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THE USE OF PORTABLE CONTINUOUS MONITORING DEVICES TO DETERMINE SOOT CONCENTRATIONS IN DIESELIZED MINES

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ABSTRACT

The paper describes the use of portable aerosol monitors in determining real-time concentrations of diesel soot and respirable total dust in dieselized mines. The field studies were conducted in a simulated diesel environment in the laboratory where no other type of dust was present, and in four underground mines with multi-diesel machine operations. Two packages for the real-time monitoring of diesel soot were prepared which included two types of aerosol monitors: a Miniram, model PDM-3, and a Sibata, model PDS-1. These monitors utilize the principle of light-scattering to measure the airborne mass concentration in the environment.

The monitoring device results were compared against the Time-Weighted-Average (TWA) values produced by the gravimetric filter sampling method, permitting calibration factors to be determined for each field test. Both instrument packages provided comparable results. The instrument calibration factors varied for different tests, which may be due to different material composition, particle size distribution, density and shape of the aerosols. This approach for real-time determination of diesel soot is found to be simple, inexpensive and easy to use. More field tests for diesel soot determination and further research on size distribution of particulates in dieselized mines are required.

INTRODUCTION

During the last few years, CANMET has made a considerable effort in the area of monitoring and control of air quality in dieselized mines. In such environments, the pollutants of main concern are gaseous emissions (CO, NO, NO_2, SO_2) and particulates. To simplify the criteria by which to judge the air quality in dieselized mines, French, I.W. and Mildon, C.A. (1984) proposed an Air Quality Index (AQI), which combines all these pollutants in to a single index. In this way, air quality can be described by a single index. It is a powerful tool which can be used to assess the performance of various options available for the control of air quality in dieselized mines. Recently, CANMET assessed the performance of ceramic filter technology using the AQI criterion for the reduction of diesel soot in underground mines. In this work, various monitoring instruments were used to determine the TWA values of diesel pollutants. These instruments are described in a paper by Gangal, M.K., Mogan, J.P. and Dainty, E.D. (1986).

While studying the CO_2 surrogate behaviour with other pollutants in dieselized mines with multi-diesel machine operation, it became necessary to monitor all the pollutants simultaneously on a real-time basis. As a consequence, there is a need to monitor diesel generated gases and particulates (diesel soot) on a real-time basis. These instruments should be inexpensive, light-weight, battery-powered, and easy to use in harsh mining environment. Also, these instruments must have an analog signal output for storing data electronically for data analysis. While it was easier to find instruments for gaseous measurements that fitted the above requirements, instruments for diesel soot monitoring were not readily available. Further, French, I.W. and Mildon, C.A. (1984) concluded that in dieselized mines, diesel soot (or respirable combustible dust - RCD) is the pollutant of greatest health concern. Diesel soot is a carbonaceous material which is virtually completely respirable and therefore is carried into the alveoli or air exchange compartments of the lungs. Thus, it is thought that the soot itself might result in physical impairment of lung function by causing fibrosis leading to a form of restrictive pulmonary disease. Of even greater concern is the propensity of soot to adsorb other chemical components such as the mutagenic/ carcinogenic polynuclear aromatic hydrocarbons along with gases such as SO_2 and NO_2 and acids.

Therefore, the determination of soot is of prime importance. At present there is no regulatory level for soot, but CANMET recommended a value of 2 mg/m^3 for RCD. Although not presently in force, there is a conviction in the USA, as a result of extensive animal testing, that soot concentration is indeed the main concern, and that its interim Threshold Limit Value (TLV) should be 1 mg/m^3.

This may ultimately be reduced to 0.2 mg/m^3. French, I.W. and Mildon, C.A. (1984), have now revised their recommendation for RCD downward from 2.0 to 0.5 mg/m^3, in view of the recent animal study data.

This paper mainly deals with the use of instrument packages for the real-time monitoring of diesel soot (RCD) and total respirable dust (TRD). These packages were used in a purely diesel soot environment in the laboratory, and in four underground mines.

DESCRIPTION OF THE MONITORING PACKAGE

As mentioned earlier, the objective is the real-time monitoring of diesel soot by portable instruments, which are inexpensive, battery-powered, light-weight and easy to use in the harsh underground mine environment. These instrument packages use portable aerosol monitoring devices which are based on the principle of light scattering. The monitors measure the concentration of any airborne particles, both solid and liquid, based on their factory gravimetric calibration, using a standard Arizona road dust. In the underground mining environment, the measured concentration will include diesel soot, mineral dust, fumes, smoke, fogs, water droplets etc. Therefore, it is necessary to calibrate these monitors in the same environment where they will monitor the diesel soot. This can be done by simultaneously measuring TWA value of diesel soot by the gravimetric method. When this calibration is applied to the monitors, they provide real-time measurement of soot.

The sampling configuration used for the real-time monitoring is shown in Figure 1. The sample air passes through the cyclone into the chamber of the aerosol monitor and the dust particulates from the same sample are collected on the filter, before exiting to the environment. A constant flow pump located at the end of the instrument package draws the air sample at 2

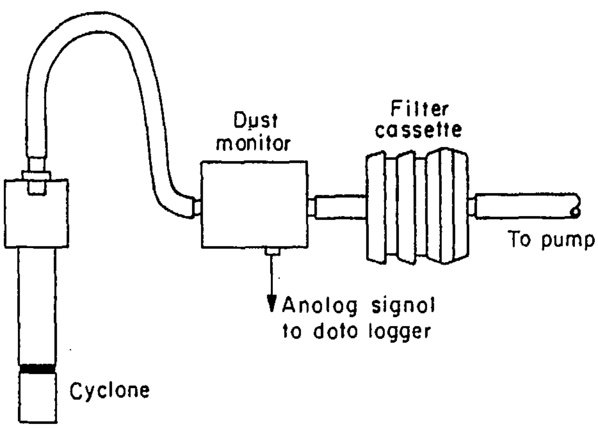

Figure 1. Sampling Configuration used in this study

L/min. While the light scattering aerosol monitors do not require a cyclone, Marple, V.A. and Rubow, K.L. (1984) have determined in their study of mineral dust concentrations that such instruments can be affected by variation in the particle size distribution of the aerosol and by water droplets. To reduce errors due to these factors, a cyclone has been included into this configuration.

The monitor's signal analog output is connected to a data logger which stores data in its memory once every minute. If required, the data logging time frequency can be changed. The data logger used in the package is a Grant model 1201 Squirrel. For this work, two monitoring packages were assembled. The dust monitor in the first package was a Miniram model PDM-3, and a Sibata model PDS-1 in the second. Both of these monitors weigh about 0.5 kg, contain a chareable battery suitable for about 10 hours sampling, and measure aerosol concentrations over the range of 0.01 to 10.0 mg/m^3 or from 0.1 to 100.0 mg/m^3. The resolution for monitors is $\pm$0.02 mg/m^3 with a sensitivity of 0.01 mg/m^3. The Sibata's light scattering configuration response to particles is in the size range of 0.01 to 10 microns.

These monitors can be used in a passive mode or an active mode. In the passive mode, air surrounding the monitors passes freely through its open sensing chamber by natural convection and circulation. The passive sampling does not require any pump. In the monitoring package the sampling is done in the active mode and the measurement is independent on the volume of air passing through the instrument. However, the monitored aerosol will depend on the particle size distribution, density, shape and surface properties of particulates being monitored. This requires a field calibration, which is achieved by collecting the particulates on the filter paper connected in series with the monitor. The TWA value of soot in the collected sample is determined in the laboratory and the calibration factor is obtained by dividing this value by the time integrated value produced by the monitor.

One of the advantages of these monitoring packages is that, they can provide the dust concentration from a short-term measurement provided the instrument calibration under similar conditions is known. The short term measurement of dust concentration is not possible using the filter gravimetric method due to the very small amount of particulate deposited on the filter for accurate weighing. Also, dust distribution with time can be monitored.

EXPERIMENTAL PROCEDURE

Both of the real-time monitoring packages were used during field experiments. Both packages were placed side by side to compare the performance of one with the other. The experiment was conducted in a laboratory simulated diesel environment, which contained only diesel soot, ie. no other dust particulates were present in the environment. This provided instrument calibration factors for 100% soot. The packages were also used in four underground mines. These mine environments contained mineral dusts as well as diesel soot and possibly other combustible materials, such as drill oil mist.

The dust cassettes were prepared in the laboratory prior to use in the mine. The monitors were calibrated for zero adjustment by allowing clean air to pass through them. The zero adjustment was done in a clean room at the surface. The data logger, pumps and the monitors were turned on at the same time. The data logger was programmed for sampling at every minute, which recorded the data from both monitors and clock time, in its memory. At the end of the sampling period, all the instruments were turned off and dust cassettes were removed and sealed for later analysis in the laboratory. The data from the loggers was transferred to a portable micro-computer using the data logger transfer-analysis program. The analysis program was used every day to analyse the data and to confirm that proper data had been stored in the microcomputer.

During sampling, particulates were collected on a 37 mm Gelman A/E type glass fiber filters and TWA filter analysis was done as follows. For the TWA analysis of respirable combustible dust (RCD), the filter was combusted for about four hours in a pre-heated oven at 500°C. The weight loss of the filter was due to the combustible matter which, when divided by the total sampling air volume, provides the RCD (soot) part of the total dust concentration. The total respirable dust (TRD) concentration is calculated by dividing the total collected dust on the filter by the total sampling air volume. In order to reduce moisture error, the filters were kept in an oven at 120°C for minimum of two hours and then weighed. Also, five fresh unused filters were combusted at 500°C to determine the weight loss due to combustible material in the filter. This indicated that unused Gelman glass fiber type A/E filters contained an average of 0.30 mg of combustible material. This weight was subtracted from the combustible weight of the field filters in order to obtain soot results for the mine.

In the mine air there are several combustible contaminants: some airborne ore dusts, drill oil mist, fuel and lubricants evaporated from hot machine surfaces, and combustion-generated soot (100% respirable). Ore samples taken from nickel and zinc mines contained no combustible material. Drill oil mist and lubricants etc. vary, depending on the circumstances, but these are thought to be 25% or less of the RCD. Therefore, RCD is considered to be a good approximation for diesel soot.

The data from the data logger analysis program was later transferred to Lotus/123 software for the determination of the instrument calibration factors, and for analysis and graph preparation. The calibration factor for each instrument and experiment was calculated by dividing the TWA values obtained from the gravimetric method by the corresponding time integrated values measured. This factor when multiplied by the real-time values obtained from the monitor, provided the continuous measurement of RCD and TRD.

DISCUSSION OF THE RESULTS

Table 1 summarizes the Miniram results at four dieselized mines and in the simulated diesel particulates-only environment. In all the cases the monitoring was done at an exhaust location in the ventilation system, to measure the particulate concentration produced by all the diesel vehicles in operation. The instrument time-integrated respirable mass concentration (RMC) in mg/m^3 was obtained by taking the average of all the one minute readings. This value includes all the respirable aerosols present in the environment. The TWA values in the table for RCD and TRD were obtained by the gravimetric analysis of the filters in series with the monitors. It should be mentioned that during monitoring, a confirmatory independent gravimetric sampling was also done for RCD and TRD. This is not shown in the table due to lack of space. Most of the gravimetric results obtained from the Miniram, Sibata and independent cassette filters produced reasonably close RCD and TRD concentrations. This indicated that the sampling flow passing through the instrument dust cassette was representative of the environment sampled.

Table 1 shows that the percentage of RCD (soot) in the TRD varies from 79% to 92%. In the 7th test, the RCD contribution to TRD is only 26%, which is reasonable as the monitored data is from a blast plus light diesel activity. The time plot of RCD, TRD and RMC during the blast, is also shown in Figure 8. The instrument calibration factor for RCD varies from 0.31 to 0.68 and for TRD from 0.34 to 0.74 in the mine diesel environment. It should be noted that the instrument factor is 0.67 for the diesel soot only environment. The data indicates that the monitors should be calibrated separately for each field test. If a number of tests are conducted for different operations in a mine, then it may be possible to predict these factors for similar operations.

Table 2 shows results for the Sibata instrument package. This instrument package provided results similar to those discussed above. Some of the differences are due to the slight variation in the gravimetric data obtained from filter cassettes. A comparison of the results obtained from both instruments is discussed later.

Figure 2 shows a time series plot of simultaneously monitored data for RCD and diesel-produced CO_2 concentration in a mine with multi-diesel operation. The diesel-produced CO_2 was obtained by subtracting the CO_2 concentration in the fresh air (0.035 %), from the monitored data. It clearly shows that the both curves have the similar characteristic. Figure 3 is produced from the data of Figure 2, which indicates the linear relationship of diesel soot with CO_2. This means

Table 1. Determination of Instrument TWA Calibration Factor from Mimiram (PDM-3) and Gravimetric Data

No	Mine	Respirable Particulate (mg/m^3) Instrument Integrated value RMC	Cassette Filter TWA value TRD	Cassette Filter TWA value RCD	Percent of RCD to TRD	Instrument Correction Factor for TRD	Instrument Correction Factor for RCD	Remarks
1	Lab	0.92	0.62	0.62	100	0.67	0.67	Single diesel engine, diesel soot only, air flow and loads changed during the experiment
2	A	0.74	0.30	-	-	0.41	-	Dry mine, multi-diesel engines
3	B	4.59	3.40	3.14	92	0.74	0.68	Very wet mine, multi-diesel engines
4	D	2.65	1.40	1.10	79	0.53	0.42	Mine in development, no drilling during experiment, multi-diesel engines
5	C	2.8	1.13	0.96	85	0.40	0.34	Typical mine in operation, multi-diesel engines
6	C	3.59	1.23	1.13	92	0.34	0.31	Data includes blast period which is 15% of total monitoring time, multi-diesel engines
7	D	3.85	2.02	0.53	26	0.52	0.14	Data includes blast period which is 50% of total monitoring time, rest is light diesel activities from multi-diesel engines

RMC = Respirable mass concentration, TRD = Total respirable dust, RCD = Respirable combustible dust

Table 2. Determination of Instrument TWA Calibration Factor from Sibata (PDS-1) and Gravimetric Data

No	Mine	Respirable Particulate (mg/m^3) Instrument Integrated value RMC	Cassette Filter TWA value TRD	Cassette Filter TWA value RCD	Percent of RCD to TRD	Instrument Correction Factor for TRD	Instrument Correction Factor for RCD	Remarks
1	Lab	1.18	0.57	0.57	100	0.83	0.83	Single diesel engine, diesel soot only, air flow and loads changed during the experiment
2	A	1.46	0.64	0.59	92	0.44	0.40	Dry mine, multi-diesel engines
3	B	4.33	3.78	3.53	93	0.87	0.82	Very wet mine, multi-diesel engines
4	D	2.85	1.89	1.31	69	0.66	0.46	Mine in development, no drilling during experiment, multi-diesel engines
5	C	3.18	1.46	1.02	70	0.46	0.32	Typical mine in operation, multi-diesel engines
6	C	3.32	1.07	0.87	81	0.32	0.26	Data includes blast period which is 15% of total monitoring time, multi-diesel engines

RMC = Respirable mass concentration, TRD = Total respirable dust, RCD = Respirable combustible dust

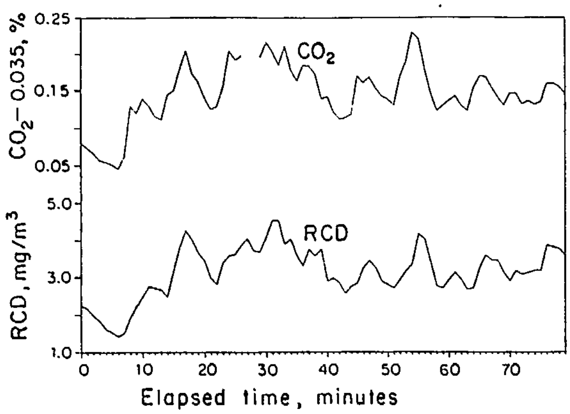

Figure 2. Respirable Combustible Dust (RCD) and CO_2 Concentrations in a Multi-diesel Machine Operation in an Underground Mine

that CO_2 is a surrogate for RCD in this circumstance. If such a relationship should exist with other diesel pollutants also, then the levels of other diesel-generated pollutants should be predictable by the single measurement of CO_2 alone. Based on this principle the ventilation requirements can be achieved on an air quality basis. This is likely to be more a suitable basis ultimately, than the present practice based on a fixed air quantity. The use of CO_2 surrogate in monitoring air quality in dead-end drifts has also been discussed by Schnakenberg, G.H., Johnson, J.H. and Schaefer, P. (1984).

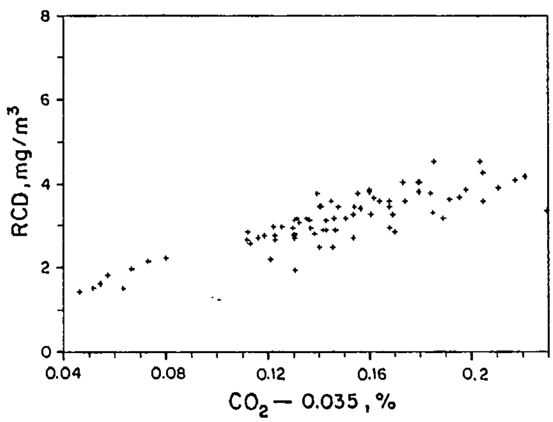

Figure 3. Respirable Combustible Dust (RCD) Versus CO_2 Concentrations in a Multi-diesel Machine Operation in an Underground Mine

Figure 4 compares the time-integrated respirable mass concentration (RMC) data monitored by the Miniram PDM-3, and the Sibata PDS-1 instruments in six tests. The RMC data is as monitored by the devices without making any corrections. Since both monitors are based on the light scattering principle and were factory calibrated with Arizona road dust, it is worthwhile to compare them, one against the other. The straight line fit, shown in Figure 4, is drawn from the regression analysis. The coefficient of correlation was found to be 0.98, which indicates a good linear relationship. Figure 5 shows the time variation of diesel soot measured by both of the packages. For this test the diesel environment in the laboratory test cell was simulated by running a Deutz F6L912W air-cooled, nominal 67 kW diesel engine. The fresh air was drawn into the test cell by a ventilation fan. During the test, fan speed and load factors were changed to vary the soot production in the environment. Figure 5 indicates a good agreement for soot determination by both the instruments. The readings from both instruments were recorded every minute. The response of both instruments is good. The sudden drop in soot concentrations is due to change in air volumes supplied in the test room. It should be noted that TWA soot value from Miniram filter was 8% higher than the corresponding value from the Sibata filter in these circumstances. This is the reason that the soot concentrations measured by Miniram are slightly higher than obtained by Sibata.

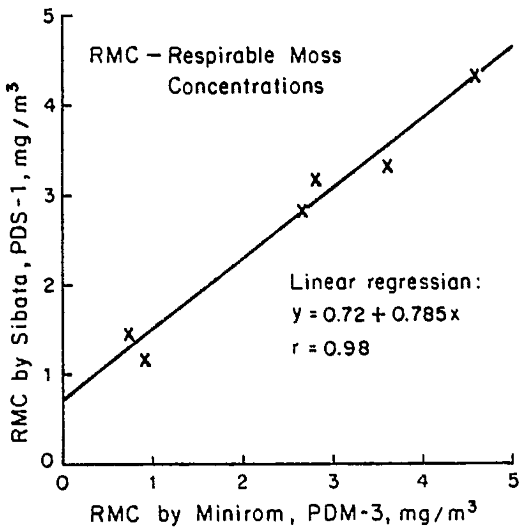

Figure 4. Comparison of Respirable Mass Concentrations by Miniram and Sibata Aersol Monitors in Dieselized Operations

The measurement of respirable mass concentrations (RMC) as measured by both instruments in the multi-diesel environment at mine C are shown in Figure 6. The duty cycles of the vehicles in operation are clearly shown in the figure. During this test it was noticed that the ventilation in the system reduced after about 80 minutes which increased the value of RMC, as indicated in the figure. These values, when multiplied by the instrument calibration factors for respirable combustible dust, provide the real-time values for diesel soot shown in Figure 7. This curve has a similar trend as that of Figure 6.

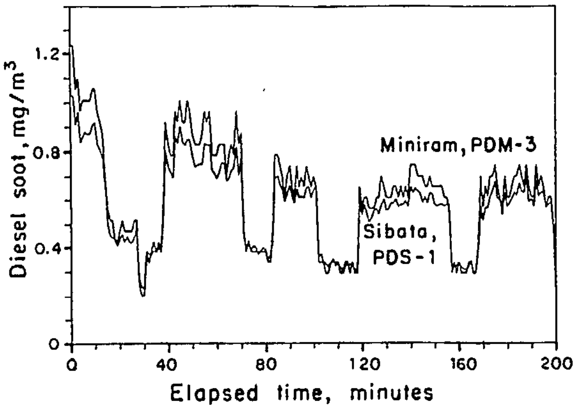

Figure 5. Real-time Monitoring of Diesel Soot in a Laboratory Simulated Diesel Environment. Ventilation and Engine Duty Loads were Changed during the Experiment

These results indicate that the diesel soot in the environment can easily be measured by the instrument package on the real time basis, thus providing a means of studying time variations in diesel soot levels.

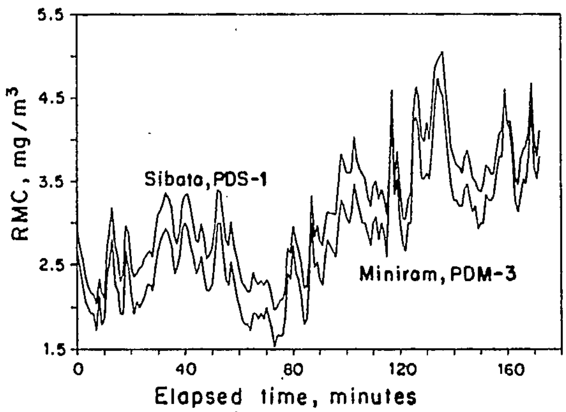

Figure 6. Respirable Mass Concentration (RMC) Measurements by Miniram and Sibata Aersol Monitors in a Dieselized Mine

The instrument package with the Miniram device was used to study time variation in respirable dust levels during a blast at mine D. In this case only one round of explosives was fired. The 55 holes drilled were filled with a total of 180 kg. ANFO (ammonium nitrate plus 5% diesel fuel), and 72 kg. of Dupont NBL 4032 stick explosive (40 mm diameter, 600mm length per stick). The time plot with respirable mass concentration, total respirable dust and respirable combustible dust are shown in Figure 8. It took about 70 minutes after the blast before dust values were back to the background level. As expected, some

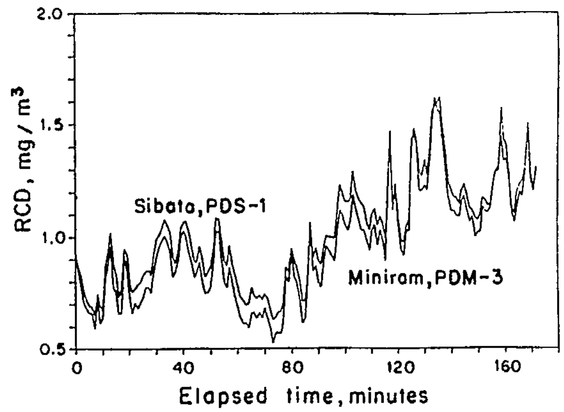

Figure 7. Real-time Monitoring of Respirable Combustible Dust (RCD) in Multi-diesel Engine Environment in an Underground Mine

respirable combustible dust was produced during blasting by the presence of diesel fuel in the explosive.

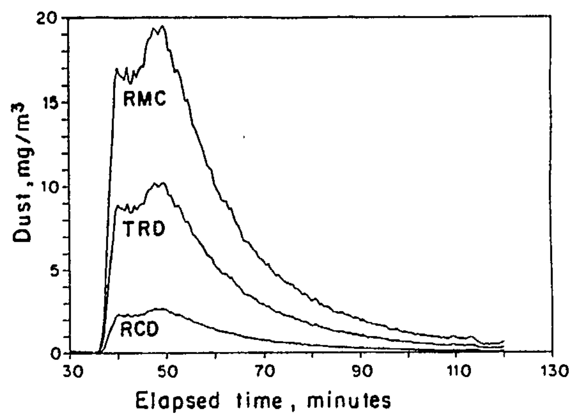

Figure 8. Respirable Combustible Dust (RCD), Total Respirable Dust (TRD) and Respirable Mass Concentration (RMC) during a Blast in an Underground Mine

CONCLUSIONS

The monitoring instrument packages equipped with the Miniram, PDM-3 and the Sibata, PDS-1 respectively, were found to be suitable for use in the underground mines for monitoring real-time concentration of diesel soot and total respirable dust. The monitoring packages require an individual calibration factor for each different mining operation and different environment. The instrument package can be used for short-term determination of soot, provided it is pre-calibrated in that environment. The instrument calibration depends on dust size distribution, shape, density and chemical composition. If greater discrimination is required, the combustible matter in mines originating from sources other than diesel machine, should be eliminated or should be separately measured. The results obtained from both instruments were in close agreement. Further research in the field of size distribution of particulates in dieselized mines is recommended.

ACKNOWLEDGEMENTS

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