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Performance Evaluation of Two Light-Scattering Dust Monitors

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	mg/m^3	milligram per cubic meter
h	hour	min	minute
in	inch	mm	millimeter
lb	pound	µm	micrometer
L/min	liter per minute	mV	millivolt
		oz	ounce
m^3/min	cubic meter per minute	pct	percent
mg	milligram	s	second

PERFORMANCE EVALUATION OF TWO LIGHT-SCATTERING DUST MONITORS

By R. P. Vinson[1] and K. L. Williams[2]

ABSTRACT

The Bureau of Mines evaluated two real-time light-scattering dust monitors by measuring their response to Pittsburgh Seam coal dust and Arizona road dust (ARD). Both monitors, the model PDS-1, a personal dust sensor, and the model PCD-1, a digital dust indicator, are made in Japan by Sibata Scientific Ltd. Tests were conducted inside a laboratory aerosol chamber designed to maintain a uniform spatial distribution of the test dust. PDS-1 and PCD-1 measurements of concentrations for each test dust were averaged over 4-h test periods and compared with simultaneous gravimetric measurements.

Both dust monitors responded linearly with mass concentration with both coal dust and ARD. However, the linear response of the PDS-1 differed from that of the PCD-1 for both dusts.

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INTRODUCTION

One of the primary objectives of the Bureau of Mines is the elimination of coal miners' pneumoconiosis ("black lung") by reducing exposure to harmful dusts. Dust monitoring is critical to reducing respirable dust levels in mines. Most of the dust sampling in U.S. coal mines is done to determine compliance with dust standards. Measurements to determine compliance are made periodically, usually every two months, with an approved sampler. Federal regulations (1)[3] require gravimetric dust samples to be taken over an 8-h work shift. With gravimetric samplers, respirable dust particles are physically collected during the work shift and later weighed at a remote location. Since determination of compliance is based on the average of several shift-long measurements, the delayed analysis inherent in gravimetric techniques poses no problem. Furthermore, since the standard is based on a 2mg/m^3 mass concentration, the gravimetric approach is quite suitable. When operated carefully, these samplers can provide an accurate measurement of the average mass concentration of dust to which miners are exposed.

Although gravimetric samplers (commonly called personal samplers) have been used for other than compliance purposes, they are often too slow and labor intensive for effective research or immediate dust control purposes. In an earlier Bureau study, it was found that a fast-response instrument is more effective for evaluating dust control systems (2). Timely adjustment of dust control system operating parameters requires more immediate dust level information than is possible with the gravimetric sampler.

Light-scattering techniques have made possible rapid, real-time measurements of dust concentrations. The Bureau has played an important role in developing real-time dust monitors. For example, in recent years the Bureau sponsored the development of two light-scattering real-time dust monitors, the RAM-1 (3) and the MINIRAM (4).

Many other light-scattering dust monitors are commercially available. The University of Minnesota evaluated several of these instruments for the Bureau in 1983 (5). Two light-scattering instruments that were not available at the time of that evaluation have since been evaluated by the Bureau. The evaluation of these two monitors, the model PDS-1 personal dust sensor and the model PCD-1 digital dust indicator, is the subject of this report. The report discusses the ability of these instruments to measure mass concentrations of Pittsburgh Seam coal dust and ARD.[4] No attempt has been made to assess the mine-worthiness of these instruments.

TEST EQUIPMENT AND PROCEDURES

THE PDS-1 AND PCD-1 DUST MONITORS

The PDS-1 Personal Dust Monitoring System has three major components: The PDS-1 Personal Dust Sensor, the MDM-1 Minidosimeter, and a portable computer (Manufacturer specifications are listed in appendix A).

The PDS-1 (fig. 1) is a portable, battery-powered, light-scattering dust detector. Dust particles diffuse into the PDS-1 sensing chamber, which contains a light source and detector. The detector senses light scattered by particles passing through the light beam. The detected light is converted into an electric analog signal, which may be used to activate an audible alarm in the PDS-1 if the signal exceeds a preset level. The PDS-1 incorporates a reference light-scattering board which is a translucent material that scatters a portion of the

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

[4] ARD is a carefully sized, commercial test dust used primarily to test the efficiency of air filters for internal combustion engines.

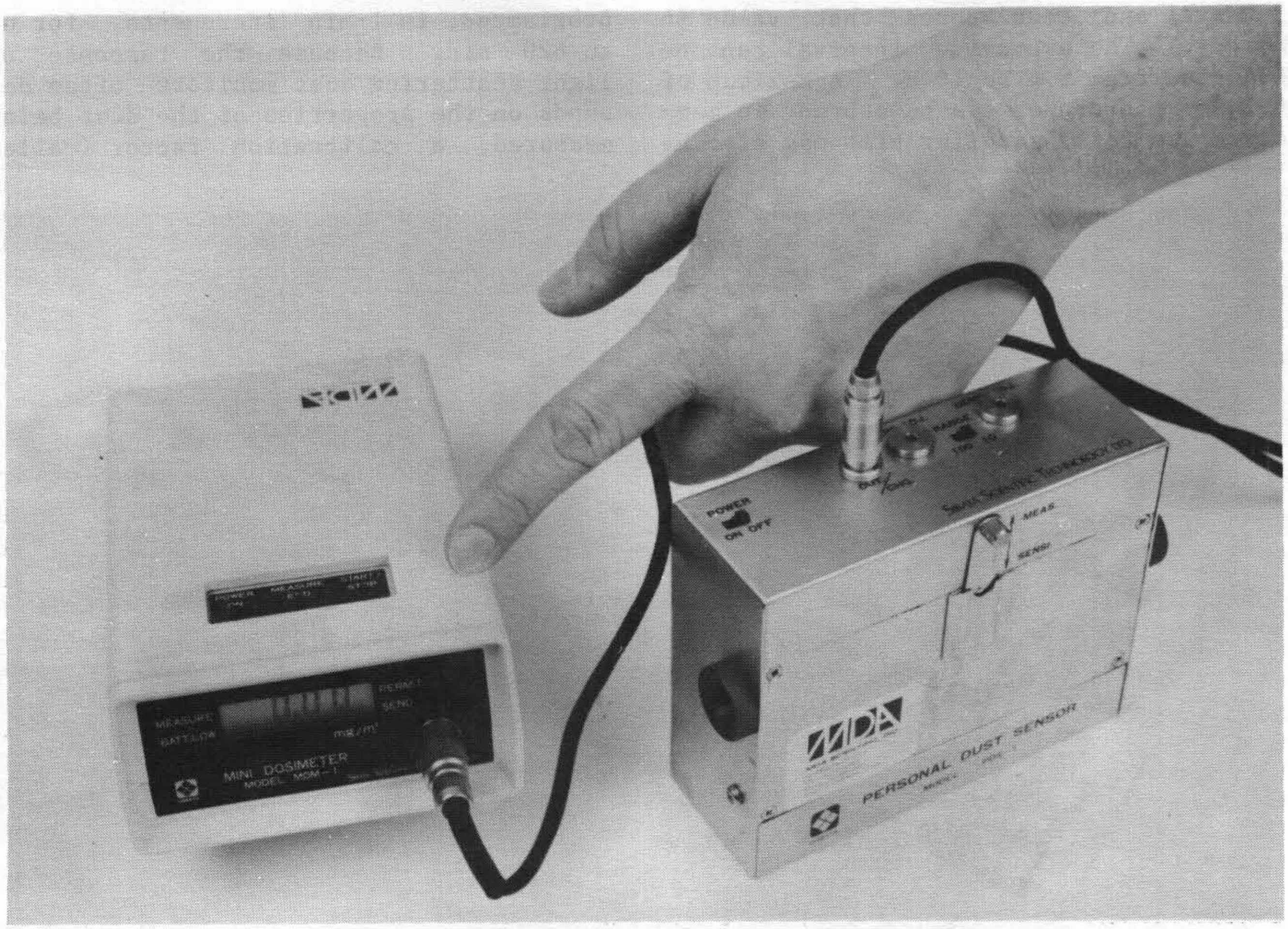

FIGURE 1.—PDS-1 Personal Dust Sensor and MDM-1 Mini Dosimeter.

light beam. Each time the board is inserted into the light beam, the same amount of light is scattered to the detector. The gain of the instrument can then be adjusted to indicate some arbitrary value. The manufacturer calibrates the instrument to directly indicate the mass concentration for ARD. By inserting the reference board and noting the instrument reading, the manufacturer determines the numerical value that should be indicated whenever the board is inserted in the future. The predetermined reference value is supplied with each unit.

The analog signal from the PDS-1 can also be sent to the MDM-1 Mini Dosimeter (fig. 1), which is a battery-powered data acquisition system capable of storing 800 1-min dust concentration averages. A digital display on the MDM-1 is continuously updated to indicate the current dust concentration. Data stored in the MDM-1 can be retrieved by a small portable computer (fig. 2) that is programmed to do elementary statistical analyses on the dust sampling data. Three PDS-1s were made available and used for this evaluation. This improved the statistical validity of the test data.

The PCD-1 digital dust indicator (fig. 3; specifications in appendix A) is a battery-powered, light-scattering dust monitor with a built-in air pump and microprocessor. Dust-laden air is drawn into the PCD-1 sensing chamber where, as in the PDS-1, dust is detected by light-scattering techniques. The microprocessor contains user-friendly, menu-driven software that gives the PCD-1 great versatility. A keypad on the top of the PCD-1 allows the operator to program the PCD-1. In operation, the PCD-1 averages the signal for a preset averaging interval and then stores that value in memory. The averaging interval can be adjusted from 6 s to 10 h. A maximum of 6,200 6-s averages can be stored in memory. The total sampling time may also be programmed, in 1-min increments, for up to 620 min. Because the response of light-scattering dust monitors often depends on the properties of the dust being measured, a calibration factor (called

FIGURE 2.—MDM-1 and portable computer.

FIGURE 3.—PCD-1 digital dust indicator.

the "K Factor") may be entered into the microprocessor so that the true mass concentrations are displayed and stored in memory. The PCD-1 also features a RS232C port, which is a digital interface, used for communicating with other computers.

AEROSOL CHAMBER

All tests were conducted in an aerosol chamber designed specifically for evaluating dust sampling instrumentation. The chamber is similar to the one used by the University of Minnesota to evaluate the other light-scattering dust monitors (5-6). (See the introduction to this report.) The hexagonal 8-ft-high chamber is supported by a 2-ft high triangular base. Dust-laden air, produced by the dust generating system, passes through a krypton-85[5] particle-charge neutralizer and enters the top of the chamber through a 1-5/8-in-diam pipe. At the top center of the chamber, the dust-laden air first strikes a special target that evenly disperses it, then passes it through a honeycomb flow straightener designed to minimize turbulence. Drawn by a blower at the base of the chamber, the dust-laden air then passes the sampling instrumentation, which is located on a round, rotatable table near the base of the chamber. The air finally passes through a perforated metal instrument table and is collected by a large, highly efficient filter located just above the blower.

The aerosol chamber's dust generation system consists of a fluidized-bed aerosol generator and a dilution-air system. The fluidized-bed aerosol generator can disperse dry powders with particle sizes from 0.1 to 20-µm-diam. Air blown through the bottom of a small cylinder containing bronze beads produces a fluidized bed. A loop of continuous ball chain carries the dust from a reservoir into the fluidized bed of bronze beads. The motion of the beads breaks apart any dust particle agglomerates. Air blown through the bed then carries the dust particles out of the fluidized bed to the aerosol chamber.

The amount of dust introduced into the chamber can be varied by changing the chain speed or airflow rate through the bed of bronze beads. Changing these parameters, however, can change the particle size distribution of the dust that enters the chamber. Since the response of a light-scattering instrument is often affected by changes in particle size distribution, random changes could introduce error into the determination of instrument response. Thus, whenever possible, an adjustable diluter was used to vary dust concentrations in the chamber without changing the dust generator operating parameters. First, the generator was allowed to stabilize at a high dust generation rate. A diluter system was then used to divert a selectable portion of the dust-laden air, filter the dust particles from that portion, and return the filtered air downstream of the dust generation system. The diluter thus reduced the dust concentration entering the aerosol chamber without varying the operating parameters of the fluidized-bed generator. The dust concentration could be further reduced by feeding a controlled amount of filtered dilution air with the dust-laden air into the aerosol chamber. The addition of the dilution air, however, increased the total airflow rate through the chamber, thereby increasing the velocity of air past the sampling inlets of the instrument being tested.

REFERENCE MEASUREMENTS

Gravimetric dust samples were collected during each test to provide reference measurements for comparison to measurements made by the light-scattering instruments. Five preweighted 37-mm-diam polyvinyl chloride (PVC) membrane filters in cassettes were connected to the outlets of five cyclones. Chamber air was sampled through the cyclones at 2 L/min,

[5] Krypton-85 gas, sealed in a small tube, emits beta and gamma radiation to ionize air molecules in a larger concentric tube through which the generated dust must pass. Charged particles passing through the ionized air surrender much of their charge to the ionized air molecules.

this flow caused the respirable fraction of the dust to be deposited on the preweighted filters. After sampling, the filters were removed and weighed. The average respirable dust concentration in the chamber during the test period was calculated as

$$C = M/(F \cdot T),$$

where C = concentration, mg/m^3,

M = mass of collected dust, mg,

F = sampling flow rate (0.002 m^3/min),

and T = sampling time, min.

The calculated values of C for each of the five cassette samplers were then averaged. The standard deviation for each test was also calculated. The coefficient of variation (CV) was then calculated by dividing the standard deviation by the average concentration for each test (table 1). The average concentration for each test was then compared to the time-averaged value indicated by each of the light-scattering monitors during the same test period.

TABLE 1. - Reference respirable dust concentrations[1]

Test	Number of samples	Mean, mg/m^3	Standard deviation	CV, pct
		ARD		
1....	5	1.829	0.194	10.6
2....	5	2.256	.159	7.1
3....	5	2.241	.163	7.2
4....	4	.810	.022	2.7
5....	5	.728	.044	6.0
6....	5	.348	.021	6.0
7....	5	3.403	.319	9.4
8....	5	4.619	.294	6.4
9....	5	3.532	.259	7.3
10....	5	4.593	.334	7.3
		COAL DUST		
11....	5	2.459	0.095	3.8
12....	5	2.073	.130	6.3
13....	4	2.115	.054	2.5
14....	5	2.492	.031	1.2
15....	4	2.555	.062	2.4
16....	5	2.600	.035	1.4
17....	5	2.246	.051	2.3
18....	5	.446	.020	4.5
19....	5	.393	.027	7.0
20....	5	.431	.015	3.6
21....	5	5.517	.129	2.3
22....	5	5.451	.151	2.8
23....	5	5.230	.140	2.7

CV Coefficent of variation.
[1]As measured by gravimetric cassette samples.

OTHER DUST MEASUREMENTS

Several filter samples were collected during each test without cyclone precollectors to provide a measure of the total dust concentration[6] in the test chamber (table B-1, appendix B). These samples were collected at three locations in the test chamber, at 2 L/min, with the same type filter cassettes as were used for collecting the respirable samples. The inlets of these filter cassettes were faced downward during sampling. The ratio of the reference respirable dust concentration to the total dust concentration provided a crude measure of the particle size distribution of the test dust in the chamber (table 2).

Finally, the RAM-1[7] a light-scattering dust monitor previously characterized by the Bureau (7), was used to monitor the behavior of the dust generator before and during each test period. The data gathered by this instrument was helpful in determining when the dust concentration in the chamber had stabilized after startup of the dust generating system and in detecting unexpected changes in the generator output.

[6]The term *total* dust refers to all dust particles in the aerosol chamber, both respirable size and larger. In essence, total dust is all dust collected by the filter cassettes without any size-selective precollector.

[7]Reference to specific products does not imply endorsement by the Bureau of Mines.

TABLE 2. - Ratios of total dust concentrations to reference respirable dust concentrations (T/R)

Test	Concentration, mg/m^3		T/R[1]	Test	Concentration, mg/m^3		T/R[1]
	Respirable[1]	Total[2]			Respirable[1]	Total[2]	
	ARD				COAL DUST		
1...........	1.829	5.998	3.28	11...........	2.459	5.501	2.24
2...........	2.256	8.121	3.60	12...........	2.073	5.799	2.80
3...........	2.241	NA	NA	13...........	2.115	5.669	2.68
4...........	.810	3.307	4.08	14...........	2.492	6.034	2.42
5...........	.728	1.257	1.73	15...........	2.555	6.516	2.55
6...........	.348	.743	2.13	16...........	2.600	6.537	2.51
7...........	3.403	10.538	3.10	17...........	2.246	5.278	2.35
8...........	4.619	16.036	3.47	18...........	.446	1.155	2.59
9...........	3.532	13.959	3.95	19...........	.393	.877	2.23
10...........	4.593	15.971	3.48	20...........	.431	1.175	2.73
				21...........	5.517	9.668	1.75
				22...........	5.451	9.954	1.83
				23...........	5.230	9.322	1.78

NA Not available. [1]From table 1. [2]From table B-1.

RESULTS AND DISCUSSION

REFERENCE MEASUREMENTS

Table 1 lists the respirable dust concentration data used to evaluate the light-scattering monitors. In table 1, entries under the heading "Mean, mg/m^3" represent the mean of the reference *respirable* dust concentration measurements from the five previously described gravimetric cassette samplers. For ARD, these means ranged from 0.35 to 4.62 mg/m^3 with CV's between 2.7 and 10.6 pct. Since each of the five respirable dust cassette samplers was located in a different position (fig. 4), the low CV's indicate that the ARD was fairly evenly distributed in the aerosol chamber. (Table B-1, appendix B) lists the *total* ARD reference measurements.

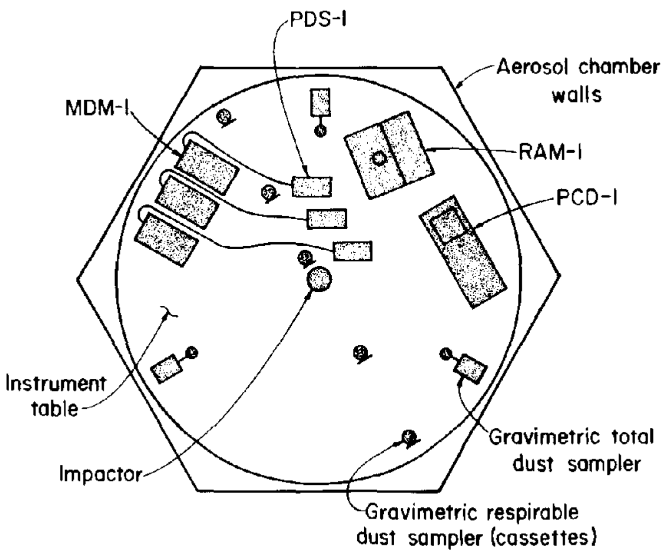

FIGURE 4.—Aerosol chamber, sectional top view.

The respirable coal dust concentration data are also listed in table 1. Mean coal dust concentrations ranged from 0.39 to 5.52 mg/m^3 with CV's ranging from 1.1 to 6.9 pct. Again, dust concentrations were fairly uniform in the aerosol chamber. Table B-1 lists the total reference coal dust concentrations.

PDS-1 RESPONSE

Figure 5 is a plot of the readings from each of the three PDS-1 units versus the mass concentration of respirable coal dust determined gravimetrically for reference. (The plotted PDS-1 data are listed in appendix C.) The PDS-1 values are time-averages of the instrument readings over the test period. Each corresponding gravimetric reference value is the mean of five measurements determined from filter samples taken during the test period, as previously described.

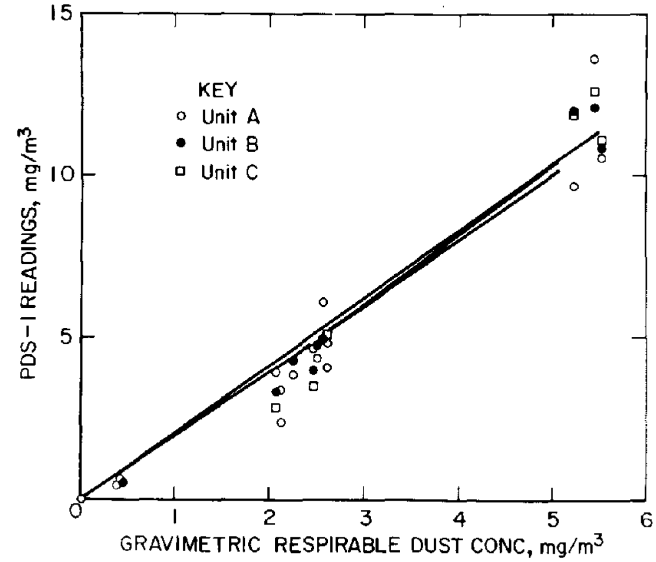

FIGURE 5.—PDS-1 readings versus gravimetric concentrations for coal dust.

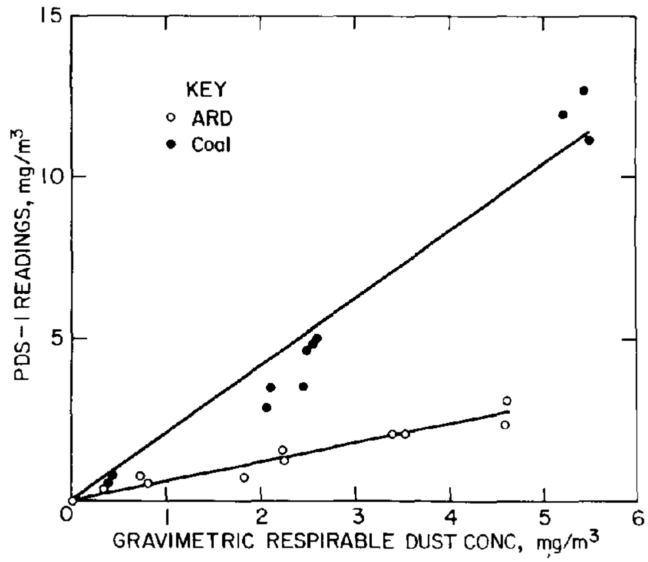

FIGURE 6.—PDS-1 readings versus gravimetric concentrations for ARD and coal dust.

Agreement between the readings from units A, B, and C was good (fig. 5). Regression lines were calculated for each unit to fit the equation

$$y = Mx,$$

where y = PDS-1 reading, mg/m^3,

M = slope,

and x = gravimetric respirable dust concentration, mg/m^3.

This calculation forced the regression line for each unit through the origin. The response of each unit to mass concentration is represented by M. The values for M ranged from 2.00 to 2.06, representing response variations of only a few percent. These results imply that if PDS-1 units are calibrated with the reference board to the manufacturer's recommended value, they will agree well with each other.

Figure 6 compares the response of one PDS-1 unit with corresponding gravimetric values, using both ARD and coal dust. (See appendix C, data for unit.) Again, each PDS-1 response value represents a time-average of the output, and again, the reference gravimetric measurement is the mean of five measurements. The PDS-1 response to ARD was significantly different than the PDS-1 response to coal. The M value was 0.59 for ARD, as opposed to 2.06 for coal dust. These data imply that the response of the PDS-1 depends significantly on characteristics of dust particles other than mass, such as size and index of refraction, as is the case for other instruments based on light-scattering (_5_, _7_). Nevertheless, for a particular dust, the response was linear with mass concentration over the ranged tested. For both coal and ARD, the coefficient of determination (r^2) was greater than 0.9 when the data were fitted to the equation $y = M/x$.

PCD-1 RESPONSE

Since only one PCD-1 unit was available for testing, inter-unit comparison was not possible.

Figure 7 shows the response of the PCD-1 versus corresponding gravimetric values, for both ARD and coal dust. (See appendix C for the PCD-1 data.) Again, the response to ARD was different than the response to coal dust. The values of M were 0.22 for ARD and 0.16 for coal dust. Again, the response was linear with mass concentration for each dust. The slopes (M) of these responses could have been changed by entering a "K factor" into the PCD-1's microprocessor. For these tests the "K factor" was kept

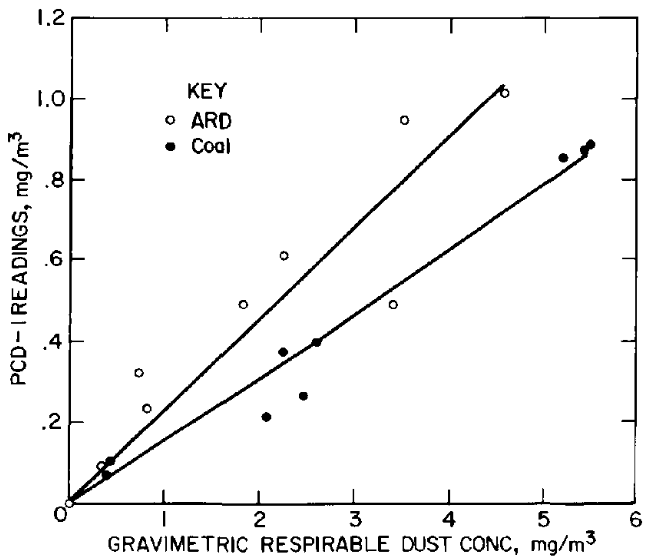

FIGURE 7.—PCD-1 readings versus gravimetric dust concentrations for ARD and coal dust.

at unity. The value of r^2 was 0.84 for ARD and 0.97 for coal dust. For the PCD-1, the slopes of the curves show the response to ARD was greater than the response to coal. For the PDS-1, the situation was reversed.

EFFECT OF PARTICLE SIZE DISTRIBUTIONS

In the absence of impactor data, ratios of total to respirable dust concentration measurements (T/R) provided some indication of the particle size distribution. Table 2 shows the T/R ratios for both the ARD and coal dust tests.

Some variability existed in the size distribution, as indicated by the T/R ratios. Variability also existed in the responses of the light-scattering instruments, as indicated by the ratios of the PDS-1 and PCD-1 readings to the gravimetric determinations of mass concentration (M). Nevertheless, no statistically significant correlation could be found between changes in particle size distribution and the responses of the instruments. Theoretically, particle size can have an effect on the response of light-scattering instruments. More careful measurement and control of particle size distributions during similar tests would be needed to confirm size dependence.

CONCLUSIONS

Both the PDS-1 and the PCD-1 responded linearly with mass concentration for both ARD and coal dust over the range of about 0.3 to 5 mg/m³. However, the instruments' responses to ARD and coal dust were different. The PCD-1's response to ARD was greater then its response to the coal dust. The situation was reversed for the PDS-1. The major difference between the two instruments is that the PCD-1 draws air into its light-sensor chamber with an air pump, whereas the PDS-1 has no air pump.

As is the case with many light-scattering dust monitors, response depends on characteristics of the dust particles other than mass. The apparent response differences observed using ARD and coal dust probably resulted from differences in the indexes of refraction of these two dusts. However, this could not be determined by the data collected during these tests.

REFERENCES

1. U.S. Code of Federal Regulations. Title 30--Mineral Resources; Chapter I--Mine Safety and Health Admin., Department of Labor; Subchapter O--Coal Mine Safety and Health; Part 70--Mandatory Health Standards--Underground Coal Mines, Sec. 70.100 (a); July 1, 1985.

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APPENDIX A.--MANUFACTURER'S SPECIFICATIONS

PDS-1 Personal Dust Sensor

Range:	0.01 to 10 mg/m^3 or 0.1 to 100 mg/m^3
Sensitivity:	0.01 mg/m^3
Particle size range:	0.01 to 10 µm
Calibration:	Built-in reference board
Power source:	Rechargeable Ni-Cd batteries
Operating time:	9 h
Dimensions:	4-3/8 by 3-1/2 by 1-1/2 in
Weight:	1 lb 7 oz

MDM-1 Mini Dosimeter

Input range:	0 to 1000 mV
Resolution:	1 mV
Precision:	±0.5 pct full scale
Data acquisition:	180 data points per min; stores 800 1-min averages
Display:	3-1/2-digit mass concentration from 0 to 10.00 mg/m^3
Data output:	Serial (ASCll) TTL level
Power source:	Rechargeable Ni-Cd batteries
Operating time:	12 h
Dimensions:	3-3/8 by 1-3/4 by 6-1/8 in
Weight:	10 oz

PCD-1 Digital Dust Indicator

Range:	0.001 to 9.999 mg/m^3
Sensitivity:	0.001 mg/m^3
Particle size range:	0.01 to 10.00 µm
Power source:	Rechargeable Ni-Cd batteries
Operating time:	10 h
Dimensions:	11 by 3-1/2 by 5-3/4 in
Weight:	8 lb

APPENDIX B.--TOTAL DUST CONCENTRATIONS

Table B-1 lists the means of several total ARD and coal dust concentration measurements. The means for ARD ranged from 0.743 to 16.036 mg/m^3, with CV's ranging from 0.6 and 9.3 pct. The coal dust means ranged from 0.877 to 9.954 mg/m^3, with CV's ranging from 1.0 and 13.2 pct.

TABLE B-1. - Total dust concentrations[1]

Test	Number of samples	Mean, mg/m^3	Standard deviation	CV, pct	Test	Number of samples	Mean, mg/m^3	Standard deviation	CV, pct
ARD					COAL DUST				
1......	1	5.998	NAp	NAp	11......	3	5.501	0.221	4.0
2......	1	8.121	NAp	NAp	12......	3	5.799	.559	9.6
3......	0	[2]NA	NAp	NAp	13......	3	5.669	.122	2.1
4......	3	3.307	0.309	9.3	14......	3	6.034	.059	1.0
5......	3	1.257	.063	5.0	15......	3	6.516	.399	6.1
6......	3	.743	.027	3.6	16......	3	6.537	.405	6.2
7......	3	10.538	.424	4.0	17......	3	5.278	.694	13.2
8......	3	16.036	1.333	8.3	18......	3	1.155	.046	4.0
9......	3	13.959	.715	5.1	19......	3	.877	.031	3.5
10......	3	15.971	.094	.6	20......	3	1.175	.062	5.3
					21......	3	9.668	.641	6.6
					22......	3	9.954	.654	6.6
					23......	3	9.322	.504	5.4

NAp Not applicable. [1]As measured by gravimetric cassette samplers. [2]Lost sample.

APPENDIX C.--PDS-1 AND PCD-1 TEST DATA

(Milligrams per cubic meter)

Test	PDS-1			PCD-1	Test	PDS-1			PCD-1
	Unit A	Unit B	Unit C			Unit A	Unit B	Unit C	
ARD					COAL DUST				
1........	[1]NA	NA	0.740	0.489	11........	4.661	3.982	3.520	0.265
2........	1.695	NA	1.271	.609	12........	3.959	3.353	2.872	.214
3........	NA	1.392	1.560	NA	13........	2.410	3.407	3.485	NA
4........	NA	.521	.526	.232	14........	4.370	4.759	4.649	NA
5........	NA	.658	.749	.321	15........	6.092	4.945	4.833	NA
6........	NA	NA	.343	.094	16........	4.074	4.866	4.998	.396
7........	NA	NA	2.037	.487	17........	3.862	4.307	NA	.373
8........	NA	NA	3.053	NA	18........	.582	.584	.622	NA
9........	5.028	2.341	2.034	.942	19........	.460	.471	.522	.072
10........	NA	4.348	2.321	1.010	20........	.629	.692	.735	.105
					21........	10.604	10.887	11.127	.883
					22........	13.674	12.153	12.670	.870
					23........	9.681	12.035	11.931	.851

[1]Data not available because of malfunction of dust monitor.