	2212	5.673E+06	2.157E+05	2.48
4PB......	15.6	351	1423	249	627	431	1555	9.787E+06	6.274E+05	2.22
5PB......	16.0	387	1441	307	818	494	1657	1.480E+07	9.249E+05	2.38
6PB......	18.1	681	2144	489	1321	838	2518	7.693E+06	4.250E+05	3.70
7PB......	19.1	636	2024	494	903	805	2216	3.812E+07	1.996E+06	3.28
8PB......	22.5	752	2994	614	2024	970	3613	5.243E+07	2.330E+06	3.29
9PB......	17.6	503	1784	342	1290	608	2201	3.386E+07	1.924E+06	2.81
10PB.....	25.4	325	1601	200	698	381	1747	6.093E+07	2.399E+06	1.26
11PB.....	21.7	560	1699	565	1770	796	2454	3.949E+07	1.820E+06	2.54
12PB.....	18.6	414	1744	387	1397	566	2234	4.464E+07	2.400E+06	2.19
1PBB.....	16.5	649	2571	436	1535	782	2994	7.928E+07	4.805E+06	3.87
2PBB.....	19.5	658	2691	476	1948	812	3322	3.023E+07	1.550E+06	3.32
3PBB.....	20.6	609	1739	414	1041	737	2027	4.888E+07	2.373E+06	2.91
1PBC.....	22.5	547	3269	520	2704	755	4243	2.876E+07	1.278E+06	2.39
2PBC.....	21.1	431	1886	267	1139	507	2203	8.902E+07	4.219E+06	2.01
3PBC.....	22.6	342	996	160	467	378	1100	4.242E+06	1.877E+05	1.49
AVERAGE..	19.8	530	1956	403	1331	667	2379	3.450E+07	1.752E+06	2.69
STD. DEV.	3.3	148	615	143	580	199	805	2.485E+07	1.257E+06	.82

TABLE A-1. - TEST RESULTS FOR PB-60--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......	80.5	512	1699	267	712	577	1842	4.757E+07	5.909E+05	.63
2PC......	70.0	725	2669	543	1899	906	3276	3.053E+07	4.361E+05	1.02
3PC......	60.6	1975	5057	1748	4346	2637	6668	1.181E+07	1.949E+05	3.21
4PC......	71.0	302	2273	102	316	319	2295	3.530E+07	4.972E+05	.42
5PC......	64.7	810	2353	667	1655	1049	2877	1.136E+08	1.756E+06	1.23
6PC......	61.8	1232	4154	592	1610	1367	4456	1.847E+08	2.988E+06	1.96
7PC......	45.8	1677	4492	1134	3398	2024	5633	1.295E+07	2.828E+05	3.60
8PC......	58.3	2197	5756	1632	5293	2737	7820	5.228E+07	8.967E+05	3.71
9PC......	46.4	1726	4844	1254	3963	2134	6259	4.507E+07	9.714E+05	3.66
10PC.....	58.0	1032	2553	1050	2455	1472	3542	3.880E+07	6.173E+05	1.75
11PC.....	55.6	2206	5133	1027	3776	2434	6372	7.456E+07	1.341E+06	3.91
12PC.....	64.7	1677	5120	1161	3656	2040	6291	4.756E+07	7.348E+05	2.55
1PCB.....	87.8	854	3429	294	1134	903	3612	1.757E+07	2.001E+05	.96
2PCB.....	70.0	1882	3812	925	1917	2097	4267	4.769E+07	6.813E+05	2.65
3PCB.....	70.4	1450	4835	694	1343	1608	5018	4.059E+07	5.765E+05	2.03
1PCC.....	93.0	1557	5324	743	2744	1725	5990	5.224E+07	5.617E+05	1.65
2PCC.....	80.1	681	3968	489	2513	838	4697	5.734E+06	7.159E+04	.84
3PCC.....	74.8	1686	5186	1197	3567	2067	6295	4.071E+07	5.443E+05	2.22
AVERAGE..	67.4	1343	4037	862	2572	1607	4845	4.996E+07	7.746E+05	2.11
STD. DEV.	12.8	591	1255	455	1364	720	1685	4.171E+07	6.876E+05	1.15
2.540-CM DEPTH										
1PD......	154.2	1646	4470	560	1557	1739	4734	1.261E+08	8.178E+05	1.05
2PD......	221.7	2260	7139	1112	3812	2518	8093	1.273E+08	5.744E+05	1.00
3PD......	187.4	1757	7361	1121	3145	2084	8005	1.294E+07	6.906E+04	.92
4PD......	163.0	2482	5636	1063	2357	2700	6109	4.344E+07	2.665E+05	1.50
5PD......	187.6	605	3314	262	1165	659	3513	1.829E+07	9.751E+04	.32
6PD......	156.7	1948	5947	787	1899	2101	6243	7.525E+07	4.802E+05	1.22
7PD......	144.2	3803	8229	1606	3945	4128	9126	1.785E+07	1.238E+05	2.60
8PD......	182.6	3145	6516	1499	2922	3484	7142	3.656E+07	2.002E+05	1.70
9PD......	185.0	1935	6503	1050	2580	2201	6996	1.874E+07	1.013E+05	1.03
10PD.....	96.5	1970	5827	1112	2366	2263	6289	4.244E+07	4.398E+05	2.01
11PD.....	168.2	2411	7740	1023	2211	2619	8049	3.384E+07	2.012E+05	1.41
12PD.....	221.8	2108	7793	1081	4079	2369	8796	3.946E+07	1.779E+05	.94
1PDB.....	70.0	3225	11151	1259	2544	3462	11439	7.903E+07	1.129E+06	4.53
2PDB.....	176.1	1548	3581	627	1490	1670	3878	3.128E+07	1.776E+05	.87
3PDB.....	197.0	1570	3603	689	1454	1715	3885	1.687E+07	8.565E+04	.78
1PDC.....	192.3	1628	5991	454	1801	1690	6256	4.448E+07	2.313E+05	.83
2PDC.....	160.1	2051	6014	1059	3456	2308	6936	6.149E+07	3.841E+05	1.26
3PDC.....	168.6	2353	7215	1014	2580	2562	7662	4.250E+07	2.521E+05	1.37
AVERAGE..	168.5	2136	6335	965	2520	2348	6842	4.821E+07	3.227E+05	1.41
STD. DEV.	37.7	728	1913	346	894	791	2028	3.421E+07	2.817E+05	.93

TABLE A-2. - TEST RESULTS FOR PB-90

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						
PA1......	9.2	463	1788	698	2188	838	2826	6.115E+07	6.647E+06	4.95
PA2......	11.7	409	1841	587	1855	716	2614	2.628E+07	2.246E+06	3.44
PA3......	10.0	351	1299	538	1379	643	1894	2.488E+06	2.488E+05	3.46
PA4......	8.0	249	1085	409	1539	479	1883	3.231E+06	4.039E+05	3.06
PA5......	7.2	298	1228	480	1499	565	1938	3.997E+06	5.552E+05	4.07
PA6......	8.1	520	1490	823	1632	974	2210	6.264E+06	7.733E+05	6.32
PA7......	8.7	374	1352	583	1539	692	2049	4.866E+07	5.593E+06	4.23
PA8......	8.0	262	1188	423	1383	497	1823	1.948E+07	2.435E+06	3.23
PA9......	8.6	400	1619	685	1535	793	2231	2.555E+07	2.971E+06	4.58
1CA......	6.4	271	1183	347	1241	440	1715	3.987E+06	6.230E+05	4.17
2CA......	10.7	191	743	240	934	307	1193	2.306E+07	2.155E+06	1.76
3CA......	13.1	378	1263	365	1463	525	1933	1.497E+07	1.143E+06	2.84
AVERAGE..	9.1	347	1340	515	1516	622	2026	1.993E+07	2.150E+06	3.84
STD. DEV.	1.9	96	308	169	307	189	421	1.885E+07	2.073E+06	1.16
				0.635-CM DEPTH						
PB1......	22.8	1010	2575	1366	2865	1698	3852	4.628E+07	2.030E+06	4.36
PB2......	19.1	1063	2700	1441	3687	1791	4570	5.146E+07	2.694E+06	5.48
PB3......	18.5	921	2918	1410	2664	1684	3951	2.847E+07	1.539E+06	4.90
PB4......	17.0	867	2829	1237	2584	1510	3832	8.383E+06	4.931E+05	5.02
PB5......	15.8	961	2940	1410	2784	1706	4049	1.947E+07	1.232E+06	5.99
PB6......	17.4	729	2251	872	2157	1137	3118	2.318E+06	1.332E+05	4.13
PB7......	17.9	890	2277	1223	2139	1512	3125	4.283E+07	2.393E+06	4.89
PB8......	21.1	770	2620	1036	2446	1291	3584	7.727E+07	3.662E+06	3.59
PB9......	19.8	983	2824	1259	2535	1597	3795	8.538E+07	4.312E+06	4.89
1CB......	22.7	632	3114	627	2780	890	4174	3.101E+06	1.366E+05	2.74
2CB......	26.8	525	1957	423	1557	674	2501	9.841E+06	3.299E+05	1.93
3CB......	19.1	596	2117	676	2197	901	3051	5.035E+06	2.636E+05	3.07
AVERAGE..	19.8	829	2594	1082	2533	1366	3634	3.165E+07	1.602E+06	4.25
STD. DEV.	3.1	176	365	351	518	379	580	2.901E+07	1.436E+06	1.20
				1.270-CM DEPTH						
PC1......	76.0	1241	4025	1099	3389	1657	5262	4.815E+07	6.335E+05	1.61
PC2......	77.1	1806	6303	1646	5284	2443	8225	4.642E+07	6.021E+05	2.31
PC3......	74.9	2064	5471	1953	5080	2841	7466	2.179E+07	2.909E+05	2.71
PC4......	60.8	1548	5093	1695	4012	2295	6483	2.169E+07	3.568E+05	2.51
PC5......	77.8	1508	5191	1334	3256	2014	6127	2.206E+07	2.826E+05	1.91
PC6......	60.0	2224	4702	1561	3825	2717	6061	1.051E+08	1.751E+06	3.65
PC7......	52.3	1423	5146	1205	2469	1865	5708	5.107E+07	9.764E+05	2.68
PC8......	86.3	992	4279	796	1668	1272	4593	2.425E+07	2.810E+05	1.13
PC9......	54.8	707	4346	391	1245	808	4521	2.701E+07	4.929E+05	1.27
1CC......	68.5	1219	3665	885	2722	1506	4565	3.695E+07	5.394E+05	1.75
2CC......	47.7	1784	4110	1579	3603	2382	5466	1.426E+07	2.990E+05	3.68
3CC......	59.5	1321	3314	1205	2344	1788	4059	2.508E+07	4.215E+05	2.19
AVERAGE..	66.3	1486	4637	1279	3241	1966	5711	3.699E+07	5.773E+05	2.28
STD. DEV.	12.1	436	843	442	1235	604	1253	2.460E+07	4.217E+05	.82
				2.540-CM DEPTH						
PD1......	111.3	2326	5355	1579	3723	2812	6522	3.662E+06	3.290E+04	2.06
PD2......	172.0	2429	7157	1112	2255	2671	7504	1.119E+07	6.504E+04	1.39
PD3......	175.6	2985	8038	1979	3812	3581	8896	1.657E+07	9.437E+04	1.67
PD4......	121.4	1668	5204	930	1922	1910	5548	5.162E+07	4.252E+05	1.35
PD5......	173.0	1922	4301	805	1935	2083	4716	4.116E+07	2.379E+05	1.09
PD6......	146.5	1979	5302	979	2068	2208	5691	6.128E+06	4.183E+04	1.33
PD7......	181.2	2175	5324	876	2357	2345	5823	5.911E+07	3.262E+05	1.18
PD8......	161.8	1139	3501	649	2478	1311	4289	3.134E+07	1.937E+05	.69
PD9......	143.5	1219	5404	787	1855	1451	5714	1.744E+07	1.215E+05	.84
1CD......	192.9	1841	5591	943	2655	2069	6190	5.353E+07	2.775E+05	.94
2CD......	173.1	3118	7028	1672	3634	3538	7912	1.800E+07	1.040E+05	1.77
3CD......	186.0	1890	6205	1299	2589	2294	6723	4.542E+07	2.442E+05	1.00
AVERAGE..	161.5	2058	5701	1134	2607	2356	6294	2.960E+07	1.804E+05	1.28
STD. DEV.	25.6	604	1249	411	722	707	1317	1.984E+07	1.240E+05	.40

TABLE A-3. - TEST RESULTS FOR PB-90M

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										
MA1......	8.3	614	1619	952	1864	1133	2469	1.987E+07	2.394E+06	7.28
MA2......	8.5	632	2166	956	2117	1146	3029	7.102E+07	8.355E+06	7.31
MA3......	7.8	374	1005	565	1668	677	1947	2.033E+06	9.017E+05	4.71
MA4......	4.8	276	1174	440	1139	520	1636	1.276E+07	2.659E+06	5.65
MA5......	8.6	222	1201	342	1766	408	2136	2.316E+07	2.693E+06	2.55
MA6......	6.1	214	765	360	1352	419	1554	1.502E+07	2.463E+06	3.44
MA7......	6.5	636	1766	916	1868	1115	2571	1.362E+08	2.097E+07	9.63
MA8......	6.7	480	1454	698	1619	848	2176	1.008E+08	1.505E+07	7.06
MA9......	10.5	654	1735	903	2228	1115	2824	2.788E+07	2.655E+06	6.13
1MA......	9.3	529	1761	649	1784	838	2507	3.435E+07	3.694E+06	5.60
2MA......	7.4	578	1855	738	2139	938	2832	6.679E+06	9.026E+05	7.69
3MA......	8.7	467	1686	600	2108	761	2699	2.474E+07	2.844E+06	5.28
AVERAGE..	7.8	473	1516	677	1804	826	2365	3.954E+07	5.465E+06	6.03
STD. DEV.	1.6	164	404	224	329	276	477	4.148E+07	6.283E+06	1.94
0.635-CM DEPTH										
MB1......	18.5	1001	3278	1188	3710	1553	4951	9.890E+07	5.346E+06	5.32
MB2......	27.9	1277	3354	1499	3745	1969	5027	1.978E+07	7.091E+05	4.50
MB3......	22.6	685	1988	725	2184	997	2953	6.183E+06	2.736E+05	2.98
MB4......	21.2	752	1997	1072	2633	1309	3305	1.988E+07	9.379E+05	3.49
MB5......	18.2	894	2664	1170	2602	1472	3724	6.907E+06	3.795E+05	4.84
MB6......	17.3	903	2851	1245	2842	1538	4026	2.965E+07	1.714E+06	5.14
MB7......	21.1	1103	3225	1446	3060	1818	4446	7.320E+07	3.469E+06	5.15
MB8......	22.5	1023	4110	1352	3523	1696	5413	7.164E+07	3.184E+06	4.48
MB9......	22.2	850	2317	1027	2651	1333	3521	4.871E+07	2.194E+06	3.77
1MB......	17.7	1348	3932	1721	3963	2186	5583	7.280E+07	4.113E+06	7.49
2MB......	17.4	1330	3652	1579	3492	2064	5052	2.761E+07	1.587E+06	7.52
3MB......	19.0	1152	3158	1321	3367	1753	4616	1.606E+07	8.453E+05	5.97
AVERAGE..	20.5	1026	3044	1279	3148	1641	4385	4.094E+07	2.063E+06	5.05
STD. DEV.	3.1	221	701	270	563	343	866	3.104E+07	1.629E+06	1.42
1.270-CM DEPTH										
MC1......	67.0	1503	3914	1201	3278	1924	5106	6.387E+07	9.533E+05	2.21
MC2......	41.3	1868	5235	2042	5315	2767	7461	2.654E+07	6.419E+05	4.45
MC3......	58.0	1628	3914	1152	2678	1994	4743	6.740E+07	1.162E+06	2.76
MC4......	86.1	1192	4448	1112	3492	1630	5655	2.029E+07	2.356E+05	1.36
MC5......	53.8	1397	5071	1575	4048	2105	6488	3.240E+07	6.022E+05	2.56
MC6......	65.2	1957	6236	1699	4635	2592	7770	6.493E+06	9.959E+04	2.95
MC7......	78.9	1446	3211	1383	2967	2001	4372	1.614E+07	2.046E+05	1.80
MC8......	68.0	1259	5458	1050	2491	1639	5999	2.438E+07	3.586E+05	1.82
MC9......	91.2	894	3434	867	2869	1246	4475	4.460E+07	4.890E+05	.96
1MC......	58.9	2869	6770	2678	6396	3924	9314	1.192E+08	2.023E+06	4.79
2MC......	72.6	2602	7272	2322	4968	3487	8808	6.935E+07	9.553E+05	3.53
3MC......	65.6	2317	6205	2415	5271	3347	8141	9.197E+07	1.402E+06	3.48
AVERAGE..	67.2	1744	5097	1625	4034	2388	6528	4.855E+07	7.606E+05	2.72
STD. DEV.	13.9	598	1340	605	1264	837	1734	3.419E+07	5.671E+05	1.18
2.540-CM DEPTH										
MD1......	123.5	1761	4684	1148	2202	2102	5175	8.067E+06	6.532E+04	1.40
MD2......	130.7	2095	4359	1566	3767	2615	5762	1.138E+07	8.707E+04	1.58
MD3......	138.5	1463	5894	1219	3901	1904	7068	1.112E+07	8.029E+04	1.04
MD4......	129.6	3251	7473	1926	4226	3779	8585	1.958E+07	1.511E+05	2.47
MD5......	189.7	2295	9848	1882	5591	2968	11324	1.219E+08	6.424E+05	1.19
MD6......	150.2	3002	10742	1948	4679	3579	11717	3.237E+07	2.155E+05	1.97
MD7......	123.8	1730	4937	1241	1979	2129	5319	3.681E+07	2.973E+05	1.38
MD8......	166.4	578	4693	503	1948	766	5081	1.162E+07	6.986E+04	.34
MD9......	178.4	2433	8104	1655	3647	2942	8887	1.536E+08	8.608E+05	1.34
1MD......	142.3	2816	7704	2002	4991	3455	9179	1.036E+07	7.281E+04	1.95
2MD......	171.8	4332	10141	2309	4960	4909	11289	4.235E+07	2.465E+05	2.48
3MD......	159.3	2522	6005	2295	4937	3410	7774	2.788E+07	1.750E+05	1.56
AVERAGE..	150.4	2357	7049	1641	3902	2880	8097	4.059E+07	2.470E+05	1.56
STD. DEV.	22.5	960	2297	533	1259	1074	2481	4.729E+07	2.521E+05	.60

TABLE A-4. - TEST RESULTS FOR PRD

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										
1TA......	11.9	378	1072	761	1512	849	1854	9.105E+07	7.351E+06	3.13
2TA......	11.3	249	1099	454	2086	518	2358	8.477E+06	7.502E+05	2.17
3TA......	12.0	538	1245	925	2162	1070	2495	2.843E+06	2.369E+05	4.41
4TA......	12.6	1036	2647	2246	4657	2474	5357	6.534E+06	5.186E+05	8.10
5TA......	10.9	1045	2780	2255	5164	2486	5865	4.140E+07	3.798E+06	9.44
6TA......	9.8	734	1579	1446	2873	1621	3279	2.281E+07	2.328E+06	7.37
7TA......	5.4	342	801	738	2002	814	2156	9.029E+07	1.672E+07	6.24
8TA......	8.1	387	1116	841	1810	925	2127	3.662E+07	4.521E+06	4.70
9TA......	8.2	316	1121	672	1655	742	1999	2.657E+06	3.240E+05	3.79
10TA.....	7.2	245	965	280	605	372	1139	7.423E+06	1.031E+06	3.34
11TA.....	9.3	360	1601	423	1054	555	1917	2.084E+08	2.241E+07	3.81
12TA.....	7.8	587	2059	729	1495	936	2545	3.899E+07	4.999E+06	7.41
AVERAGE..	9.5	518	1507	981	2256	1114	2757	4.646E+07	5.441E+06	5.33
STD. DEV.	2.2	283	658	661	1367	712	1428	5.974E+07	7.087E+06	2.31
0.635-CM DEPTH										
1TB......	14.5	774	3345	1557	4577	1739	5669	3.992E+07	2.753E+06	5.25
2TB......	11.7	979	6058	1988	6494	2216	8881	1.188E+07	1.015E+06	8.23
3TB......	17.3	1005	2798	1615	3616	1902	4572	1.626E+07	9.400E+05	5.72
4TB......	19.8	1664	4466	3234	7081	3637	8372	2.445E+07	1.235E+06	8.27
5TB......	23.0	1294	4030	2553	5947	2863	7184	9.389E+07	4.082E+06	5.54
6TB......	27.8	1130	3385	2175	4879	2451	5939	2.361E+08	8.493E+06	4.00
7TB......	15.3	391	1583	596	2518	713	2974	5.409E+07	3.535E+06	2.52
8TB......	20.0	636	2113	823	1908	1040	2847	3.004E+07	1.502E+06	3.13
9TB......	17.1	970	2633	1308	2695	1628	3768	9.615E+07	5.623E+06	5.58
10TB.....	21.4	689	3607	529	1099	869	3771	3.478E+07	1.625E+06	3.17
11TB.....	17.0	552	2989	507	1779	749	3479	1.071E+07	6.298E+05	3.19
12TB.....	16.5	698	2469	729	1655	1010	2972	1.881E+08	1.140E+07	4.17
AVERAGE..	18.5	898	3290	1468	3687	1735	5036	6.970E+07	3.569E+06	4.90
STD. DEV.	4.3	352	1185	887	2061	927	2151	7.301E+07	3.388E+06	1.91
1.270-CM DEPTH										
1TC......	49.7	1068	3145	1312	2166	1692	3819	5.124E+07	1.031E+06	2.11
2TC......	46.6	1281	4679	1650	3247	2089	5696	9.190E+07	1.972E+06	2.71
3TC......	94.1	1499	4359	1824	3189	2361	5401	2.224E+07	2.363E+05	1.57
4TC......	63.7	1779	6539	2566	5916	3123	8818	1.151E+08	1.807E+06	2.75
5TC......	64.8	2397	6347	2500	5057	3464	8116	6.380E+07	9.846E+05	3.64
6TC......	93.3	1441	4025	1846	3781	2342	5523	9.034E+07	9.683E+05	1.52
7TC......	40.2	1704	4924	1539	5080	2296	7074	1.706E+07	4.245E+05	4.17
8TC......	41.6	1388	4533	1477	3345	2026	5633	1.720E+07	4.135E+05	3.28
9TC......	71.1	641	3892	627	2900	896	4854	6.737E+07	9.475E+05	.89
10TC.....	72.8	885	3723	294	1010	933	3857	3.671E+07	5.042E+05	1.20
11TC.....	63.0	1543	5226	1005	2344	1842	5728	3.438E+07	5.457E+05	2.41
12TC.....	64.2	1588	5115	1099	2607	1931	5741	1.175E+08	1.830E+06	2.43
AVERAGE..	63.8	1434	4709	1478	3387	2083	5855	6.040E+07	9.720E+05	2.39
STD. DEV.	17.8	452	1010	677	1393	747	1506	3.659E+07	6.024E+05	1.00
2.540-CM DEPTH										
1TD......	153.6	894	3567	489	1677	1019	3942	2.782E+07	1.811E+05	.57
2TD......	116.9	1962	6214	1450	3834	2439	7302	2.469E+07	2.112E+05	1.65
3TD......	176.3	2558	6205	1717	3211	3080	6987	1.220E+07	6.921E+04	1.43
4TD......	136.6	2865	10288	1361	3545	3171	10882	1.111E+08	8.136E+05	2.06
5TD......	212.4	2638	6961	1957	4034	3284	8046	5.440E+07	2.561E+05	1.22
6TD......	231.2	2411	7184	2242	5093	3292	8806	2.832E+07	1.225E+05	1.03
7TD......	169.1	2896	7428	632	2300	2964	7776	8.222E+07	4.862E+05	1.69
8TD......	207.6	1877	6748	560	1543	1959	6922	5.290E+07	2.548E+05	.89
9TD......	222.0	2082	7415	974	2135	2298	7716	1.202E+08	5.414E+05	.92
10TD.....	110.5	1615	4559	498	965	1690	4660	4.680E+07	4.235E+05	1.44
11TD.....	167.8	1655	4448	454	867	1716	4532	1.854E+07	1.105E+05	.97
12TD.....	218.3	2669	8496	1045	2433	2866	8837	2.657E+08	1.217E+06	1.20
AVERAGE..	176.9	2177	6626	1115	2637	2482	7201	7.041E+07	3.906E+05	1.26
STD. DEV.	41.8	605	1842	624	1315	749	2010	7.090E+07	3.386E+05	.42

TABLE A-5. - TEST RESULTS FOR CRD

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										
1SA......	9.5	200	1085	142	383	246	1151	9.295E+07	9.784E+06	2.07
2SA......	11.0	254	1143	182	654	312	1317	7.238E+07	6.580E+06	2.27
3SA......	9.3	165	961	133	476	212	1072	2.051E+07	2.205E+06	1.74
4SA......	11.2	76	770	40	200	86	795	8.238E+06	7.355E+05	.66
5SA......	8.1	89	667	53	227	104	705	9.372E+07	1.157E+07	1.08
6SA......	4.5	133	872	102	516	168	1013	1.149E+07	2.553E+06	2.92
7SA......	9.1	169	1170	80	280	187	1203	2.903E+07	3.190E+06	1.83
8SA......	6.8	209	1601	85	374	225	1644	4.003E+08	5.887E+07	3.03
9SA......	15.6	289	1294	133	414	318	1359	1.450E+07	9.293E+05	1.82
10SA.....	7.3	102	921	71	236	125	950	6.174E+07	8.457E+06	1.38
11SA.....	9.4	120	1214	67	369	137	1269	8.640E+07	9.191E+06	1.26
12SA.....	6.4	151	1112	111	560	188	1245	8.685E+07	1.357E+07	2.33
AVERAGE..	9.0	163	1068	100	391	192	1144	8.151E+07	1.064E+07	1.87
STD. DEV.	2.8	66	252	42	142	75	258	1.060E+08	1.579E+07	.71
0.635-CM DEPTH										
1SB......	28.4	254	1917	125	467	282	1973	1.878E+07	6.612E+05	.88
2SB......	27.3	262	1579	160	454	307	1643	6.495E+06	2.379E+05	.95
3SB......	22.0	298	1139	191	627	354	1300	2.798E+07	1.272E+06	1.33
4SB......	10.2	178	1032	107	449	207	1125	9.434E+07	9.249E+06	1.72
5SB......	15.6	400	1744	289	663	494	1865	5.669E+07	3.634E+06	2.53
6SB......	16.3	342	1850	138	391	369	1891	3.635E+07	2.230E+06	2.07
7SB......	22.8	512	1979	262	1259	575	2346	3.434E+08	1.506E+07	2.21
8SB......	21.2	494	2295	200	850	533	2447	5.116E+07	2.413E+06	2.29
9SB......	19.4	583	2353	258	632	637	2436	3.255E+08	1.678E+07	2.96
10SB.....	20.8	302	1908	165	818	344	2076	4.769E+07	2.293E+06	1.43
11SB.....	19.2	405	3999	218	810	460	4080	4.408E+07	2.296E+06	2.07
12SB.....	20.8	543	4065	360	1197	651	4238	3.353E+07	1.612E+06	2.57
AVERAGE..	20.3	381	2155	206	718	435	2285	9.050E+07	4.812E+06	1.92
STD. DEV.	4.9	129	960	75	284	145	967	1.161E+08	5.684E+06	.66
1.270-CM DEPTH										
1SC......	56.9	845	3109	178	583	864	3163	3.422E+07	6.014E+05	1.46
2SC......	60.4	627	2633	280	796	687	2751	4.746E+06	7.858E+04	1.02
3SC......	66.5	681	3367	320	1219	752	3581	1.669E+07	2.510E+05	1.01
4SC......	64.2	810	3154	214	921	837	3285	3.640E+07	5.669E+05	1.24
5SC......	61.9	974	3487	302	1023	1020	3634	5.609E+07	9.061E+05	1.55
6SC......	55.7	845	2598	307	654	899	2679	1.486E+08	2.667E+06	1.49
7SC......	41.1	1704	6232	689	1810	1838	6489	1.543E+08	3.754E+06	4.08
8SC......	51.5	1272	6543	498	1543	1366	6723	1.864E+08	3.620E+06	2.43
9SC......	63.8	1668	5222	734	1463	1822	5423	3.541E+08	5.550E+06	2.57
10SC.....	51.7	556	3492	178	667	584	3555	1.509E+08	2.919E+06	1.06
11SC.....	70.4	1388	6659	560	1361	1497	6796	2.365E+08	3.359E+06	1.94
12SC.....	77.7	1312	9092	476	1824	1396	9273	1.051E+08	1.352E+06	1.66
AVERAGE..	60.1	1057	4632	395	1155	1130	4779	1.237E+08	2.135E+06	1.79
STD. DEV.	9.7	399	2076	193	446	437	2110	1.037E+08	1.748E+06	.88
2.540-CM DEPTH										
1SD......	135.7	1263	4835	454	1001	1342	4937	1.772E+07	1.306E+05	.92
2SD......	155.8	1615	4715	427	1134	1670	4849	1.570E+08	1.008E+06	1.02
3SD......	208.7	1495	4679	476	1001	1568	4785	4.349E+07	2.084E+05	.70
4SD......	121.0	796	3968	102	280	803	3977	1.320E+07	1.091E+05	.65
5SD......	230.2	1370	4919	245	685	1392	4967	4.457E+07	1.936E+05	.59
6SD......	215.3	1583	3323	147	396	1590	3346	7.936E+06	3.686E+04	.72
7SD......	143.4	2122	5293	365	912	2153	5371	4.197E+06	2.927E+05	1.46
8SD......	185.0	2700	6939	649	1655	2777	7133	8.088E+07	4.372E+05	1.44
9SD......	158.9	3999	9883	743	1948	4067	10074	2.164E+08	1.645E+06	2.48
10SD.....	156.9	1072	7593	249	756	1101	7630	3.268E+07	2.083E+05	.67
11SD.....	168.2	2153	9372	507	1210	2212	9450	7.365E+07	4.379E+05	1.26
12SD.....	134.4	2558	14109	707	2091	2654	14263	1.333E+08	9.915E+05	1.87
AVERAGE..	167.8	1894	6636	423	1089	1944	6732	6.875E+07	4.749E+05	1.15
STD. DEV.	34.9	880	3141	211	567	897	3174	6.742E+07	4.882E+05	.58

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 Int. vol.	Volume, cu µm Cum. vol.	Weight, mg/ton Int. wt.	Weight, mg/ton Cum. wt.
				0.318-cm (1/8-in) DEPTH				
PB-60.............	8.02222	0.94	23,053	23,053	1.0026E+04	1.0026E+04	11.7	11.7
		1.83	13,680	36,733	4.3897E+04	5.3922E+04	51.1	62.8
		2.62	8,942	45,675	8.4208E+04	1.3813E+05	98.0	160.8
		3.63	11,309	56,984	2.8322E+05	4.2135E+05	329.7	490.5
		5.06	9,263	66,246	6.2833E+05	1.0497E+06	731.4	1,221.9
		6.86	12,815	79,061	2.1662E+06	3.2158E+06	2,521.6	3,743.6
		8.51	6,147	85,208	1.9836E+06	5.1994E+06	2,309.1	6,052.7
				0.635-cm (1/4-in) DEPTH				
PB-60.............	19.7722	0.94	8,685	8,685	3.7772E+03	3.7772E+03	4.4	4.4
		1.83	5,540	14,225	1.7776E+04	2.1553E+04	20.7	25.1
		2.62	3,878	18,103	3.6521E+04	5.8074E+04	42.5	67.6
		3.63	5,436	23,539	1.3614E+05	1.9422E+05	158.5	226.1
		5.06	4,826	28,365	3.2736E+05	5.2158E+05	381.1	607.2
		6.86	7,282	35,647	1.2309E+06	1.7525E+06	1,432.9	2,040.1
		8.51	4,475	40,122	1.4440E+06	3.1965E+06	1,681.0	3,721.0
				1.27-cm (1/2-in) DEPTH				
PB-60.............	67.4167	0.94	4,323	4,323	1.8801E+03	1.8801E+03	2.2	2.2
		1.83	2,624	6,947	8.4208E+03	1.0301E+04	9.8	12.0
		2.62	1,926	8,876	1.8161E+04	2.8462E+04	21.1	33.1
		3.63	2,591	11,467	6.4885E+04	9.3348E+04	75.5	108.7
		5.06	2,174	13,641	1.4747E+05	2.4082E+05	171.7	280.3
		6.86	3,160	16,801	5.3410E+05	7.7492E+05	621.7	902.1
		8.51	1,825	18,626	5.8906E+05	1.3640E+06	685.7	1,587.8
				2.54-cm (1-in) DEPTH				
PB-60.............	168.5	0.94	1,396	1,396	6.0708E+02	6.0708E+0	0.7	0.7
		1.83	864	2,260	2.7722E+03	3.3793E+0	3.2	3.9
		2.62	670	2,930	6.3127E+03	9.6920E+0	7.3	11.3
		3.63	941	3,871	2.3557E+04	3.3249E+0	27.4	38.7
		5.06	901	4,772	6.1109E+04	9.4358E+0	71.1	109.8
		68.6	1,351	6,123	2.2844E+05	3.2280E+0	265.9	375.8
		8.51	859	6,983	2.7734E+05	6.0013E+0	322.8	698.6
				0.318-cm (1/8-in) DEPTH				
PB-90.............	9.14167	0.94	12,175	12,175	5.2938E+03	5.2948E+03	6.2	6.2
		1.83	7,302	19,477	2.3432E+04	2.8727E+04	27.3	33.4
		2.62	5,287	24,765	4.9790E+04	7.8517E+04	58.0	91.4
		3.63	6,749	31,514	1.6903E+05	2.4755E+05	196.8	288.2
		5.06	5,548	37,062	3.7635E+05	6.2389E+05	438.1	726.3
		6.86	9,027	46,088	1.5258E+06	2.1497E+06	1,776.2	2,502.4
		8.51	4,150	50,239	1.3393E+06	3.4890E+06	1,559.1	4,061.5
				0.635-cm (1/4-in) DEPTH				
PB-90.............	19.8333	0.94	10,678	10,678	4.6436E+03	4.6436E+03	5.4	5.4
		1.83	5,750	16,428	1.8452E+04	2.3096E+04	21.5	26.9
		2.62	3,846	20,274	3.6216E+04	5.9312E+04	42.2	69.0
		3.63	5,154	25,428	1.2909E+05	1.8840E+05	150.3	219.3
		5.06	4,461	29,889	3.0261E+05	4.9100E+05	352.3	571.6
		6.86	6,572	36,461	1.1108E+06	1.6018E+06	1,293.1	1,864.7
		8.51	3,695	40,156	1.1925E+06	2.7943E+06	1,338.1	3,252.9

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.
			1.27-cm (1/2-in) DEPTH					
PB-90............	66.3083	0.94	2,395	2,395	1.0416E+03	1.0416E+03	1.2	1.2
		1.83	1,557	3,953	4.9976E+03	6.0392E+03	5.8	7.0
		2.62	1,178	5,130	1.1089E+04	1.7128E+04	12.9	19.9
		3.63	1,564	6,694	3.9160E+04	5.6287E+04	45.6	65.5
		5.06	1,554	8,248	1.0540E+05	1.6169E+05	122.7	188.2
		6.86	2,459	10,706	4.1561E+05	5.7730E+05	483.8	672.0
		8.51	1,704	12,410	5.4979+05	1.1271E+06	640.0	1,312.0
			2.54-cm (1-in) DEPTH					
PB-90............	161.525	0.94	695	695	3.0217E+02	3.0217E+02	0.4	0.4
		1.83	482	1,176	1.5455E+03	1.8477E+03	1.8	2.2
		2.62	336	1,513	3.1650E+03	5.0127E+03	3.7	5.8
		3.63	498	2,011	1.2482E+04	1.7495E+04	14.5	20.4
		5.06	498	2,509	3.3752E+04	5.1247E+04	39.3	59.7
		6.86	763	3,272	1.2899E+05	1.8024E+05	150.2	209.8
		8.51	565	3,836	2.8223E+05	3.6247E+05	212.1	422.0
			0.318-cm (1/8-in) DEPTH					
PB-90M...........	7.76667	0.94	36,888	36,888	1.6042E+04	1.6042E+04	18.7	18.7
		1.83	21,265	58,152	6.8235E+04	8.4277E+04	79.4	98.1
		2.62	14,750	72,902	1.3890E+05	2.2318E+04	161.7	259.8
		3.63	19,347	92,249	4.8454E+05	7.0772E+05	564.1	823.9
		5.06	16,485	108,734	1.1182E+06	1.8259E+06	1,301.7	2,125.6
		6.86	21,530	130,264	3.6393E+06	5.4652E+06	4,236.5	6,362.1
		8.51	11,433	141,697	3.6893E+06	9.1545E+06	4,294.7	10,656.8
			0.635-cm (1/4-in) DEPTH					
PB-90M...........	20.4667	0.94	11,006	11,006	4.7864E+03	4.7864E+03	5.6	5.6
		1.83	6,861	17,867	2.2016E+04	2.6802E+04	25.6	31.2
		2.62	4,964	22,831	4.6743E+04	7.3545E+04	54.4	85.6
		3.63	6,431	29,261	1.6105E+05	2.2517E+05	187.5	273.1
		5.06	6,119	35,380	4.1505E+05	6.4965E+05	483.2	756.3
		6.86	8,361	43,741	1.4134E+06	2.0630E+06	1,645.3	2,401.6
		8.51	4,226	47,967	1.3636E+06	3.4266E+06	1,587.4	3,988.9
			1.27-cm (1/2-in) DEPTH					
PB-90M...........	67.2167	0.94	3,628	3,628	1.5779E+03	1.5779E+03	1.8	1.8
		1.83	2,264	5,893	7.2658E+03	8.8437E+03	8.5	10.3
		2.62	1,625	7,517	1.5298E+04	2.4141E+04	17.8	28.1
		3.63	2,246	9,764	5.6262E+04	8.0404E+04	65.5	93.6
		5.06	2,134	11,898	1.4477E+05	2.2517E+05	168.5	262.1
		6.86	3,169	15,066	5.3560E+05	7.6077E+05	623.5	885.6
		8.51	2,041	17,107	6.5848E+05	1.4193E+06	766.5	1,652.2
			2.54-cm (1-in) DEPTH					
PB-90M...........	150.35	0.94	980	980	4.2626E+02	4.2626E+02	0.5	0.5
		1.83	659	1,640	2.1162E+03	2.5424E+03	2.5	3.0
		2.62	508	2,147	4.7796E+03	7.3220E+03	5.6	8.5
		3.63	738	2,886	1.8492E+04	2.5814E+04	21.5	30.1
		5.06	676	3,561	4.5834E+04	7.1648E+04	53.4	83.4
		6.86	1,038	4,599	1.7548E+05	2.4713E+05	204.3	287.7
		8.51	645	5,244	2.0801E+05	4.5514E+05	242.1	529.8

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				
PRD..............	9.54167	0.94	24,918	24,918	1.0837E+04	1.0837E+04	12.6	12.6
		1.83	16,370	41,288	5.2530E+04	6.3367E+04	61.2	73.8
		2.62	11,983	53,271	1.1284E+05	1.7620E+05	131.4	205.1
		3.63	16,169	69,440	4.0495E+05	5.8115E+05	471.4	676.5
		5.06	14,999	84,439	1.0174E+06	1.5986E+06	1,184.4	1,860.9
		6.86	22,611	107,050	3.8220E+06	5.4206E+06	4,449.2	6,310.2
		8.51	12,258	119,308	3.9555E+06	9.3761E+06	4,604.6	10,914.7
				0.635-cm (1/4-in) DEPTH				
PRD..............	18.45	0.94	15,093	15,093	6.5640E+03	6.5640E+03	7.6	7.6
		1.83	9,828	24,921	3.1535E+04	3.8099E+04	36.7	44.4
		2.62	7,317	32,238	6.8899E+04	1.0700E+05	80.2	124.6
		3.63	10,273	42,510	6.8899E+05	3.6427E+05	299.5	424.1
		5.06	9,932	52,442	6.7374E+05	1.0380E+06	784.3	1,208.4
		6.86	14,982	67,425	2.5325E+06	3.5705E+06	2,948.1	4,156.5
		8.51	9,521	76,945	3.0723E+06	6.6428E+06	3,576.5	7,732.9
				1.27-cm (1/2-in) DEPTH				
PRD..............	63.7583	0.94	4,670	4,670	2.0309E+03	2.0309E+03	2.4	2.4
		1.83	3,054	7,724	9.7986E+03	1.1830E+04	11.4	13.8
		2.62	2,060	9,784	1.9403E+04	3.1232E+04	22.6	36.4
		3.63	2,823	12,607	7.0705E+04	1.0194E+05	82.3	118.7
		5.06	2,699	15,306	1.8308E+05	2.8502E+05	213.1	331.8
		6.86	4,066	19,372	6.8725E+05	9.7226E+05	800.0	1,131.8
		8.51	2,686	22,058	8.6682E+05	1.8391E+06	1,009.1	2,140.9
				2.54-cm (1-in) DEPTH				
PRD..............	176.858	0.94	1,665	1,665	7.2401E+02	7.2401E+02	0.8	0.8
		1.83	1,034	2,699	3.3189E+03	7.0429E+03	3.9	4.7
		2.62	826	3,525	7.7788E+03	1.1822E+04	9.1	13.8
		3.63	1,157	4,682	2.8976E+04	4.0798E+04	33.7	47.5
		5.06	1,078	5,760	7.3137E+04	1.1394E+05	85.1	132.6
		6.86	1,636	7,397	2.7662E+05	3.9055E+05	322.0	454.6
		8.51	953	8,350	3.0745E+05	6.9800E+05	357.9	812.5
				0.318-cm (1/8-in) DEPTH				
CRD..............	9.01667	0.94	53,941	53,941	2.3459E+04	2.3459E+04	27.3	27.3
		1.83	32,304	86,245	1.0366E+05	4.2712E+05	120.7	148.0
		2.62	24,049	110,294	2.2647E+05	3.5358E+05	263.6	411.6
		3.63	32,432	142,725	8.1225E+05	1.1658E+06	945.5	1,357.1
		5.06	30,418	173,143	2.0634E+06	3.2292E+06	2,402.0	3,759.1
		6.86	43,830	216,973	7.4087E+06	1.0638E+07	8,624.5	12,383.6
		8.51	22,690	239,663	7.3219E+06	1.7960E+07	8,523.4	20,907.0
				0.635-cm (1/4-in) DEPTH				
CRD..............	20.3333	0.94	24,426	24,426	1.0623E+04	1.0623E+04	12.4	12.4
		1.83	15,368	39,794	4.9313E+04	5.9935E+04	57.4	69.8
		2.62	10,923	50,717	1.0286E+05	1.6279E+05	119.7	189.5
		3.63	15,197	65,914	3.8061E+05	5.4340E+05	443.1	632.6
		5.06	14,006	79,919	9.5006E+05	1.4935E+06	1,106.0	1,738.5
		6.86	19,634	99,553	3.3187E+06	4.8122E+06	3,863.3	5,601.9
		8.51	10,380	109,932	3.3494E+06	8.1616E+06	3,899.0	9,500.9

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					
CRD..............	60.15	0.94	9,985	9,985	4.3425E+03	4.3425E+03	5.1	5.1
		1.83	6,342	16,327	2.0350E+03	2.4693E+04	23.7	28.7
		2.62	4,736	21,063	4.4596E+04	6.9288E+04	51.9	80.7
		3.63	6,650	27,713	1.6654E+05	2.3583E+05	193.9	274.5
		5.06	6,110	33,823	4.1449E+05	6.5032E+05	482.5	757.0
		6.86	8,792	42,615	1.4861E+06	2.1365E+06	1,730.0	2,487.1
		8.51	4,485	47,100	1.4474E+06	3.5839E+06	1,684.9	4,172.0
			2.54-cm (1-in) DEPTH					
CRD..............	167.792	0.94	2,047	2,047	8.9027E+02	8.9027E+02	1.0	1.0
		1.83	1,317	3,364	4.2250E+03	5.1152E+03	4.9	6.0
		2.62	987	4,351	9.2937E+03	1.4409E+04	10.8	16.8
		3.63	1,379	5,729	3.4530E+04	4.8939E+04	40.2	57.0
		5.06	1,230	6,960	8.3460E+04	1.3240E+05	97.2	154.1
		6.86	1,814	8,774	3.0670E+05	4.3909E+05	357.0	511.2
		8.51	1,017	9,791	3.2812E+05	7.6721E+05	382.0	893.1

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 per 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.

Milligrams ARD per short ton coal were calculated as follows:

$$\text{ARD (mg/ton)} = \frac{\text{sp. ARD} \times \text{g/ton}}{K} = \text{sp. ARD} \times 1.163 \times 10^{-3},$$

or

$$\frac{\text{sp. ARD} \times \text{coal density}^{1} \times \text{g/ton}}{f},$$

where sp. ARD = average specific airborne respirable dust, in cu μm/g of coal cut;

g/ton = 907,185;

f = volume-to-mass conversion factor for ARD, in cu μm, that is 6.24×10^{10}, allowing insertion of required coal density, in lb/cu ft;

and K = volume-to-mass conversion factor for ARD, in cu μm, that is 7.80×10^{8}, using coal density of 80 lb/cu ft only.

[1] Coal density refers to solid material, not bulk density.

APPENDIX C.--FORCE DATA FROM IGNITION TESTS

TABLE C-1. - Cutting force of conical test bits, pounds

Bit type	Depth of cut		Layer			
	cm	in	1	2	3	4
PB-90.............	0.254	0.10	448	704	592	632
	.254	.10	456	712	632	608
	.381	.15	440	712	608	576
	.381	.15	496	512	536	520
	.508	.20	NA	904	808	712
	.508	.20	568	808	696	768
PB-90M............	.254	.10	448	688	792	664
	.254	.10	344	696	656	512
	.381	.15	624	928	752	NR
	.381	.15	384	522	536	560
	.508	.20	696	1,032	NR	NR
	.508	.20	776	976	840	NR

NA Not available.
NR Not run, owing to ignition on previous layer.

NOTE.--All tests were run at a spacing of 1.905 cm (0.75 in) at 60 rpm.

TABLE C-2. - Cutting force of radial test bits--single layer, pounds

Bit	Test 1	Test 2	Test 3	Test 4
PRD...............	480.0	396.0	540.0	456.0
CRD...............	292.0	304.0	336.0	312.0

NOTE.--Tests were run at a cut depth of 0.635 cm (0.25 in) and a spacing of 1.27 cm (0.50 in) at 60 rpm. Each test was one layer or 24 cuts (see table 2 in the main text).

TABLE C-3. - Cutting force of radial test bits--multiple layer, pounds

Bit type	Layer			
	1	2	3	4
PRD:				
Test 1......................	432	392	456	536
Test 2......................	360	596	428	536
CRD:				
Test 1......................	312	324	332	348
Test 2......................	232	340	332	321

NOTE.--Tests were run at a cut depth of 0.508 cm (0.20 in) and a spacing of 1.905 cm (0.75 in) at 60 rpm. Each test was four layers of 16 cuts per layer (see table 3 in the main text).

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

$$T = \frac{(\bar{y}_2 - \bar{y}_1) - D_0}{\sqrt{\frac{(n_2 - 1)\, s_2^2 + (n_1 - 1)\, s_1^2}{(n_2 + n_1 - 2)} \times \frac{1}{n_2} + \frac{1}{n_1}}},$$

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_0 = 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.

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[1] Mendenhall, W. Introduction to Linear Models and the Design 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 D-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)
PB-90M, PB-90.	3.341[a]	1.509[b]	1.055	1.345[b]
PRD, PB-90....	1.983[a]	.998	.295	-.119
PRD, CRD......	4.960[a]	5.108[a]	1.560[b]	.532
PB-90M, CRD...	6.976[a]	6.946[a]	2.177[a]	1.702[b]
PB-90, CRD....	5.043[a]	5.894[a]	1.411[b]	.639
PB-90M, PRD...	.804	.233	.735	1.419[b]
PB-90, PB-60..	2.064[a]	4.242[a]	.442	-.455
PB-90M, PB-60.	5.373[a]	5.804[a]	1.404[b]	.493
PRD, PB-60....	3.715[a]	4.370[a]	.687	-.522
PB-60, CRD....	2.649[a]	2.714[a]	.816	.861

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

NOTE.--Lack of superscript letter indicates < 70-pct conficence level.

TABLE D-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)
PB-90M, PB-90.	1.763[a]	0.735	0.898	0.821
PRD, PB-90....	1.544[b]	1.852[a]	1.859[a]	2.019[a]
PRD, CRD......	-1.041	-.651	-2.179[a]	-.492
PB-90M, CRD...	-1.055	-1.611[b]	-2.591[a]	-1.437[b]
PB-90, CRD....	-1.847[a]	-1.897[a]	-3.001[a]	-2.025[a]
PB-90M, PRD...	.009	-1.388[b]	-.885	-1.178[c]
PB-90, PB-60..	-1.313[b]	-.303	-.886	-1.640
PB-90M, PB-60.	1.401[b]	.590	-.058	-.751
PRD, PB-60....	1.251[c]	2.085[a]	.808	.597
PB-60, CRD....	-1.982[a]	-2.222[a]	-2.993[a]	-1.084[c]

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

NOTE.--Lack of superscript letter indicates < 70-pct conficence level.

TABLE D-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)
PB-90M, PB-90.	2.286[a]	2.429[a]	1.208[c]	0.916
PRD, PB-90....	1.982[a]	.616	-.287	.486
PRD, CRD......	4.232[a]	4.786[a]	2.169[a]	.917
PB-90M, CRD...	6.043[a]	8.745[a]	3.315[a]	1.230[c]
PB-90, CRD....	5.471[a]	7.112[a]	2.520[a]	.529
PB-90M, PRD...	-.476[a]	1.067[a]	1.431[b]	.549
PB-90, PB-60..	2.703[a]	5.027[a]	.717	-.311
PB-90M, PB-60.	4.581[a]	7.399[a]	1.812[a]	.717
PRD, PB-60....	3.787[a]	3.977[a]	.451	.161
PB-60, CRD....	1.890[a]	2.839[a]	1.470[b]	.820

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

NOTE.--Lack of superscript letter indicates < 70-pct conficence level.

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