MINERAL DUST AND DIESEL EXHAUST AEROSOL MEASUREMENTS IN UNDERGROUND METAL AND NONMETAL MINES

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INTRODUCTION

Measurement of the contribution of diesel exhaust to respirable aerosol in mine environments has become increasingly important because of current concerns over the occupational health effects resulting from exposure to diesel emissions. In response to this, the U.S. Bureau of Mines is developing and evaluating new sampling methods for measuring diesel aerosol in underground mines. Two such techniques are being studied by the Bureau, size selective sampling and Chemical Mass Balance (CMB) modeling. These techniques use measurable physical or chemical characteristics of a mine aerosol sample to infer the amount of diesel particulate material contained in the sample.

Size selective sampling is being adapted for measurement of diesel aerosol by the Particle Technology Laboratory (PTL) of the University of Minnesota under sponsorship by the Bureau.[1] It is based on the premise that diesel and mineral dust aerosol can be physically separated by size and collected during sampling using inertial impaction. An independent effort by the National Institute for Occupational Safety and Health to develop a size selective sampling technique was also sponsored by the Bureau.[2]

The second technique, CMB modeling, is being developed by the Bureau as an alternative measurement technique to referee the results obtained using size selective sampling.[3] It compares measured trace element "finger prints" of aerosol sources with similar profiles of mine aerosol samples. From these, the portions of the sample contributed by each source can be determined. Results of these investigations in underground coal mines have confirmed that diesel and coal dust aerosol are of different size and can be measured separately using size selective sampling techniques.[4]

A major difference in diesel usage among underground mines is the requirement for exhaust gas cooling systems in coal and gassy noncoal mines. Nongassy mines usually employ limited exhaust conditioning in the form of catalytic converters, which have limited effect on primary exhaust particulate. The cooling system in most general use in gassy mines is the water scrubber. This device has little effect on most of the gases but removes particulate material from the exhaust.[5] Because of this, exhaust aerosol characteristics in nongassy mines are expected to be different. To see if size selective sampling techniques can be used in such mines, the Bureau and the University of Minnesota conducted a second study in three metal and nonmetal mines, two nongassy and one rated as gassy.

FIELD STUDIES

The field study conducted in metal and nonmetal mines is summarized in Table I. The table indicates each mine's geographical region, the material being mined, and the type of haulage equipment used. The studies consisted of collecting size-differentiated aerosol samples at four locations in a working section employing diesel haulage equipment: the air intake entry (I), beltway entry—where applicable (B), air return entry (R), and haulage way (H). These locations are illustrated in Figure 1 for the soda ash mine.

Aerosol samples were collected using Micro-Orifice, Uniform Deposit Impactor (MOUDI) and respirable dichotomous samplers.[4] The MOUDI, used for size distribution measurements, is a 10-stage cascade impactor with particle separation sizes at 15, 10, 5.62, 3.16, 1.78, 1.0, 0.562, 0.316, 0.178, and 0.1 µm plus an after-filter. The dichotomous sampler was used to collect aerosol for the elemental analysis used in the CMB model calculations. It consists of an impaction-type inlet designed to pass sample aerosol with an efficiency approximating the American Conference of Governmental Industrial Hygienists (ACGIH) respirable dust sampling criteria, followed by two MOUDI impaction stages, both with 0.7-µm separation sizes, plus an after-filter.[6] Configured in this way, the dichotomous sampler provides a partition of the collected respirable aerosol sample into two size fractions, greater and less than 0.7 µm in size. This partition was selected because it was close to the size found to separate diesel exhaust and coal dust aerosol components in laboratory studies and the impactor stages were available.[1] Both samplers operate with a 30 lpm sample flow rate.

Trace element profiles of mine aerosol sources used in the CMB analysis were obtained from samples of the material from which the diesel or mineral dust aerosols originate. Exhaust source aerosol samples were collected from the tailpipes of the haulage vehicles operating in the mine. Bulk material samples were collected of the mineral being mined. In each

Table I
Mine Data for Metal/Nonmetal Mines Visited 1985-1987

Mine	Region	Haulage	Type of Material
D	Midwest	Diesel	Shale
E	West	Diesel*	Soda Ash
F	West	Diesel	Quartzite

*Gassy mine, water scrubbers used on diesel equipment.

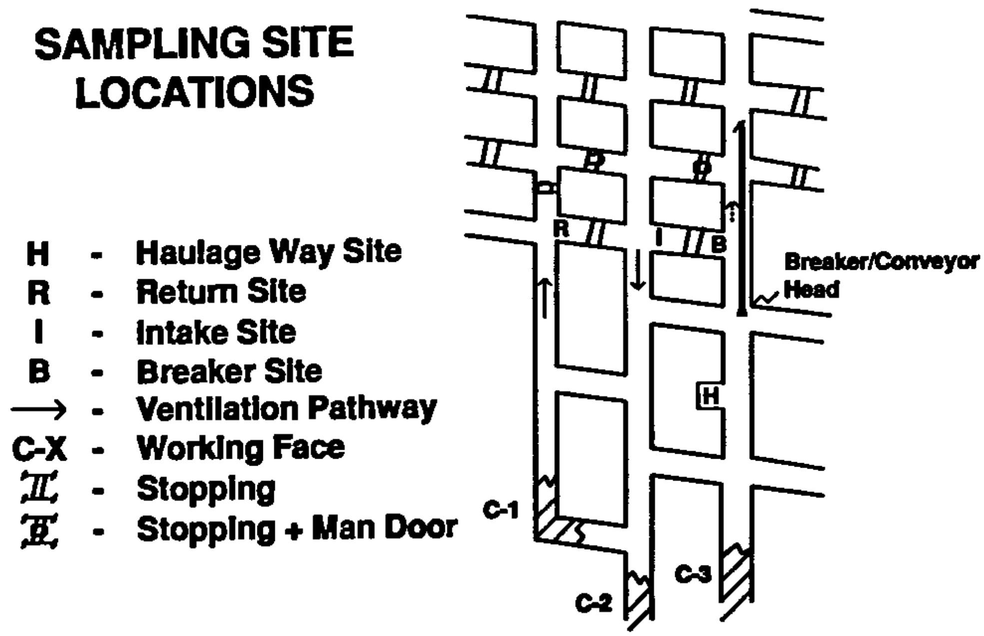

Figure 1. Sampling site locations used for in-mine sampling experiments are indicated together with ventilation vectors.

case, the profiles obtained are assumed to be representative of the aerosols originating from these sources.

To enhance the diesel tailpipe samples, a tracer material, a nominal 10 parts per billion of indium as indium 2,4 pentanedionate in xylene, was added to the fuel supply for the vehicles operating in the test section of the mines. The trace element analysis technique used, instrumental neutron activation analysis (INAA), is very sensitive to indium, which is rarely found in nature.[7]

Aerosol samples at haulage way or beltway locations were collected periodically during the entire mine work shift. Since they were collected in areas where workers are exposed, they are the samples of primary interest. Sample collection was only done when the conveyor belt was on and diesel haulage equipment was in use. The samples collected are therefore biased toward high concentrations of both diesel and mineral aerosol and are not representative personal exposure samples for the work shift. Although not analyzed for the study, sampling at the return location was conducted once during the shift, while the continuous miner was in operation.

Measurement and Analysis Techniques

Only two measurement techniques were used in the field study. These were gravimetric analysis of the impaction substrates and after-filters from both the MOUDI and dichotomous samplers and elemental analysis of the dichotomous samples using INAA.[3]

INAA was performed at the University of Rhode Island.[8] Analyses were performed on dichotomous substrates and after-filter pairs containing sufficient aerosol mass for irradiation (1 mg or more), quality control blanks of both substrate and after-filter, and samples of the aerosol source materials. The source materials were analyzed in triplicate, and average values for the resulting element concentrations were used in the CMB analysis.

Modal Analysis

Average aerosol size distributions measured in the haulage way of the diesel-equipped mines visited are shown in Figure 2. The measured aerosol size distributions were modeled using a sum of two log-normal functions to fit the data.[9] Each

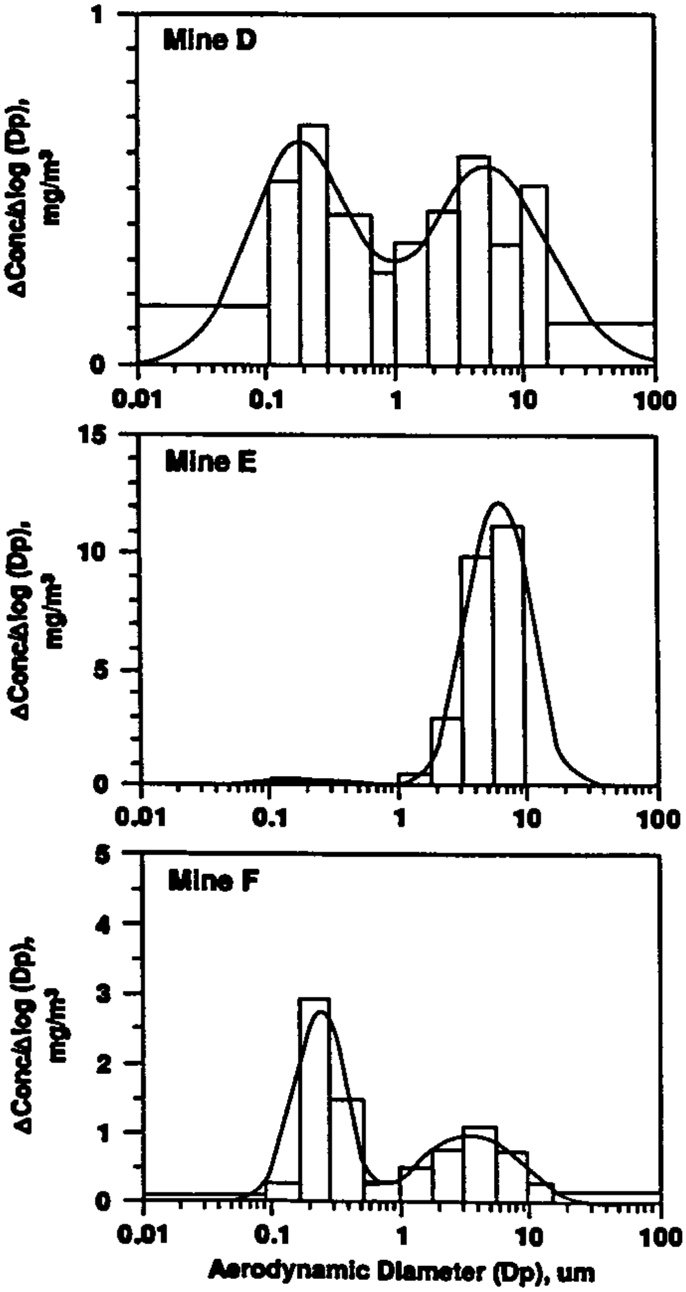

Figure 2. Average mass size distribution measured in the haulage entries of mines D, E, and F.

function represents one of the maxima, or modes, evident in the data. The log-normal distribution parameters, given in Table II for the average distributions, are the mass mean diameter (MMD), geometric standard deviation (σg), and mode concentrations.

For coal mines, each mode was identified with the aerosol contributed by a primary aerosol source diesel exhaust aerosol for the submicron mode and mineral dust for the coarse particle mode.[3] Under this assumption, the separate contributions from these sources to the total aerosol concentration can be determined using modal analysis. For these noncoal mines, the results of the size measurements are very similar. Two well-separated aerosol modes are evident for each of the mines. It remains for the CMB analysis to determine whether the same interpretation can be made.

CMB Model Analysis

CMB model analysis permits the relating of elements or chemical components in an aerosol sample collected at a given location to those same components in the sources of the aerosol.[10,11] The model is expressed as:

$$C_i = \sum_{j=1}^{p} a_{ij} S_j \qquad (1)$$

Here, p is the number of aerosol sources, C_i is the mass concentration of the ith elemental component of the sample in $\mu g/m^3$, a_{ij} is the fractional amount of component i in emissions from source j, and S_j is the amount of the aerosol mass concentration attributable to source j. S_j/(total sample mass concentration) is termed the source apportionment fraction. Apportionment of the source is achieved by measuring trace element component profiles of the aerosol sources, thus obtaining values for a_{ij}, analyzing the aerosol in the collected aerosol sample for the same components, and determining S_j using a least squares analysis of the overdetermined system of equations expressed by equation 1.

The CMB analysis used for the work employs effective variance weighing for the least squares calculation of the source apportionment terms S_j in equation 1.[3,11] In this analysis the S_j are determined by minimizing the following chi-square (X^2 function:

$$\chi^2 = \sum_i \frac{\left(C_i - \sum_j a_{ij} S_j\right)^2}{\sigma_c^2 + \sum_j \sigma_{a_{ij}}^2 S_j^2} \qquad (2)$$

Here σ_c is the standard error in C_i, and σ_a is the standard error in a_{ij}. The minimization was carried out using a direct search technique rather than matrix inversion calculations.

RESULTS

Average values for the CMB source apportionments are given for mines E, F, and G in Table III for the fine, sub-0.7 µm, and coarse, super-0.7 µm, portions of the dichotomous samples. Errors quoted in the table are more indicative of the variability of the results from sample to sample than of the true statistical errors. In each case diesel exhaust is the dominant component of the submicron aerosol, greater than 92%. These apportionments deviate from those of the coal

Table II

Summary of Log-normal Size Distribution Parameters for Average Aerosol Distributions Measured in Haulage Entries of Diesel Equipped Metal and Nonmetal Mines

Mine	Submicron			Coarse		
	Mass mean dia.[1] μm	Geometric std. dev[2] σg	Mode[3] conc. mg/m³	Mass mean dia.[1] μm	Geometric std. dev[2] σg	Mode conc. mg/m³
D	0.18 ± 0.03	2.5 ± 0.2	0.6 ± 0.2	5.1 ± 1.0	3.1 ± 0.3	0.7 ± 0.2
E	0.16 ± 0.13	2.4 ± 0.7	0.20 ± 0.06	6.1 ± 3.3	1.8 ± 0.3	7.5 ± 4.0
F	0.26 ± 0.04	1.6 ± 0.1	1.4 ± 0.3	3.8 ± 0.7	2.4 ± 0.3	1.1 ± 0.8

1 Mass Mean Diameter (MMD)
2 Geometric Standard Deviation (σg)
3 Mode concentration

Table III

CMB Source Apportionment Results for Mines E, F, and G

Mine	Source	RESPIRABLE SIZE FRACTION, %	
		SUB-0.7 μm	SUPER-0.7 μm
D	Diesel	94 ± 12	25 ± 20
	Ore	5.6 ± 0.8	75 ± 13
E[1]	Diesel	95 ± 7	<20
	Ore	4.9 ± 4.8	81 ± 7
F	Diesel	92 ± 12	40 ± 5
	Ore	<12	60 ± 5

1Gassy mine, wet scrubber used.

mine samples in that a significant fraction of the respirable coarse aerosol in the mines where diesel equipment does not use a wet scrubber is diesel—up to 40% for Mine F.[3] This translates to approximately 20% of the total diesel aerosol being greater than 0.7 μm in size.

Applying modal analysis to concurrent size distribution samples permits a comparison with the CMB analysis results. Table IV gives this comparison for coarse particle contamination of the sub-0.7 μm aerosol in the three diesel equipped metal and nonmetal mines. The two analyses give the same result, within the quoted errors.

Table IV

Average Coarse Particle Contamination of Sub-0.7 μm Samples for Mines E, F, and G

Mine	Analysis	
	Modal %	CMB %
D	4 ± 2	5.6 ± 0.8
E	<2	4.9 ± 4.8
F	2± 1	<12

CONCLUSION

Using the results of the limited CMB analysis, two points can be made concerning the contribution of the various diesel mine sources to both fine and coarse fractions of the respirable aerosol concentrations in the metal and nonmetal mine environment:

1. Diesel exhaust aerosols are the dominant component of the submicron mode aerosol measured in the diesel mines. More than 90% of the measured aerosols is contributed from diesel sources.

2. As much as 20% of the diesel exhaust aerosol contributes directly to the coarse part of respirable aerosol in the mine atmosphere.

It is not clear that the size selective technique used in the measurement of coal mine diesel aerosol can be extended to diesel-equipped metal and nonmetal mines. That technique depends on separating the collected aerosol sample into two size fractions at 0.8 μm.[4] In metal and nonmetal mines the substantial contribution to the respirable coarse fraction made by diesel exhaust aerosol compromises the use of size selective sampling, reducing the accuracy to less than 80%. As a result, alternate, carbon-specific, methods for determining diesel aerosol concentrations should be used in such mines if higher accuracy is desired. One such method is thermal-evolved gas analysis.[12] This technique permits analysis of the volatile, carbonate, and elemental carbon fractions of an aerosol sample. It should permit an unambiguous analysis of elemental carbon (soot) in a mine aerosol sample.

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