

## MEASUREMENT OF COAL DUST AND DIESEL EXHAUST AEROSOLS IN UNDERGROUND MINES

KENNETH L. RUBOW,\* Ph.D. • Bruce K. Cantrell,† Ph.D. • Virgil A. Marple,\* Ph.D.

\*Particle Technology Laboratory, Mechanical Engineering Department  
University of Minnesota, Minneapolis, MN 55455, USA

†U.S. Department of the Interior, Bureau of Mines, Minneapolis, MN 55417, USA

### ABSTRACT

In a cooperative study by the University of Minnesota and the U.S. Bureau of Mines, diesel exhaust and mineral dust concentrations have been measured for aerosols generated in the laboratory and in five underground coal mines. Three mines utilized diesel-powered haulage equipment and two used all-electric equipment. Two source apportionment techniques have been applied to differentiate between the mineral dust and diesel exhaust aerosol concentrations measured. The first technique, using a micro-orifice, uniform deposit impactor (MOUDI) for size selective sampling, is based on modeling aerosol size and the premise that the diesel exhaust portion of the aerosol is predominantly submicron and the mineral dust portion is mostly greater than one micrometer in size. The second technique, Chemical Mass Balance (CMB) modeling, was used to referee the analysis of diesel exhaust and mineral dust aerosol concentrations from the size selective sampling results.

The MOUDI size distribution data were modeled to obtain parameters describing the fine and coarse fractions of the sampled aerosol and to estimate the contributions to each mode from both mineral dust and diesel exhaust aerosol sources. The results showed the size distribution of the mixed aerosols exhibited two definite modes with the minimum between the modes occurring at 0.8  $\mu\text{m}$ . Less than 5 pct of the coal mine diesel aerosol was found in the coarse size fraction. CMB analysis confirms the original premise for using aerosol size to separate diesel exhaust and mineral dust aerosol during sampling.

Based on the results from the size selective sampling, a personal diesel aerosol sampler has been developed for measuring diesel aerosol mass concentrations. This sampler uses an inertial impactor to size separate the respirable aerosol at 0.8  $\mu\text{m}$ . All material less than 0.8  $\mu\text{m}$  is collected on an afterfilter for subsequent gravimetric analysis.

### INTRODUCTION

Measurement of the contribution of diesel exhaust to respirable aerosol in mine environments has become increasingly important because of recent research which suggests that exposure to diesel exhaust particulate matter may have adverse occupational health effects. To support these efforts, the U.S. Bureau of Mines is developing and evaluating new sampling methods for the measurement of diesel aerosol in underground coal mines.

Two of these techniques are size selective sampling and chemical mass balance modeling (CMB). Size selective sampling, is being adapted for diesel aerosol sampling by the Particle Technology Laboratory (PTL) of the University of Minnesota under sponsorship by the.<sup>1</sup> 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.

The second technique, CMB, is an alternative measurement technique used to referee the results obtained using size selective sampling.<sup>2</sup> It compares elemental 'finger prints' of the aerosol sources with similar profiles measured for mine aerosol samples. From this the portions of the sample contributed by each source can be determined.

The Bureau and the PTL have conducted a study in five coal mines using both size selective sampling and the CMB techniques. This study was undertaken as a follow-on to the laboratory study of size selective sampling applied to the measurement of diesel aerosol.<sup>1</sup> The results from the laboratory and field studies are summarized in this paper. The design of a prototype personal diesel aerosol sampler, based on the size selective results, is also presented.

### LABORATORY EXPERIMENT

Laboratory experiments were conducted to investigate the

feasibility of using the Micro-Orifice, Uniform Deposit Impactor (MOUDI) to measure the size distribution of aerosols containing various mixtures of coal dust and diesel exhaust aerosols.<sup>1</sup> The objective of the work was to determine the mass concentration of diesel exhaust aerosol in an airborne mixture of coal dust and diesel exhaust aerosol from the size distribution of the mixed aerosol. A prototype seven stage MOUDI with cut sizes ranging from 0.1 to 10  $\mu\text{m}$  was used.<sup>3</sup>

The experiment successfully demonstrated that coal dust and diesel exhaust aerosol can be separated and measured on the basis of size. Data from the tests, typified in Figure 1, show that the overall diesel exhaust/coal aerosol size distribution is bimodal with the diesel exhaust (accumulation) mode aerosol having a mass median aerodynamic diameter (MMD) of approximately 0.15  $\mu\text{m}$ . The coal (coarse particle) mode has a MMD in the 3 to 10  $\mu\text{m}$  size range. A clear separation between the two modes exists in the 0.7 to 1.0  $\mu\text{m}$  size range with the minimum near 0.8  $\mu\text{m}$ . Analysis of a combined size distribution permits a quantitative determination of the diesel aerosol contribution to within 15%.

## FIELD STUDIES

The five mines visited during the field study are summarized in Table I. The table indicates each mine's geographical region, coal type being mined, and type of haulage equipment used. Three of the mines, A, B, and H were equipped with diesel haulage equipment and C and G had all electric equipment. The electric equipped coal mines were used to generate comparison samples for a mine environment without diesel aerosol.

Measurements consisted of collecting size differentiated aerosol samples at four locations in longwall development sections employing a continuous miner: in the air intake entry, conveyor beltway entry, air return entry, and haulage way. A ten stage MOUDI was used for most of the field size distribution measurements and a dichotomous sampler was used to collect aerosol for the elemental analysis used in the CMB model calculations. The samplers and CMB analysis are described elsewhere.<sup>2,4</sup> Both samplers were operated at a flow rate of 30 lpm.

Aerosol samples were collected at the intake and haulage or beltway locations periodically during each mine work shift. Sampling at the return location was usually conducted only once during the shift, while the continuous miner was in operation. Samples of primary interest were those collected at the conveyor belt or in the haulage way since they are from areas where workers are exposed. These were collected only when the breaker was on and diesel haulage equipment was in use. As a result, no attempt was made during the field experiments to take representative exposure samples for the work shift. The focus of the study was on developing a method for measuring the diesel component of a mine aerosol containing a mixture of both diesel exhaust particulate and mineral dust.

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.

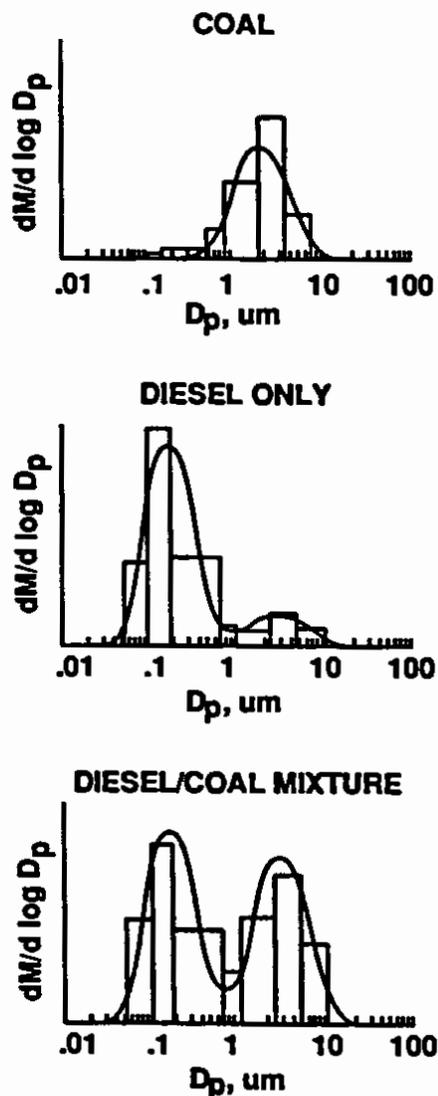


Figure 1. Laboratory diesel/coal dust size distributions.

Bulk material samples were collected of coal and the rock dust used in the mine as an explosion and fire retardant. For the diesel equipped mines visited, exhaust source aerosol samples were collected from the tailpipes of the haulage vehicles operating in the mine. In each case, the assumption is made that the profiles thus obtained are representative of the aerosols originating from these sources.

Where collection of diesel tailpipe aerosol samples was not feasible, diesel fuel and diesel lubricating oil were collected to use as a surrogate for the diesel exhaust aerosol source.<sup>5</sup> To enhance the use of diesel fuel as a surrogate for diesel aerosol emissions, 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), was performed by the University of Rhode Island.<sup>6</sup>

## FIELD MEASUREMENT RESULTS

Average aerosol size distributions measured in the haulage

Table I  
Mine Data for Operations Visited FY 85-87

Mine	Region	Haulage	Coal Rank
A	West	Diesel	HVB* C <sup>1</sup>
B	West	Diesel	HVB C <sup>2</sup>
C	East	Electric	HVB B <sup>1</sup>
G	East	Electric	HVB A <sup>3</sup>
H	Midwest	Diesel	HVB B <sup>3</sup>

\* HVB - High Volatile Bituminous

#### Sources

<sup>1</sup> Based on ASTM Standards.

<sup>2</sup> Company information

<sup>3</sup> 1987 Keystone Coal Industry Manual. McGraw-Hill, Inc., New York, 1987, 1244 pp.

way of the diesel equipped and all-electric coal mines are shown in Figures 2 and 3. The MOUDI separates and collects the sampled aerosol in several size intervals by aerodynamic diameter. The number of size intervals provides enough differential size resolution to model the measured aerosol size distributions with empirical functions. This analysis, termed modal analysis, uses a sum of two log-normal functions to fit the data.<sup>7</sup> Each 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 ( $\sigma_g$ ) and mode concentrations.

Each mode can be identified with the aerosol contributed by a primary aerosol source; diesel exhaust aerosol for the sub-micron mode and mineral dust for the coarse particle mode. Under this assumption, the separate contributions from these sources to the total aerosol concentration can be determined using modal analysis. Treating each mode as a source connected entity, also permits the determination of that portion of the coarse particle mode that encroaches on a sample of submicron mode aerosol as it might be collected by a size selective sampler. This is done by integrating the distribution function for the coarse particle mode over the range of sizes for which the submicron mode aerosol is collected. An illustration of such modal overlap for the average diesel/coal size distribution of Figure 2 is given in Figure 4. The range of integration is 0.001 to 0.8  $\mu\text{m}$ . Shaded areas indicate the portion of the submicron and coarse aerosol that will contribute to a sub-0.8  $\mu\text{m}$  sample.

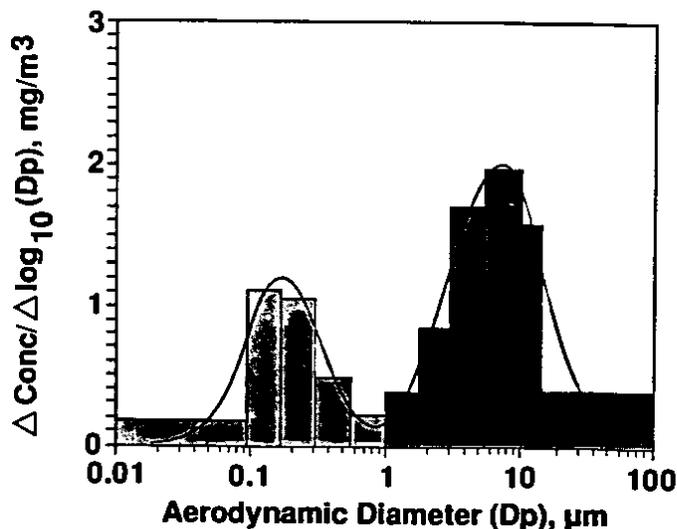


Figure 2. Average mass size distribution measured in the haulage entries of diesel equipped coal mines.

A comparison between modal and CMB analysis results is given in Table III. Values from the modal analysis for the fraction of sub-0.7  $\mu\text{m}$  aerosol contributed by the coarse particle mode are  $7 \pm 5\%$  for mine A,  $15 \pm 7\%$  mine B, and less than 2% for mine H. Results for mine A and H are well within each others stated variability. There is a barely resolvable difference between the two analysis results for

Table II  
Summary of Log-normal Size Distribution Parameters for Average Aerosol Distributions Measured in Haulage Entries of Diesel Equipped and All-electric Coal Mines

Mine Type	Submicron			Coarse		
	Mass Mean Dia. <sup>1</sup> um	Geometric Std. Dev. <sup>2</sup>	Mode <sup>3</sup> Conc. mg/m <sup>3</sup>	Mass Mean Dia. um	Geometric Std. Dev.	Mode Conc. mg/m <sup>3</sup>
Diesel	0.17±0.04	2.0±0.3	0.88±0.52	6.8±1.6	2.3±0.3	1.8±0.8
Electric	0.46±0.10	2.6±0.9	0.06±0.04	7.2±2.0	2.0±0.3	1.2±0.8

<sup>1</sup> Mass Mean Diameter (MMD)

<sup>2</sup> Geometric Standard Deviation ( $\sigma_g$ )

<sup>3</sup> Mode Concentration

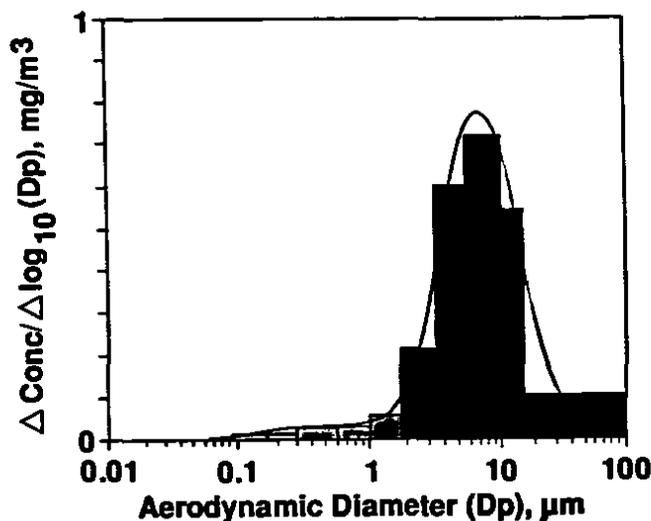


Figure 3. Average mass size distribution measured in the haulage entries of all-electric equipped coal mines.

mine B. This difference may be due to the limited number of samples analyzed.

Using the results of the limited CMB analysis, two key points can be made concerning the contribution of the various diesel mine sources to fine and coarse aerosols in the mine environment. These are:

1. Diesel emissions aerosol is the dominant component of the submicron mode aerosol measured in the diesel mines. From 75 to 90% of the measured aerosol concentration is contributed from diesel sources.
2. Coal is the primary component of the coarse aerosol, as much as 92%.

Table III  
Average Coarse Particle Contamination of Sub-0.7  $\mu\text{m}$  Samples for Mines A, B and H

Mine	Analysis	
	Modal %	CMB %
A	7±5	<8
B	15±7	25±4
H	<0.2	<4

These points confirm the basic assumptions advanced to justify the use of the MOUDI or other size selective sampler to separate and measure diesel and mineral dust aerosol in the mine environment. Separate confirmation for the assumption that the mineral aerosol contributes predominantly in the coarse aerosol size range is found in the average size distribution measurement results for the all-electric equipped coal mines in Figure 3.

The optimum particle size for the separation of diesel from mineral dust aerosol was determined from the average size distribution measured in the haulage entries of the three mines using diesel equipment. This analysis treated the submicron mode as entirely diesel aerosol and the coarse particle mode as entirely mineral. Integrating the log-normal functions that describe the size distribution modes from zero up to a given size, as illustrated in Figure 4, the aerosol mass that would be collected by a sampler with that separation size was determined. Using these results, the gravimetric error made by assigning the aerosol mass collected by the sampler to diesel aerosol alone was calculated as a function of separation size. The least error,  $\pm 7\%$ , occurs for size separation at 0.8  $\mu\text{m}$ .

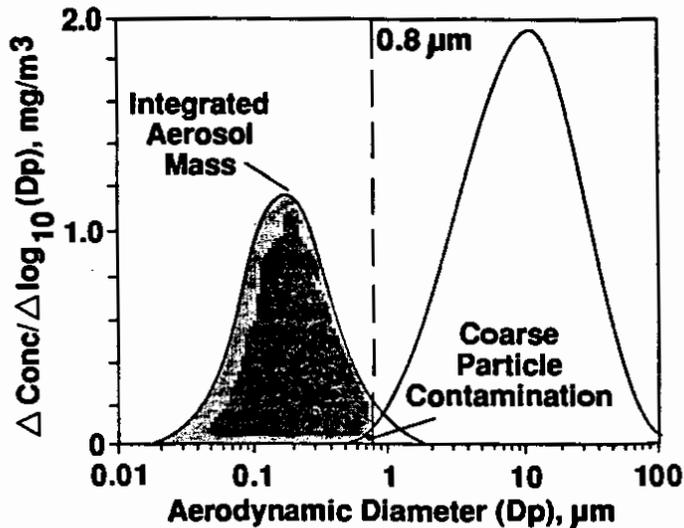


Figure 4. Illustration of the integration of aerosol mode functions to calculate aerosol mass less than 0.8  $\mu\text{m}$ .

### PERSONAL DIESEL AEROSOL SAMPLER

A prototype personal diesel exhaust aerosol sampler has been designed for underground coal mines. The sampler was designed on the premise that size selective sampling techniques can be used to separate diesel exhaust aerosol, which is predominantly submicron in size, from coal dust aerosol, which is mostly greater than a micron in size. The sampler has three stages and employs inertial impaction for particle separation. The first, sample inlet/preclassifier, stage is a composite impactor with an aerosol penetration efficiency that conforms to either the American Conference of Industrial Hygienists (ACGIH) or the British Medical Research Council (BMRC) respirable dust sampling criteria. This first stage serves as a preclassifier to select the respirable portion of the sample aerosol and prevent overloading of the second stage. The second stage is a multiple-orifice impactor with a sharp separation or cut size that passes only aerosol smaller than 0.8  $\mu\text{m}$ . The respirable aerosol larger than 0.8  $\mu\text{m}$  is deposited on an impaction plate. The third stage, which is a filter, collects all aerosol less than 0.8  $\mu\text{m}$  aerodynamic diameter. This instrument is a research prototype and the design permits the second stage impaction substrate to be removed for gravimetric and chemical analysis. To increase the amount of sample for such analysis, the sample flow rate for the prototype will be 4 lpm. The sampler can be modified for the DORR-OLIVER 10 mm cyclone preclassifier and a flow rate of 2 lpm.

A schematic diagram of the sampler is presented in Figure 5. The sampler inlet is a 2.5 cm. ring of nozzles in the sampler cover. These nozzles are part of a preclassifier/impactor with an aerosol collection efficiency that can approximate either the ACGIH or the BMRC respirable dust sampling criteria.<sup>8</sup> The impaction surface for this first section is a porous plate impregnated with oil to reduce particle bounce and blow off. A sample stream next passes to a multiple-orifice impactor with a cutpoint of 0.8  $\mu\text{m}$ . The impaction plate for this stage is a removable aluminum foil

coated with silicone oil. The sample stream then passes through a filter which removes the remaining aerosol. Sampler height is 2.5 cm. The sampler divides the respirable aerosol into two size fractions, greater and less than 0.8  $\mu\text{m}$ . These samples can be used to measure the concentrations of the diesel and mineral dust portions of respirable coal mine aerosol.

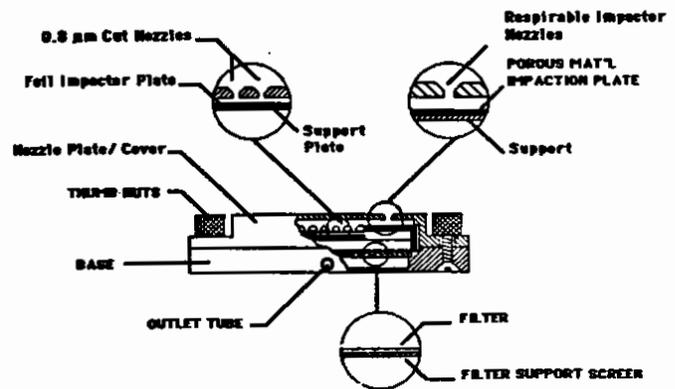
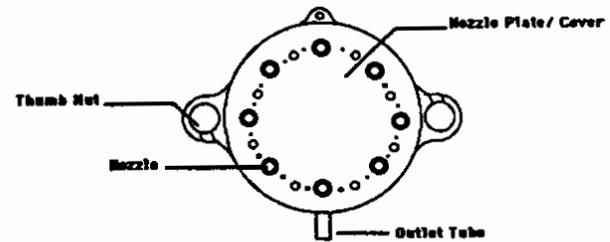


Figure 5. Schematic diagram of personal respirable/diesel aerosol impactor sampler.

The primary limitations on a personal diesel sampler based on size selective sampling are diesel aerosol loss from the sample, contamination by coarse particle mode aerosol, and resolution of the gravimetric analysis performed on the sample. Of secondary importance is the presence of background aerosol in the sample. The latter is due to external diesel, atmospheric, or nondiesel sources of submicron aerosol. The final sample contains most of the diesel particulate material present in the mine air plus a small amount of mineral dust, usually less than 10%. If a sample flow rate of 2 lpm is used and gravimetric analysis is to within 0.1 mg, a sub-0.8  $\mu\text{m}$  aerosol concentration should have a limit of detection of 0.3  $\text{mg}/\text{m}^3$ .

### CONCLUSIONS

The primary result from this study is that size selective sampling can be effective as a technique for measuring diesel aerosol concentrations in underground coal mines. The MOUDI size distribution data were modeled to obtain parameters describing the fine and coarse fractions of the sampled aerosol and to estimate the contributions to each mode from both mineral dust and diesel exhaust aerosol

sources. The results showed the size distribution of the mixed aerosols exhibited two definite modes with the minimum between the modes occurring at 0.8  $\mu\text{m}$ . CMB analysis confirms the original premise for using aerosol size to separate diesel exhaust and mineral dust aerosol during sampling.

A personal diesel aerosol sampler has been developed for measuring the diesel aerosol concentration in underground coal mines. This device consists of three sequential stages. The first stage classifies aerosol in the sample stream according to the BMRC respirable efficiency curve. The second stage separates the resulting respirable aerosol into two parts by aerodynamic diameter using a single stage impactor with a cutpoint of 0.8  $\mu\text{m}$ . The third stage collects the <0.8  $\mu\text{m}$  diameter aerosol on a media that is suitable for gravimetric analysis.

## REFERENCES

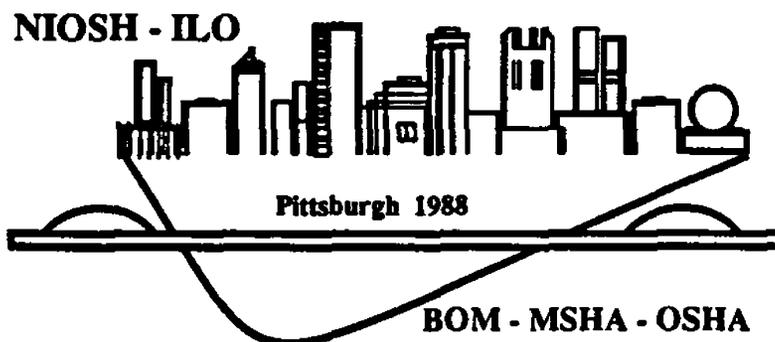
1. Marple, V.A., Kittelson, D.B., Rubow, K.L. and Fang, C.P.: *Methods for the Selective Sampling of Diesel Particulate in Mine Dust Aerosols*. BuMines OFR 44-87, NTIS PB88-130810, Washington (1986).

2. Cantrell, B.K.: Source Apportionment Analysis Applied to Mine Dust Aerosols: Coal Dust and Diesel Emissions Aerosol Measurement. *Proc. 3rd Mine Vent Symp.*, pp.495-501. Soc. Mining Eng., State College, PA, (1987).
3. Marple, V.A. and Rubow, K.L.: *Development of a Micro-Orifice Uniform Deposit Impactor*. U.S. Dept. of Energy, No. DOE/PC/61255, Wash. D.C. (1984).
4. Cantrell, B.K. and Rubow, K.L.: Mineral Dust and Diesel Aerosol Measurements in Underground Metal and Non-metal Mines. Proceedings of the VIIth International Pneumoconioses Conf. *National Institute for Occupational Safety and Health et. al.*, Pittsburgh, PA (1988).
5. Pierson, W.R. and Brachaczek, W.W.: Particulate Matter Associated with Vehicles on the Road. II. *Aerosol Sci. and Tech.*, 2:1-20 (1983).
6. Rahn, K.A.: *The Chemical Composition of the Atmospheric Aerosol*. University of Rhode Island, Tech. Rpt, Narragansett, RI, (1976).
7. Whitby, K.T. *Modeling of Atmospheric Aerosol Particle Size Distributions*. U.S. EPA Grant Rpt, No. R800971, (1975).
8. Marple, V.A. and McCormack, J.E.: Personal Sampling Impactor with Respirable Aerosol Penetration Characteristics. *Am. Ind. Hyg. Assoc. J.*, 44:916-922 (1983).

ACKNOWLEDGEMENTS: This research has been partially supported by the Department of the Interior's Mineral Institute program administered by the Bureau of Mines through the Generic Mineral Technology Center for Respirable Dust under grant number G 1135142. The authors would also like to acknowledge the assistance of Dr. Kenneth Rahn and his staff in performing the INAA used in this work.

*Proceedings of the VIIth International Pneumoconioses Conference*  
*Transactions de la VIIe Conférence Internationale sur les Pneumoconioses*  
*Transacciones de la VIIa Conferencia Internacional sobre las Neumoconiosis*

Part **I**  
Tome  
Parte



Pittsburgh, Pennsylvania, USA—August 23–26, 1988  
Pittsburgh, Pennsylvanie, États-Unis—23–26 août 1988  
Pittsburgh, Pennsylvania EE. UU—23–26 de agosto de 1988



**U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES**  
Public Health Service  
Centers for Disease Control  
National Institute for Occupational Safety and Health



## **Sponsors**

**International Labour Office (ILO)**  
**National Institute for Occupational Safety and Health (NIOSH)**  
**Mine Safety and Health Administration (MSHA)**  
**Occupational Safety and Health Administration (OSHA)**  
**Bureau of Mines (BOM)**

**September 1990**

## **DISCLAIMER**

**Sponsorship of this conference and these proceedings by the sponsoring organizations does not constitute endorsement of the views expressed or recommendation for the use of any commercial product, commodity, or service mentioned.**

**The opinions and conclusions expressed herein are those of the authors and not the sponsoring organizations.**

**DHHS (NIOSH) Publication No. 90-108 Part I**