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METHODS FOR THE SELECTIVE SAMPLING OF DIESEL PARTICULATE IN MINE DUST AEROSOLS

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Particle Technology Laboratory

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16. Abstract (Limit: 200 words)

This paper describes an investigation into time-integrated and real-time methods for determining the diesel exhaust particulate concentration in underground mines, particularly coal mines. The microorifice uniform deposit impactor is recommended for obtaining the time-integrated measurement of the size distribution. The mass concentration of diesel exhaust particles can be obtained from the particle size distribution of mine aerosols. On a mass basis, diesel exhaust particles are primarily in the submicrometer size range while coal dust particles are larger. Size distribution measurements made in the laboratory and in three underground coal mines exhibited two distinct modes with the diesel exhaust particles in the smaller particle mode and the coal particles in the larger particle mode. The point of separation between the two modes occurred in the 0.7- to 1.0-µm size range. The separation was found to be independent of mass fraction of the diesel exhaust particles, particle concentration and sampling site. Methods recommended for further consideration as real-time monitors of diesel exhaust aerosols in mines are photometers and filter pressure drop techniques. A preclassifier would be required in both cases to separate the larger dust particles from the sample.

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Mining research

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Particles	Diesel
Instrumentation	Sampling

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Diesel and mine dust measurement

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FOREWORD

This report was prepared by the University of Minnesota, Department of Mechanical Engineering, Minneapolis, Minnesota, under USBM Contract Number J0145022. The contract was initiated under the Coal Mine Health and Safety Program. It was administered under the technical direction of Pittsburgh Research Center with Mr. Kenneth L. Williams acting as the Technical Project Officer. Ms. Gladys Barrera was the Contract Administrator for the Bureau of Mines. This report is a summary of the work recently completed as part of this contract during the period August 27, 1984 to July 26, 1986. This report was submitted by the authors on October, 1986.

Reference to specific brands, equipment, or trade names in this report is to facilitate understanding and does not imply endorsement by the Bureau of Mines.

This report contains no patentable features.

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CHAPTER 1

EXECUTIVE SUMMARY

1.1 Background

As a consequence of the increased usage of diesel-powered equipment in underground coal and noncoal mines, there is greater interest in finding an instrument or measurement technique to quantify the contribution of diesel exhaust particles to the overall respirable aerosol concentration. The use of mobile, diesel-powered mining equipment is widespread in noncoal mines and is being increasingly employed in coal mines. The exhaust from these diesel engines contains particles which, along with the particles from mineral sources, become the aerosol to which the miners are exposed. Since the diesel exhaust particles are rather small, typically 85% to 95% submicrometer diameter, they can contribute significantly to the quantity of respirable matter. This contribution can be as high as 60% to 90% of the respirable mass to which workers are exposed (Knight, 1980; Rienbold, 1979).

One procedure for reducing the quantity of respirable particles to which miners are exposed is to control the emissions at the source. However, what is not readily known is the contribution of the diesel exhaust particles to the overall respirable aerosol. Thus, a sampling method or instrument which selectively measures the quantity of diesel exhaust particles in the respirable size range is needed.

1.2 Purpose and Scope of the Contract

The University of Minnesota under contract to the U. S. Bureau of Mines has investigated the feasibility of using the microorifice uniform deposit impactor (MOUDI) to measure the size distribution of aerosols containing various mixtures of coal dust and diesel exhaust aerosols. The objective of the work was to determine if the relative mass concentration of diesel exhaust particles, in an airborne mixture of coal dust and diesel exhaust particles, can be determined from the size distribution of the mixed aerosol. In general, the mass of diesel exhaust particles is attributable to submicrometer size particles while that of the coal dust to the larger particles. With the MOUDI, the particle size distribution is determined with the diesel exhaust and coal particles separated on the basis of their aerodynamic equivalent diameters, a parameter of importance from the standpoint of human health effects. A seven stage MOUDI with cut sizes ranging form 0.1 to 10 micrometer was used.

As this contract was written, the first six months were to be devoted to a literature search, laboratory investigations, and recommendations of sampling methodology, with the next 12 months spent providing technical assistance to the Bureau of Mines during the field study phase. The field study phase involved implementation of the recommended instrumentation and test plan.

This report summarizes activities performed during the contract. Each chapter deals with one of the major contract tasks. These tasks are:

Chapter 2 - Literature review of the coal and diesel exhaust particle size distributions and instrumentation to monitor each type.

Chapter 3 - Laboratory studies to determine feasibility of using MOUDI to separate the diesel exhaust and coal dust fractions in mixed aerosol.

Chapter 4 - Evaluation of two photometers for use as possible monitors of the diesel exhaust and mineral related particle concentrations.

Chapter 5 - Recommended methods, instruments and test plan for measurement of diesel exhaust and mineral related particles in underground mines.

Chapter 6 - Results from field studies.

1.3 Results

The MOUDI has been successfully shown to separate coal from diesel exhaust aerosols. Data from both laboratory and field tests 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 µm. The coal (coarse particle) mode has a MMD in the 3 to 10 µm size range. A clear separation between the two modes exists in the 0.7 to 1.0 µm size range with the minimum in the vicinity of 0.8 µm. This primary finding is supported by test results from both laboratory and field sampling.

A summary of the literature review is presented in Chapter 2. The size distribution characteristics of diesel exhaust particles and coal mine dust are given. Research has shown that the size distributions of each aerosol type, when measured independently of the other, are significantly different. On a mass basis, diesel exhaust particles are essentially all less than about 1 µm while coal dust particles are greater than about 1 µm. Lastly, various instruments capable of monitoring the diesel exhaust and/or coal dust concentrations were reviewed.

Extensive laboratory tests were performed to determine if the MOUDI could be used to separate diesel exhaust from coal dust particles on the basis of particle size. These tests were performed by varying the amount of coal dust and diesel exhaust in a sampling manifold. These results, as reported in Chapter 3, show that the size distributions of the diesel exhaust/coal aerosol mixture exhibit two definite modes with the minimum between the two modes in the 0.7 to 1.0 µm size range.

Evaluations of two photometers, i.e the GCA RAM-1 and Metrex Mineral/Diesel Photometer are presented in Chapter 4. These photometers were considered as possible candidates to selectively measure the diesel exhaust and mineral-related dust mass fractions in real-time. The response of the GCA RAM-1 to coal and diesel exhaust particles was theoretically determined as a function of particle size. The results show that the response is highly dependent on particle size. The response of the Metrex photometer was experimentally determined for both coal and diesel exhaust particles. Three photometers were used in these tests. Due to various electronic problems with these units, only limited data could be obtained. Consequently, no conclusions can be made as to the applicability of the Metrex photometer.

Chapter 5 describes the recommended instruments, sampling methodology and test plan for the in-mine verification of the laboratory findings. The MOUDI was recommended as the sampler to obtain the time-integrated measurements and to be used in the field studies. For the real-time measurement, photometers, such as the GCA RAM-1 and MINIRAM used in combination with a preclassifier and possibly the Metrex Mineral/Dust Photometer were recommended for further considerations.

The results of the field study are presented in Chapter 6. Tests were conducted in three underground coal mines, two utilizing diesel-powered equipment and the third exclusively using electric equipment. A total of 28 size distributions were obtained in the two diesel mines and 17 in the electric mine. The sampling sites included the primary intake and return to the section, the beltway and a haulage way. These sites were selected in an attempt to obtain a wide variety of diesel exhaust and dust concentrations. The results, in all cases, clearly show a separation between the diesel exhaust and dust (coal and rock) modes with a minimum in the 0.7 to 1.0 μm size range.

1.4 Recommendation for Future Work

This project showed that the concentrations of diesel exhaust and coal dust aerosol in underground coal mines can be individually obtained by first separating the two aerosol types on the basis of particle size. The key to making this separation is the location of the separation point.

Future work should be in the areas of:

1. Perform field tests in noncoal mines employing diesel-powered equipment to determine if there still exists clear separation in the diesel exhaust and mineral particle size distribution modes. If this separation does exist, determine at what particle size separation occurs.

2. Determine the effect of diesel exhaust scrubbers on the removal of the larger diesel exhaust particles. Laboratory tests showed that approximately 10% of the diesel exhaust particle mass occurs in the size range above 1 μm. However, these larger particles were not observed in the field studies. Presumably, the larger particles were removed in the scrubbers used on the mining equipment. The elimination of the larger particles enhance the separation of the coal and diesel exhaust particles.

3. Develop an instrument package for separating particles on the basis of size, and next measuring the mass concentrations of the coarse and fine aerosol fractions, i.e. the mineral dust and diesel exhaust particle fractions.

4. Perform more field measurements of the diesel exhaust size distribution in underground mines if a photometer is to be used as the mass sensing device in the instrumentation package discussed in item (3). This work would determine the variability of this size distribution. This variability is important for photometric mass measurements as the response of a photometer is very dependent on particle size.

5. Reevaluate the Metrex photometer if the manufacturer eliminates the electronic problems.

6. Investigate the development of the filter pressure drop method, used in conjunction with a preclassifier to separate course particles, as an inexpensive real-time method for measuring diesel exhaust particles in mines. This method needs considerable development, however.

CHAPTER 2

LITERATURE REVIEW

The literature search involved obtaining information in two areas: size distributions of coal mine dust and diesel exhaust particles reported in the literature and possible real-time or near real-time measurement techniques which could be used to detect the diesel exhaust aerosol component in the mine aerosol.

A computer-assisted literature survey was conducted. Two key word searches were performed, one for coal mine dust-related information and the other for information pertaining to the size distribution and measurement techniques of diesel exhaust particulate matter. The key words and logic used in the search are listed in Figures 2.1 and 2.2. Data bases included were the National Technical Information Service (NTIS), Compendex and Engineering Meetings of the Engineering Index, Pollution Abstracts and MEDLINE data bases. MEDLINE is a medical data base which includes papers published in industrial hygiene and occupational health related journals.

2.1 Types of Size Distributions

Figure 2.3 shows a typical atmospheric particle size distribution. These distributions are in general trimodal (Whitby, 1978), consisting of a nuclei mode (0.005 to 0.1 μm diameter size range), an accumulation mode (0.1 to 2.0 μm diameter size range), and a coarse particle mode (2.0 to 50 μm diameter size range). The origins of the particles in each mode, as shown in the figure, result from different aerosol formation mechanisms. Analysis of workplace aerosols shows similar types of modes (Whitby, 1983).

The nuclei mode is associated with nucleation of low vapor pressure materials (e.g., lead salts, carbon, sulfuric acid) and is generally observed near emission sources. Particles in this mode tend to grow quickly by condensation and coagulation and may eventually become part of the accumulation mode.

The accumulation mode is formed by coagulation of nuclei mode particles and by nucleation and condensation of moderate vapor pressure materials like photochemical smog products. It may also be fed by heterogeneous gas to particle conversion processes. The accumulation mode is very stable. Once in the accumulation mode size range, further growth is greatly retarded and removal processes, such as settling and deposition, for particles in this size range are slow. Diesel exhaust particulate matter is primarily in this mode.

The course particle mode does not interact strongly with either of the two smaller diameter modes. The particles in this mode are formed by mechanical processes such as atomization, grinding, impacting, cutting and redispersion of powders and dusts. Some examples of such particles in the atmosphere are wind blown dusts, resuspended roadway debris, and salt particles from sea spray. Coarse particles are removed from the atmosphere mainly by sedimentation. Mine generated dusts are generally in the course particle mode.

Term Set A	Term Set B	Term Set C	Term Set D
Coal	Mine	Particle	Inhalation
Anthracit*	Mines	Particulate	Respirable
Bituminous	Mining	Dust	Sampl*
		Aerosol	Collect*
		Diesel Exhaust	Monitor*
		Diesel Fumes	Size
			Distribut*
			Concentration
			Morpholog*
			Structur*
			Compostion

LOGIC: A and B and C and D

* Root word truncated

Figure 2.1 Keywords and logic for coal mine particle literature search.

Term Set A	Term Set B	Term Set C
Diesel	Particle	Collect*
	Particulate	Monitor*
	Aerosol	Sampl*
		Measur*
		Concentrat*

LOGIC: A and B and C

* Root word truncated

Figure 2.2 Keywords and logic for diesel exhaust particle literature search.

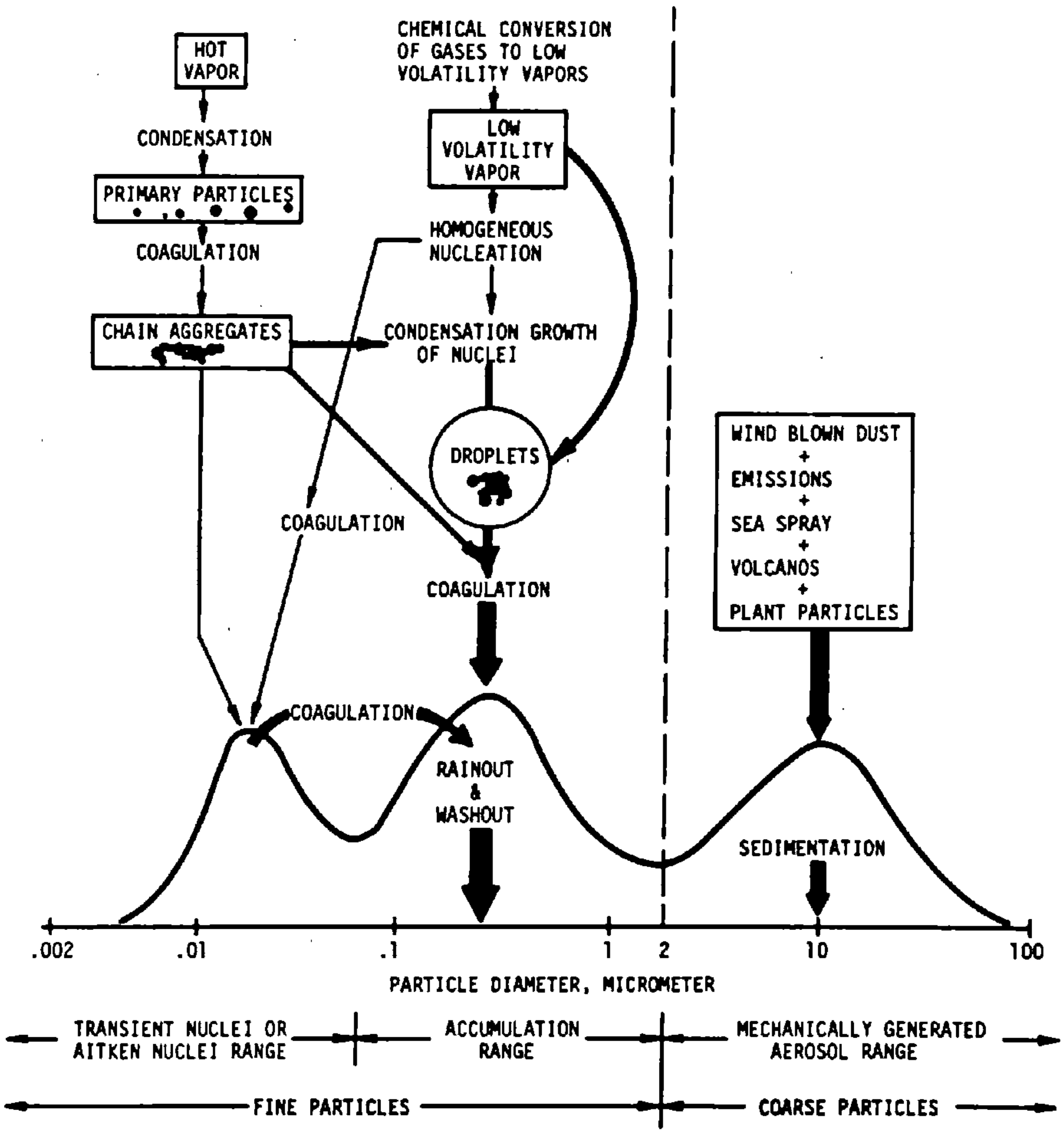


Figure 2.3 Trimodal atmospheric size distribution (Whitby, 1978).

Figure 2.4 shows three coarse particle size distributions. These distributions represent the size distribution of a freshly generated dust, the effect of particle loss on the distribution due to sedimentation and removal of the larger particles, and the respirable portion of the size distribution after the large nonrespirable particles have been removed in the respiratory tract.

2.2 Diesel Exhaust Particle Characteristics

Diesel exhaust particles are produced in a variety of sizes, shapes, and structures. Lipkea et al. (1979) have identified the major classes of particles as: solid/liquid, solid chain aggregates, liquid sulfate particles, liquid hydrocarbon particles, and solid chain agglomerate particles with high molecular weight organic compounds and/or inorganic species adsorbed on their surfaces. Of these, the two most important classes appear to be: (a) solid chain agglomerates of more or less spherical carbonaceous particles which contain adsorbed organic material and some inorganic material, and (b) liquid, or often, solid hydrocarbonaceous spheres. Both of these classes of particles are in the submicrometer diameter size range. The relative abundance of these particles appear to be related to the amount of extractible material associated with the exhaust particles (Dolan et al., 1980). The chain agglomerates are formed by coagulation of carbonaceous particles formed relatively early in the combustion process. These agglomerates show considerable fusing of the individual, roughly spherical particles of which they consist. This probably results from continuing condensation growth on the surfaces of the particles after they have coagulated (Amann et al., 1980). On the other hand, the spherical hydrocarbonaceous particles are probably formed by condensation processes fairly late in the combustion cycle.

The particle size distribution of diesel exhaust particles has an important influence on their environmental impact for several reasons:

a. Adsorption of gaseous pollutants on the surfaces of the particle depends upon the surface area, and thus, the size of the particles. The particle may then aid in transporting these adsorbed materials into the human respiratory system. These adsorbed materials may be reactive. Novakov (1980) has suggested that carbon particles may be catalytic, whereas Anderson (1980) has shown that photochemically induced reactions may occur on surfaces of diesel exhaust particles.

b. Transport and deposition of particles within the human respiratory tract depends upon particle size (Lippmann, 1976). Typical diesel exhaust particles are in the submicrometer diameter range which can penetrate deep into the lung, carrying materials adsorbed on their surfaces with them.

c. Scattering and absorption of light by these particles depend upon their physical and chemical properties (Waggoner).

d. The coagulation, diffusion, impaction, and settling of the particles are size dependent.

The size of diesel exhaust particles has been studied by a variety of means, including scanning and transmission electron microscopy, cascade impactors, electrical aerosol analyzers, spiral dust centrifuges, diffusion

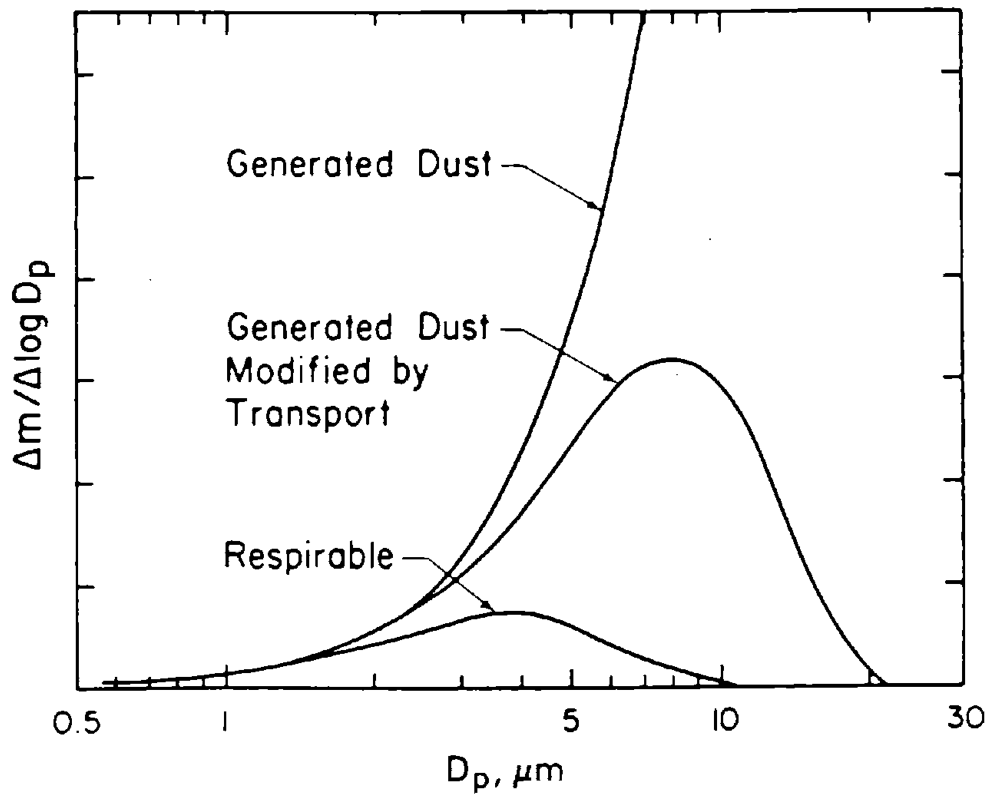


Figure 2.4 Three versions of the coarse particle size distribution (Whitby, 1983).

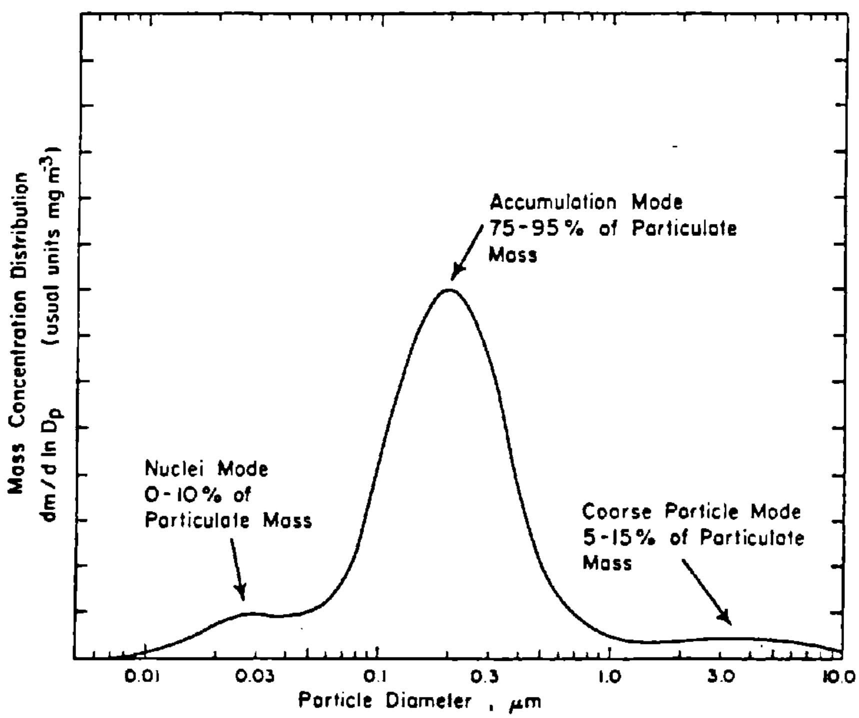


Figure 2.5 Representative size distribution of diesel exhaust particulate matter.

batteries, and optical particle counters.

The earliest work on these particles was done with transmission electron microscopes (Frey and Corn, 1967). This work revealed the basic structure of the agglomerated particle and the size distribution of the primary spherical particles which comprise agglomerates. Subsequent work with transmission and scanning electron microscopy has yielded a great deal of data on the size distributions of these primary particles (Lipkea et al., 1979). Defining the size of the agglomerates, however, is a considerably more complex problem.

Although, many characteristic dimensions can be assigned to irregularly shaped three-dimensional agglomerates, some form of equivalent diameter is normally used. The most common of these equivalent diameters are the: (a) aerodynamic diameter, which is determined by impactors and centrifuges: (b) the electrical mobility equivalent diameter, which is determined by the electrical aerosol analyzer; and (c) the diffusion diameter, which is determined by diffusion batteries.

The aerodynamic diameter is defined as the diameter of a unit density sphere that has the same settling velocity as the particle being characterized. Inertial impactors (Lodge and Chan, 1986) have been widely used to measure the aerodynamic diameters of particles. Some applications to diesel exhaust particle studies have also been reported (Hare and Baines, 1979; Dolan et al., 1980; Fang and Kittelson, 1984). However, conventional impactors cannot easily classify particles smaller than about 0.5 µm aerodynamic diameter. Hare and Baines (1979) report that more than 80% of the particle mass from a typical diesel engine is attributed to particles smaller than 0.5 µm. Thus, conventional impactors only provide information on the upper fraction of the distribution. Several recent types of impactors such as the microorifice impactor (Marple et al., 1981), the low pressure impactor (Hering et al., 1978), and the quartz crystal cascade impactor (Chuan, 1976) are able to size particles down to as low as 0.05 µm aerodynamic diameter. The microorifice impactor is described in Section 2.5. Prior to this contract, the ability of such impactors to size diesel exhaust particles had not been demonstrated.

The Stober spiral duct centrifuge (Stober, 1976) is another device which sizes particles by aerodynamic diameter. This system is capable of sizing particles down to about 0.05 µm diameter and is currently being used in the Fraunhofer Institute for Aerosol Research for exhaust aerosol studies.

The TSI Model 3030 electrical aerosol analyzer (EAA) (TSI, Inc., St. Paul, MN) measures the electrical mobility equivalent sphere diameter of a particle. Particles enter the instrument, are charged under controlled conditions, and then the electrical mobilities of the resulting charged particles are determined. The electrical mobility diameter is thus the diameter of an equivalent sphere that, when charged under the conditions produced by the charger section of the analyzer, has the same electrical mobility as the particle being sized. The EAA is capable of sizing particles in the 0.01 to 1.0 µm diameter size range. This range comprises more than 90% of the mass of particles present in the exhaust of a typical diesel engine. Thus, the EAA has been widely used to study the size distribution of diesel exhaust particles.

The equivalent diffusion diameter of a particle is the diameter of a spherical particle which has the same diffusion coefficient as the particle in question. Diffusion diameters are measured by a device called a diffusion battery (Sinclair et al., 1979) that is capable of sizing particles in the 0.002 to 0.2 µm diameter size range. Approximately half of the mass of particles found in diesel exhaust is in this size range.

It is also possible to size diesel exhaust particles using optical particle counters (Willeke and Liu, 1976). However, most optical counters have a lower size range limit of about 0.3 to 0.5 µm diameter for non-absorbing spherical particles. Thus, the optical particle counter can only yield information on the upper fraction of the diesel exhaust particle size distribution. In addition, their sensitivity to light-absorbing carbon particles is appreciably different than to non-absorbing particles for which they are intended to analyze. Irregularly shaped particles further complicate the response of optical particle counters. Marple and Rubow (1976, 1978) developed a calibration technique that allows one to obtain the response of an optical particle counter as a function of the aerodynamic particle diameter.

Figure 2.5 shows a typical diesel exhaust particle size distribution. Similar to atmospheric aerosols shown in Figure 2.3, three modes are usually present: a nuclei mode in the 0.01 to 0.1 µm diameter range, an accumulation mode in the 0.1 to 1.0 µm diameter range and a coarse particle mode in the 1 to 10 µm diameter range. For most engines and fuels, the majority of the particulate mass emitted is in the accumulation mode diameter range and consists of carbonaceous agglomerates. These agglomerates consist of coagulated nuclei that range from 0.01 to 0.05 µm in diameter (Lipkea et al., 1979; Amann et al., 1980; Frey and Corn, 1967). The nuclei mode usually constitutes less then 10% of the particulate mass and is composed of primary nuclei formed by combustion and volatile materials such as partially burnt fuel and lubricating oil. The coarse particle mode usually constitutes about 10% of the particulate mass and consists of particles of similar composition to those in the accumulation mode. Coarse particles are believed to be formed by reentrainment of large agglomerates of particles from the walls of the combustion and exhaust system (Fang and Kittelson, 1984). Diesel exhaust particles are associated with typically 5 to 40 % volatile material by mass. This volatile material tends to be associated with the smaller diameter particles (Dolan et al., 1980).

Typical diesel engines running on conventional fuels emit particles mainly in the accumulation mode size range. Under certain conditions, however, significant quantities of either nuclei mode particles or coarse particles may be emitted. Several such cases are discussed below.

Figures 2.6 to 2.8 show volume-weighted particle size distributions for three different engines. The engines are a four-stroke cycle, turbocharged direct injection heavy duty engine (an engine type common in large highway tractors), and two different four-stroke cycle, indirect injection, naturally aspirated, light duty engines. The combustion systems of indirect injection engines are similar to that of the Deutz engines commonly used in mines.

The size distributions in Figures 2.6 to 2.8 were all obtained using an EAA and are presented in volume-weighted form, i.e. the area under any part of the curve is proportional to the volume concentration of particles in that size range. Note the similarities between the size distributions despite the fact that the particles were formed by engines of different designs. The size

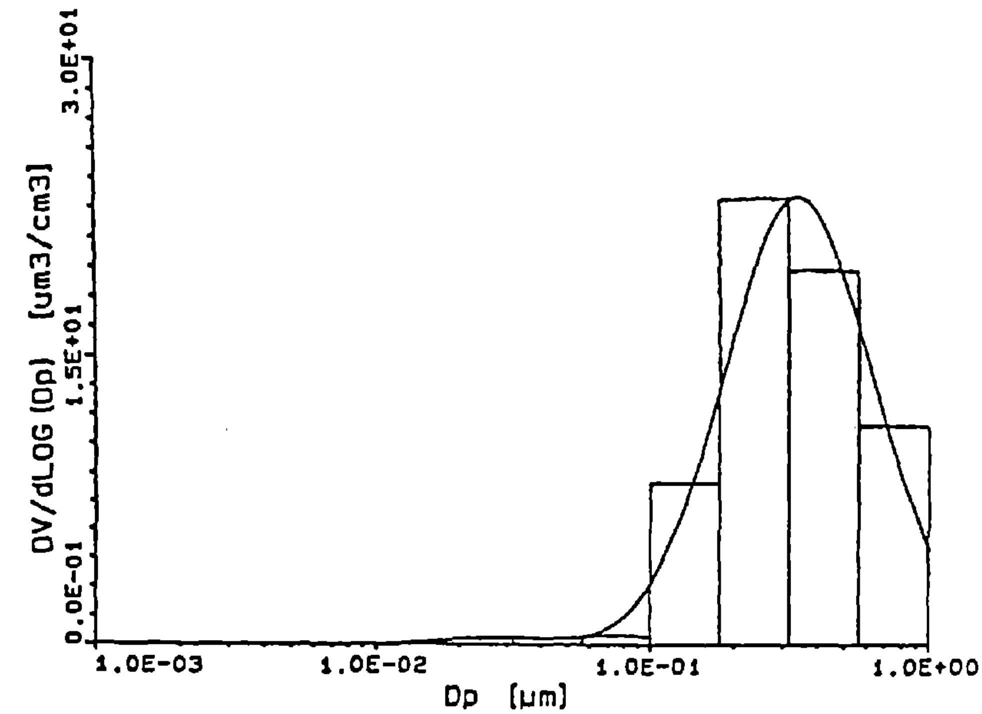


Figure 2.6 Average exhaust particle size distribution for heavy duty four-stroke cycle turbocharged diesel engine operating under transient high load conditions (Kittelson et al., 1985).

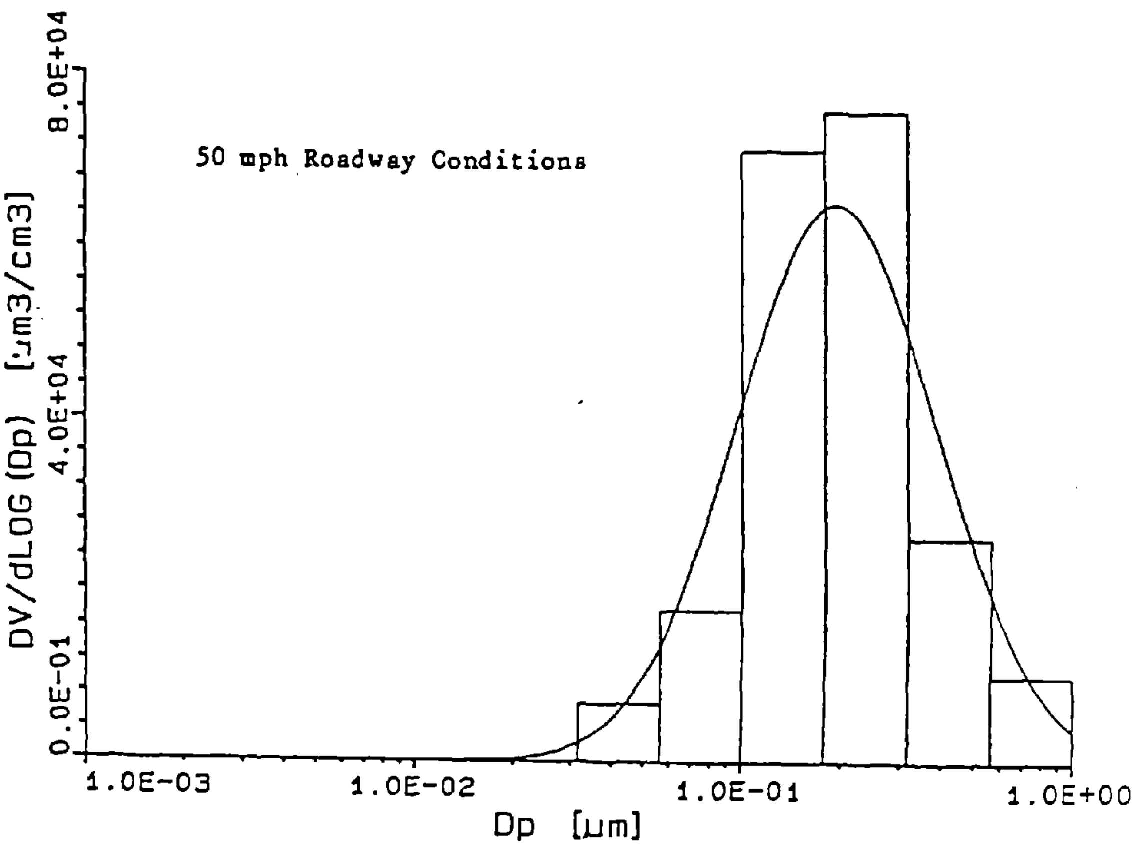


Figure 2.7 Exhaust particle size distribution measured in the laboratory for a Volkswagon Rabbit diesel engine (Kittelson et al., 1985).

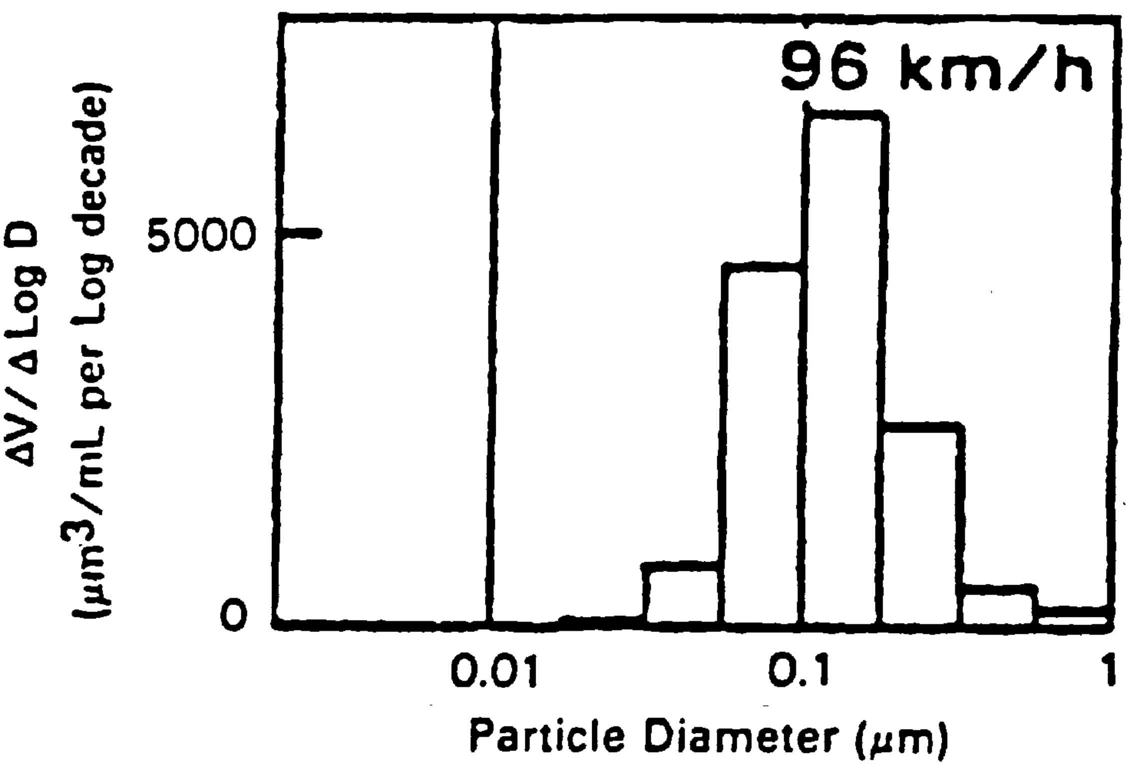


Figure 2.8 Exhaust particle size distribution for a light duty diesel engine operating at a 96 km/h roadway cruise condition (Groblicki and Begeman, 1979).

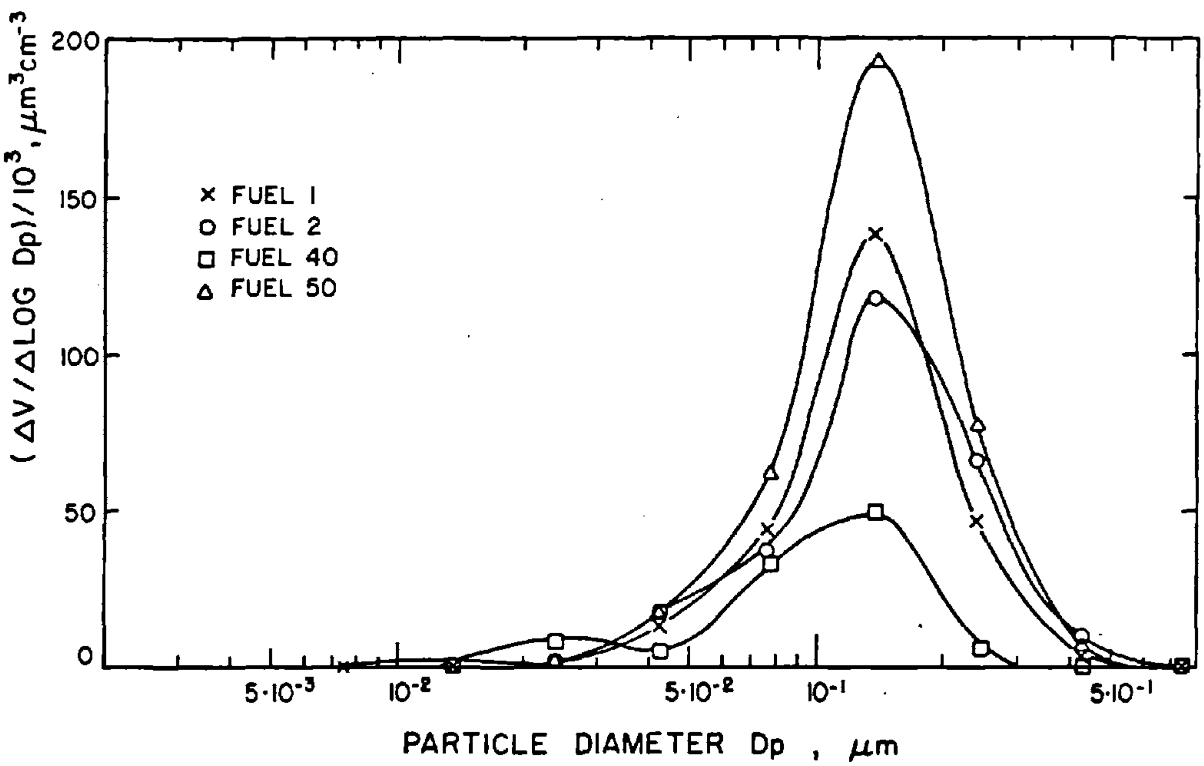


Figure 2.9 Exhaust particle size distribution showing the effect of different fuels- a #1 diesel fuel, a #2 diesel fuel, a 40 cetane reference fuel and a 50 cetane reference fuel for engine at 1800 RPM and 0.43 MPa BMEP (Kittelson et al., 1979).

distributions are all monomodal lognormal with volume mean diameters ranging from 0.15 to 0.3 μm and geometric standard deviation ranging from 1.6 to 1.8.

Other investigators such as Khatri and Johnson (1979) and Baumgard and Kittelson (1984) have reported size distributions similar to those presented here for a variety of engine types.

It does not appear that fuel characteristics, within the limits encountered with typical diesel fuels, have a strong influence on the exhaust particle size distribution. Hare and Baines (1979) examined the emissions produced by five different fuels in two light duty diesel engines. They report only slight changes in the size distributions as a result of changing fuels. Kittelson et al. (1979) examined the particulate emissions from a light duty engine operating on four different types of fuels. Three of these fuels, a #1 diesel fuel, a #2 diesel fuel, and a 50 cetane number reference fuel, could be considered to be representative of currently available diesel fuels. The fourth fuel was a 40 cetane reference fuel which was somewhat outside the range of typical fuels. Figure 2.9 shows size distributions obtained with these four fuels. The first three fuels produced essentially identical size distributions, whereas the fourth produced somewhat smaller particles in the accumulation mode, 0.1 μm versus 0.14 μm volume mean diameter, and a distinct 0.03 μm diameter accumulation mode which was barely evident with the other three fuels.

This last example shows a size distribution with a distinct nuclei mode, although the accumulation mode still comprises most of the particulate volume (or mass) observed. Another situation that gives rise to a significant nuclei mode is when barium smoke suppression additives are used to reduce exhaust smoke. Figure 2.10 shows the influence of this additive on the exhaust particle size distribution produced by a light duty engine. In this case there is strong evidence that the nuclei mode consists not of carbanaceous particles, but rather of barium salts which condense sometime during the expansion stroke.

A large nuclei mode has also been observed in an engine which produces a relatively high solvent-extractible fraction of the exhaust particles (Dolan et al., 1980). Nuclei mode particles from this engine were examined by an electron microscope and found to consist of spherical, apparently hydrocarbon particles. These particles were evidently associated with the relatively high organic extractible fraction observed.

Although the mass of coarse particles emitted by a diesel engine rarely exceeds about 15% of the total particulate mass, it is important to understand the origin of these particles. Hare and Baines (1979) have used inertial impactors to determine the size distributions of diesel exhaust particles larger than 0.4 μm aerodynamic diameter. These size distributions were obtained for two engines, five fuels, and eight different driving cycles. Engine type and fuel had only a small influence on the impactor particle size distribution, but driving cycle appeared to have a strong effect, with transient driving conditions leading to the formation of more large particles than steady operating conditions. For example, only about 5% of the particulate mass emitted was larger than about 1.0 μm aerodynamic diameter for vehicles operating at either steady 50 kph or 80 kph, whereas more than 15% of the particulate mass emitted was larger than 1.0 μm for the highly transient New York City Cycle and the Cold Start Federal Test Procedure. This probably

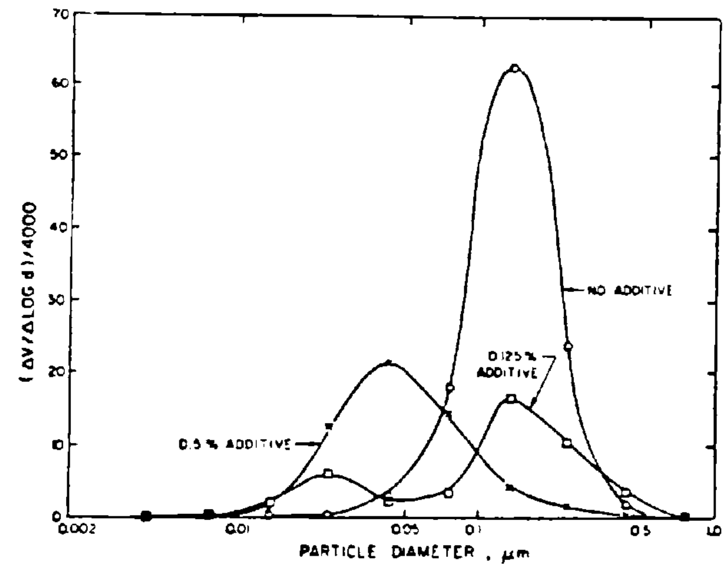


Figure 2.10 Exhaust particle size distribution showing the effect of Lubrizol 565 smoke suppression additive for diesel engine operating at 1800 RPM and 0.6 MPa BMEP (Kittelson et al., 1979).

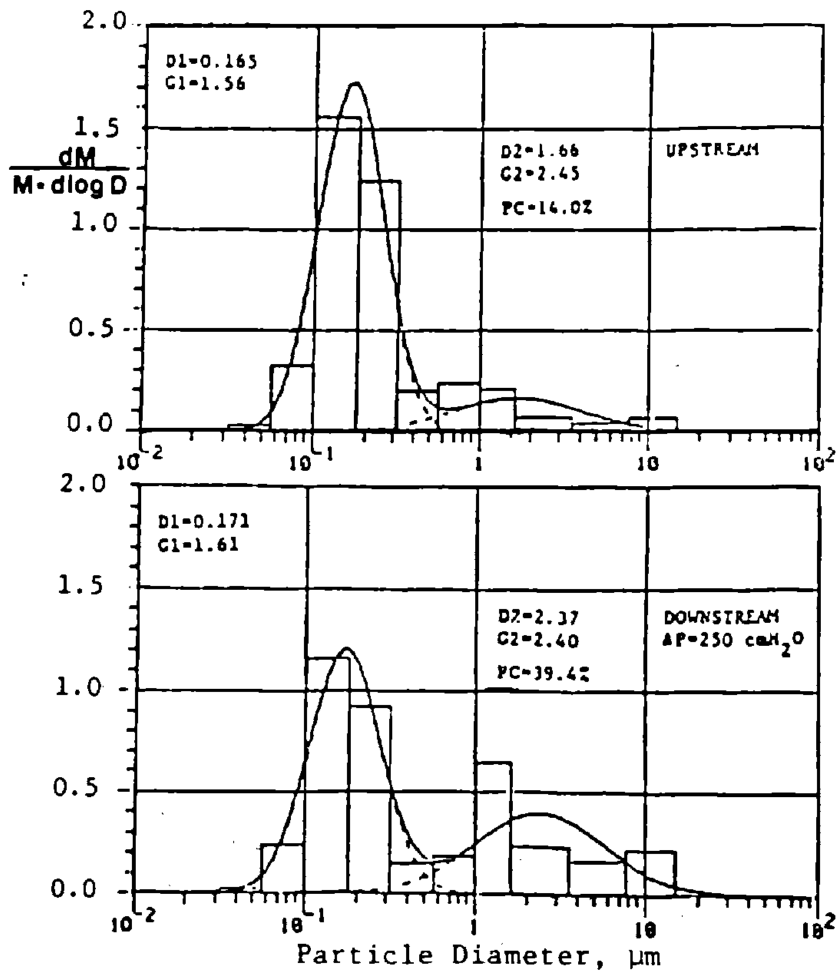


Figure 2.11 Exhaust particle size distribution upstream and downstream of particle trap on a diesel engine (Fang and Kittelson, 1984).

results from reentrainment, during the transient operation, of agglomerated particles which have deposited on the walls of the combustion chamber and exhaust system rather than by coarse particles being formed by the combustion process. Particles which deposit as accumulation and nuclei modes particles stick together and are reentrained as much larger, coarse particles by this mechanical process.

Fang and Kittelson (1984) have also demonstrated that coarse particles could be wall-related by comparing the coarse particle concentrations obtained upstream and downstream of a particle trap. The trap was known to collect and subsequently reentrain particles. Much larger concentrations of these larger particles were found downstream of the trap than upstream. Size distributions of the diesel exhaust particles observed upstream and downstream of the trap are presented in Figure 2.11.

2.3 Coal Dust Size Distribution

Numerous researchers, whose work will be presented in this section, have measured the size distribution of coal and noncoal dust aerosols found in underground mines. Essentially no data exists for particles less than about 0.5 μm due to the limits of the particle measurement methods. Particles in the submicrometer size range are of prime concern in this contract because these particles would lie in the size range of the diesel exhaust particles. Consequently, only a limited number of size distributions for the coarse particle mode are presented in this review.

Researchers have used a number of measurement techniques to obtain the particle size distribution of coal and other mine dusts. Instruments used include impactors, optical particle counters, Coulter counters, and microscopes. The measurement principle for all of these except the Coulter counter were reviewed in Section 2.2. The Coulter counter measures the volume of a particle as it passes through the sensing region and equates it to the volume of a sphere. Thus, the measured diameter is that of a sphere of equivalent volume. The particle measurement is made with the particles suspended in a liquid.

Comprehensive review of the coal mine dust size distributions is given by Willeke et al. (1971). Table 2.1 is a summary table prepared by them listing the sampling instrument, sizing method, location of sampler in the mine and the resulting approximate medium diameter and geometric standard deviation of the coal dust. They conclude that the number medium diameter of coal dust is about 0.8 μm with a geometric standard deviation of about 2.5. The corresponding mass medium diameter would be about 10 μm.

Welker et al. (1982) present a review of the relevant size distribution work performed since 1971. They cite more than 20 publications containing mine sampling results. These works include size distribution measurements as well as mineral and elemental analysis of dusts from both coal and noncoal mines. No information is given pertaining to the size distribution or possible existence of dust smaller than 0.5 μm. Data related to the coarse particle size mode show that number median diameters of dust particles are typically on the order of 1.0 μm.

Tomb et al. (1983) present data compiled from analyses conducted on dust

Table 2.1

Summary of Coal Dust Size Distribution Data
(Willeke et al., 1971)

Reference	Country	Sampling Instrument	Sizing Method	Location of Sampler	Approx. Med. Diam. µm by Nu.	by Wt.	Approx. σ_g
Wynn & Dawes, 1951	UK	Thermal Precipitator	Optical Microscope	Near coal face	0.6-1.7	—	3.6-4.3
Cartwright & Skidmore, 1961	UK	Thermal Precipitator	Electron & Optical Microscope	Laboratory Return airway (anthr. mine) Return airway (bitum. mine) Near face after blasting (bitum. mine)	0.25 0.13 0.14 0.06	— — — —	3.2 3.1 2.1 1.7
Baier & Diakun, 1964	USA	Midget Impinger	Optical Microscope	Anthracite mine Bituminous mine	0.6 0.8	— —	2.8 1.6
Walkenhorst & Bruckmann, 1966	GERM.	Sedimentation Channel with Filter	Microscope	Laboratory (?)	0.7	—	1.8
Olaf & Somolyai, 1968	GERM.	Fractiometer Coulter Counter	Microscope — — — —	In mine In mine	3.2 2.0	— —	1.6 1.6
Breuer, 1965	GERM.	BAT-Cyclone or Gothe-Filter	Andreasen Decantation	Near coal face & in lab test duct	—	4.8-9.0	2.4-3.4
Poieluiv et al., 1967	USSR	Filter	Microscope	Near coal face	—	17.	2.2

samples collected in 35 mines operating in 19 coal seams. Most of the samples are representative of dust in the environment of continuous miner operators, at section dumping points in room and pillar workings and at the tailgate of longwall faces. The samples were collected using 37-mm air monitoring cassettes that contained 37-mm membrane filters. The sampling flowrate was 2 L/min. A Model T Coulter counter was used to count and size particles in the range of 0.79 µm to greater than 20 µm. A density of 1.3 g/m^3 was assumed for the coal particles. These data are presented in Table 2.2 where M_g, M_g', and σ_g are the number median diameter, mass median diameter and geometric standard deviation. They obtained an average mass and number median diameter of 6.0 and 0.6 µm, respectively, and a geometric standard deviation of 2.4.

Particle size distribution data have been reported by Page and Jankowski (1984) for sampling sites adjacent to a moving shearer on a coal mine longwall face. A Coulter counter was used to obtain the size distribution of the respirable particles. The particles were collected on the filter after passing through 10-mm Dorr-Oliver cyclone size classifiers. They report geometric means in the 2.19 to 5.3 µm range with geometric standard deviations ranging from 1.64 to 3.73.

Ondrey and Atchison (1984) report size distribution data for a coal mine longwall. They used a Coulter counter to obtain the size distributions of the total dust collected with filter samplers. The sampling site was in the immediate return. They reported an average mass median diameter of 7.4 µm with a geometric standard deviation of 2.11.

McCawley (1984) presented mass size distributions of coal dust measured at several locations in an electric-powered continuous mining section of an underground coal mine. The size distribution measurements were made with a Sierra Model 298 impactor. The size distribution data, presented in Figure 2.12, show a coarse particle mode with a mass median on the order of 10 µm. His data also show another mode on the order of 1.0 µm. The mass in this mode appears to be less than 5% of the total mass. Data presented in Figure 2.12 have been normalized by the corresponding total mass concentration, T, measured in each test.

Particle size distributions obtained in an underground coal mine using a room-and-pillar mining method are reported by Grayson and Peng (1984). The mine was a bituminous coal mine in Southwestern Pennsylvania. Midget impingers were used to collect particle samples in the respirable size range. Particle size distributions were obtained using a microscopic particle sizing technique. Table 2.3 contains a summary of their data. They report the count median diameter (CMD), geometric standard deviation (GSD), percentage of particles less than 1 µm by number, and the silica content of each sample. The CMD range from 0.685 to 1.909 µm. The GSD range from 1.45 to 4.59.

Welker et al. (1982, 1983) report particle size distributions measured in an underground tungsten mine. A California Measurements quartz crystal microbalance (QCM) cascade impactor was used to obtain to the mass size distribution of the mineral particles. The assumption was made that the QCM was insensitive to diesel exhaust particles based on work performed by Marple and Rubow (1981). The relative mass fraction per size interval associated with mining activities is presented in Table 2.4. These data show mass median

Table 2.2

Coal Mine Particle Size Distribution Data
(Tomb et al., 1983)

Count and Mass Median Diameters, and Standard Geometric Deviations of Samples Collected at the Continuous Miner's Position

Seam	Mine	M_g (μm)	M'_g (μm)	σ_g
Upper Freeport	Russellton	0.46	3.60	2.28
		0.40	5.85	2.56
		0.66	6.30	2.38
		0.21	4.00	2.70
	Newfield	0.42	4.80	2.46
		0.42	5.70	2.53
		0.51	7.20	2.55
		0.68	5.30	2.28
		0.25	4.00	2.61
		0.45	5.35	2.47
Pittsburgh	Westland	0.57	6.45	2.45
	Arkwright	0.36	4.55	2.49
	Valley Camp No. 3	0.30	4.55	2.57
Lower Freeport	Rose Valley No. 6	0.76	3.95	2.10
Tiller	Moss No. 2	0.39	3.95	2.42
Seam 2A	Int. Harvester	0.64	4.45	2.23
Mary Lee	Bessie	0.67	4.35	2.20
Taggart	Holton Taggart	0.38	3.00	2.19
	Western Dom.	0.33	6.70	2.72
Pond Creek	Stone No. 4	0.63	4.25	2.19
Pocohontas	Olga	0.31	9.60	2.91
Pocohontas No. 4	U.S. Steel No. 9	0.31	4.65	2.58
Illinois No. 6	Orient No. 3	0.62	9.00	2.57
Paragon	Cedar Grove	1.16	4.30	1.95
U.L.M. Kittanning	Birch No. 2A	0.57	6.00	2.42
Lower Kittanning	Conemaugh	0.27	5.90	2.74
Upper Kittanning	Bethlehem No. 78	0.89	4.20	2.00
Average		0.50	5.26	2.43

Count and Mass Median Diameters and Standard Geometric Deviations of Samples Collected at Tail of Longwall Face

Seam	Mine	M_g (μm)	M'_g (μm)	σ_g
Pittsburgh	Federal No. 2	0.91	6.40	2.23
		0.94	7.60	2.30
Tiller	Moss No. 4	0.94	7.30	2.28
		0.84	7.20	2.33
Pocohontas No. 3	Gary No. 50	0.56	6.14	2.43
		0.63	7.10	2.23
Lower Kittanning	Bethlehem No. 33	0.40	6.70	2.63
		0.40	5.60	2.55
Average		0.70	6.75	2.37

Table 2.2
Continued

Count and Mass Median Diameters, and Standard Geometric Deviations of Samples Collected at the Dump Point

Seam	Mine	M_g (μm)	M'_g (μm)	σ_g (μm)
Seam 2A	Int. Harvestor	0.13	3.20	2.81
Taggart	Western Dom.	0.33	6.65	2.72
Illinois No. 6	Old Ben No. 21	0.77	4.96	2.20
Powellton	Lady Dunn	0.92	4.80	2.10
Upper Kittanning	Bethlehem No. 78	0.97	3.14	1.87
Splashdam	Harman	0.21	8.02	3.01
Average		0.55	5.13	2.45

Count and Mass Median Diameters, and Standard Geometric Deviations of Samples Collected in the Pittsburgh Seam

Location	M_g (μm)	M'_g (μm)	σ_g
Miner	0.32	4.55	2.57
Longwall (Tail)	0.28	6.40	2.78
Longwall (Tail)	0.93	6.40	2.23
Miner	0.58	6.45	2.45
Miner	0.70	10.30	2.58
Miner	0.38	4.55	2.49
Miner	0.46	3.55	2.28
Average	0.52	6.03	2.48

Table 2.2
Continued

Compilation of Size Distribution, Ash and Quartz Data by Coal Seam

		M_g (μm)		M'_g (μm)		σ_g		SiO_2 (%)		Ash (%)	
	Mines	Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.
Lower Kittanning	4	0.14–0.60	0.35	5.60– 6.70	6.05	2.42–2.74	2.60	2.3–11.5	5.40	18.6–78.3	48.0
Upper Freeport	3	0.21–0.68	0.41	3.60– 7.90	5.47	2.28–2.70	2.50	1.0– 9.6	5.10	10.1–79.2	40.6
Lower Freeport	1	0.76		3.95		2.10		1.8–15.0	6.70	39.8–61.2	47.5
Pittsburgh	7	0.27–0.94	0.56	3.40–10.50	6.12	2.12–2.92	2.44	0.5– 8.6	5.70	44.7–70.0	64.2
Splashdam	1	0.21–0.83	0.52	5.40– 8.00	6.70	2.25–3.01	2.63	2.1– 4.2	3.10	18.1–46.4	28.8
Illinois No. 6	3	0.43–0.87	0.63	3.80– 9.00	6.25	2.20–2.59	2.40	1.5– 6.2	3.10	18.6–43.7	31.6
Tiller	2	0.39–0.94	0.82	3.55– 7.30	6.40	2.11–2.42	2.28	0.7–10.0	5.00	19.7–76.0	45.6
2A	1	0.13–0.64	0.29	3.20– 4.45	3.83	2.23–2.81	2.52	6.6– 8.1	7.80	52.1–70.2	62.0
Pratt	1	0.79		5.30		2.21		1.2		11.1	
Mary Lee	1	0.67–1.12	0.90	2.68– 4.35	3.51	1.72–2.20	1.96	3.4		22.7	
Pocohontas No. 3	1	0.56–0.63	0.61	6.14– 7.10	6.86	2.43–2.45	2.45	0.5–12.0	5.00	7.5–75.0	48.2
Pocohontas No. 4	2	0.21–0.31	0.29	4.25– 9.60	7.02	2.58–2.91	2.78	9.0		74.8	
Taggart	2	0.20–0.33	0.23	3.00– 6.70	5.04	2.27–2.72	2.60	5.4– 8.0	6.70	50.4–68.5	59.5
Pond Creek	1	0.63–0.70	0.67	3.80– 4.25	4.02	2.11–2.19	2.15				
Sewell								1.4–11.2	5.30	25.2–78.5	45.29
Cedar Grove	1	1.16–0.49	1.33	4.30– 5.65	4.98	1.95–1.96	1.96	0.7– 5.0	3.03	9.5–41.2	28.17
Powellton	1	0.30–0.92	0.54	4.80– 5.80	5.30	2.10–2.67	2.42	2.6–11.3	7.13	2.40–77.3	61.51
Upper Kittanning	1	0.89–0.97	0.93	3.10– 4.20	3.70	1.87–2.05	1.96				
Rock Springs	1	0.39		6.70		2.64		6.7		36.4	

Table 2.3

Coal Mine Size Distribution Data
(Grayson and Peng, 1984)

Worker Position	Type Mining	C_N (mppcf)	% < 1 µm	CMD	GSD	Worst Hour H_N	Silica Content
CM Operator	RET	15.26	52.0	0.961	2.99	35.86	3%
LM Operator	RET	10.59	57.5	0.869	2.71	14.71	2%
Roof Bolter	DEV	31.60	44.0	1.375	3.86	66.19	5%
SC Operator	DEV	3.77	57.0	0.877	2.07	7.03	3%
CM Operator	DEV	29.96	54.0	0.926	3.03	53.51	2%
Roof Bolter	DEV	26.80	49.5	1.238	2.73	53.37	3%
Stoper Bolter	DEV	30.87	46.0	1.145	2.58	76.30	13%
Stoper Bolter	DEV	8.41	40.0	1.526	2.41	26.09	20%
LM Operator	DEV	13.62	47.5	1.909	1.45	28.74	6%
CM Operator	RET	9.12	54.0	0.926	4.13	20.64	4%
SC Operator	RET	4.77	57.5	0.869	3.35	7.16	3%
G. Motorman	-	3.27	59.0	0.847	2.98	5.62	21%
Dumper	-	4.25	57.0	0.877	3.37	6.54	4%
ML Motorman	-	4.14	68.0	0.735	2.59	10.68	22%
ML Motorman	-	4.33	71.5	0.699	2.42	6.98	22%
Boiler Attnd.	-	2.84	47.0	1.176	4.59	7.67	10%
Slate Picker	-	10.30	61.5	0.813	3.82	17.17	4%
Barge Mover	-	0.965	56.0	0.893	2.73	1.45	4%
Sampler	-	5.99	53.5	0.933	2.88	11.05	5%
Hvy Media Opr.	-	6.09	53.0	0.943	4.34	10.15	4%
Fine Coal Opr.	-	4.49	73.0	0.685	2.43	5.94	3%

Table 2.4

Particle Size Distribition Data in Underground Tungsten Mine
(Welker et al., 1983)

Mass Fractions per Size Interval Associated with Mining Operations

d_{50} (μm)	Ambient	Diesel Samples			Chute Pulling		Electric Trolley	Heavy Dust	Track Mucking	Blowpipe
		Idle	Light Load	Heavy Load	No Diesel	Diesel				
24	0.061	0.044	0.123	0.088	0.010	0.052	0.084	0.000	0.041	0.079
12	0.017	0.011	0.102	0.125	0.044	0.028	0.027	0.032	0.000	0.010
7	0.045	0.043	0.057	0.071	0.095	0.064	0.027	0.006	0.060	0.000
3.6	0.055	0.070	0.041	0.085	0.052	0.060	0.023	0.017	0.059	0.006
2.1	0.051	0.073	0.057	0.083	0.106	0.063	0.060	0.029	0.034	0.055
1.11	0.150	0.177	0.124	0.125	0.155	0.140	0.230	0.174	0.065	0.276
0.67	0.310	0.260	0.207	0.237	0.301	0.250	0.256	0.369	0.261	0.355
0.40	0.155	0.166	0.136	0.105	0.174	0.201	0.140	0.173	0.382	0.139
0.22	0.080	0.014	0.052	0.039	0.024	0.094	0.138	0.145	0.000	0.006
0.13	0.077	0.142	0.102	0.042	0.040	0.048	0.043	0.056	0.098	0.074

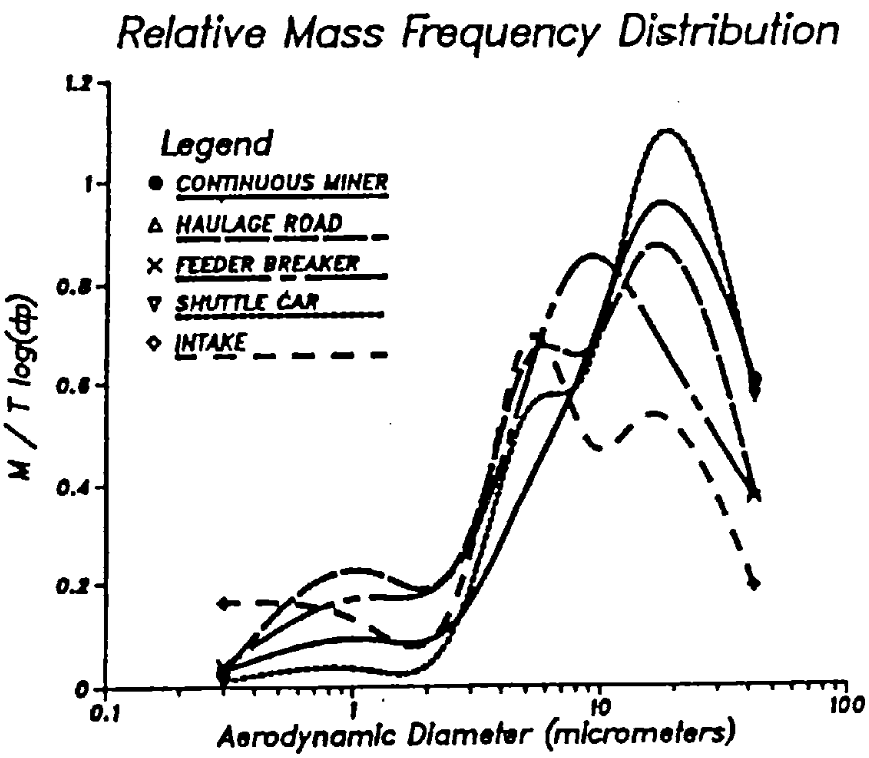


Figure 2.12 Size distribution of dust on electric section, continuous method coal mine (McCawley, 1984).

diameters in the 0.67 to 1.11 µm size interval. These sizes are much smaller than those reported for the coal mines. They also determined that the fraction of diesel exhaust particles in the respirable aerosol varied from 0 to 61%.

Particle size measurements obtained in three uranium mines are reported by Knight et al. (1983). These mines also used diesel-powered equipment. The size distribution data were obtained using an open filter and a series of two-stage samplers consisting of a filter preceded by size selectors with 50% aerodynamic cutoff diameters ranging from 1.25 to 7.1 µm. Summary particle size distributions, on the basis of total mass, quartz mass and alpha count mass, are presented in Figure 2.13. All data have been normalized by the MRC respirable mass concentration simultaneously measured with a horizontal elutriator. The data show mass median diameters of approximately 7.0 and 1.3 µm for the overall and respirable fraction of the total mass, respectively, with 52% of the respirable mass less than 1.4 µm. They also observed that most of the particles less than 1.25 µm are nonmineral, i.e. either diesel exhaust or atmospheric particulate matter.

2.4 Instrumentation Review

Techniques for determining the mass concentration of diesel exhaust particles and the mass size distribution of the diesel exhaust and mineral dust particles in underground mining environments were investigated. The techniques considered for the measurement of the diesel exhaust concentration were time-integrated as well as real-time or near real-time measurement techniques. As for the measurement of the mass size distribution, only time-integrated techniques were considered.

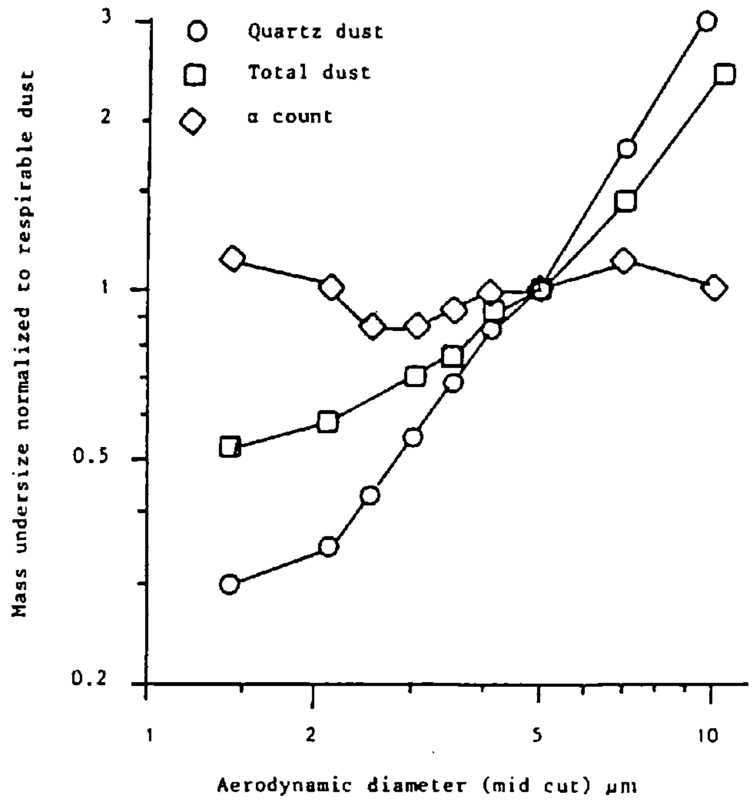


Figure 2.13 Mean size distributions as assessed by weight (total), X-ray diffraction (quartz) and alpha count (thoron daughters) in uranium mine (Knight et al., 1983).

A review of several real-time or near real-time measurement techniques that might be suitable for monitoring diesel exhaust particles was conducted. Seven different techniques were reviewed and evaluated as candidates for the in-mine sensing of diesel exhaust particles. These techniques are piezoelectic balance, laser spectrophone, long wavelength infrared adsorption, tapered element oscillating microbalance, a filter pressure drop method, photometers such as the GCA RAM-1 and MINIRAM, and the Metrex Mineral/Diesel Photometer. A brief review of each technique is given in Section 5.1 along with an assessment of the applicability for use in the mine environment. A discussion of the GCA RAM-1 and Metrex photometers are also presented in Chapter 4.

As recommended in Section 5.1, the mass size distribution as well as the mass concentration of the diesel exhaust and mineral dust particles were measured using the MOUDI in this contract. The measurement of the size distribution of these aerosols requires the use of cascade impactors. However, the need to measure particles down to 0.1 μm precludes the use of conventional impactors. The lower particle sizing limit for these impactors is typically 0.4 μm. Only low pressure impactors and the MOUDI are capable of classifying particle on the order of 0.1 μm (Lodge and Chan, 1986). For reasons given in Section 5.1, the MOUDI is more ideally suited for measurements in this application than are low pressure impactors. A description of the MOUDI is presented in Section 2.5.

2.5 Microorifice Uniform Deposit Impactor

The microorifice uniform deposit impactor (MOUDI) is a versatile cascade impactor designed to collect size fractionated samples of particles. This impactor is essentially the same as a conventional cascade impactor with the exception of two unique features: small nozzle diameters and a rotation feature which allows for a uniform particle deposit to be obtained. As a result of the small nozzle diameters, very small particles can be collected. Cutsizes as small as 0.024 µm aerodynamic diameter have been obtained. Cutsize is defined as that particle where 50% of the particles are collected on the impactor substrate. The two unique features, microorifices and the uniform deposit, have been developed and patented by this laboratory.

A seven-stage version of the MOUDI with particle cutsizes ranging from 0.10 to 10 µm aerodynamic diameter is shown in Figure 2.14. The details of the impactor design parameters are presented in Table 2.5. Typical efficiency curves for several of the impactor stages are shown in Figure 2.15. The flow rate through this impactor is 30 L/min. At the lower cutsize, 2000 nozzles of approximately 56 µm diameter are utilized. Marple and Rubow (1984a) describe in more detail the impactor and the particle calibration. Marple et al. (1981) and Marple and Rubow (1984c) describe an earlier version of the impactor.

An important feature of this impactor is that it can be used to obtain a uniform deposit of particles upon the impaction substrate by rotating the nozzles relative to the impaction substrate. A uniform deposit reduces the problem of particle bounce and, at any degree of loading, increases the accuracy by increasing the ratio of particle mass collected to the substrate mass.

As shown in Figure 2.16, the gears on alternate stages of the impactor allow the stages to be rotated to obtain the uniform deposit. A special rotation device has been developed for this purpose. The impaction stages, which do not have gears, have rings with hooks so that they cannot rotate.

In operation, the drive shaft with four spur gears is turned by an electric motor. These spur gears mesh with the four gears on the alternate stages of the cascade impactor and rotate these stages relative to the four stationary stages. Since each stage contains a nozzle plate plus the impaction plate for the stage above, as shown in Figure 2.16, the rotation of every other stage rotates every impaction plate relative to its nozzle plate. By properly placing the nozzles at radial distances about the center of rotation of these stages, a uniform deposit is obtained on the impaction plate.

The rotation of the microorifice impactor is not necessary in order to obtain a size distribution. The impactor can be used in a conventional nonrotating manner, the same as any cascade impactor, and the mass of particles on the substrate analyzed gravimetrically or analyzed by other techniques dictated by the test program.

In the underground coal mine experiments reported in Chapter 6, the rotation device was not used because it contained an nonpermissable electric motor. Instead the impaction stages were rotated periodically by hand in order to collect particles over a larger portion of the impaction surface. This would reduce any problems with particle bounce from a heavily loaded deposit.

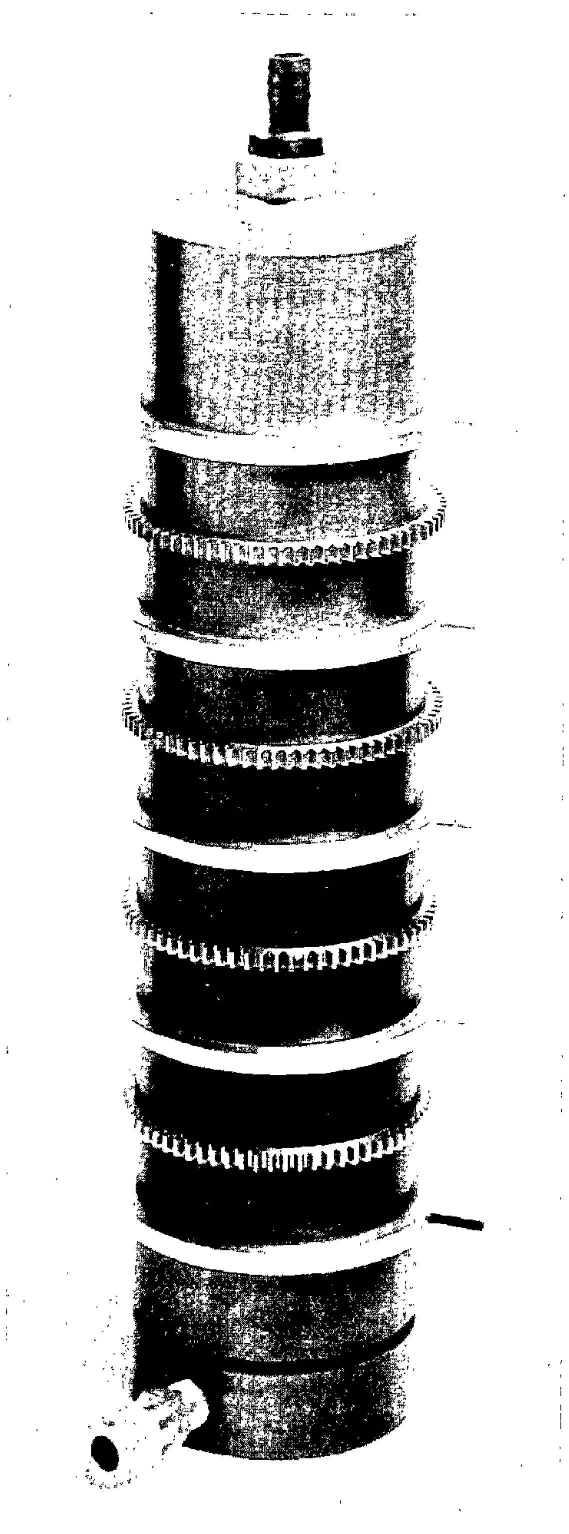


Figure 2.14 Microorifice uniform deposit impactor.

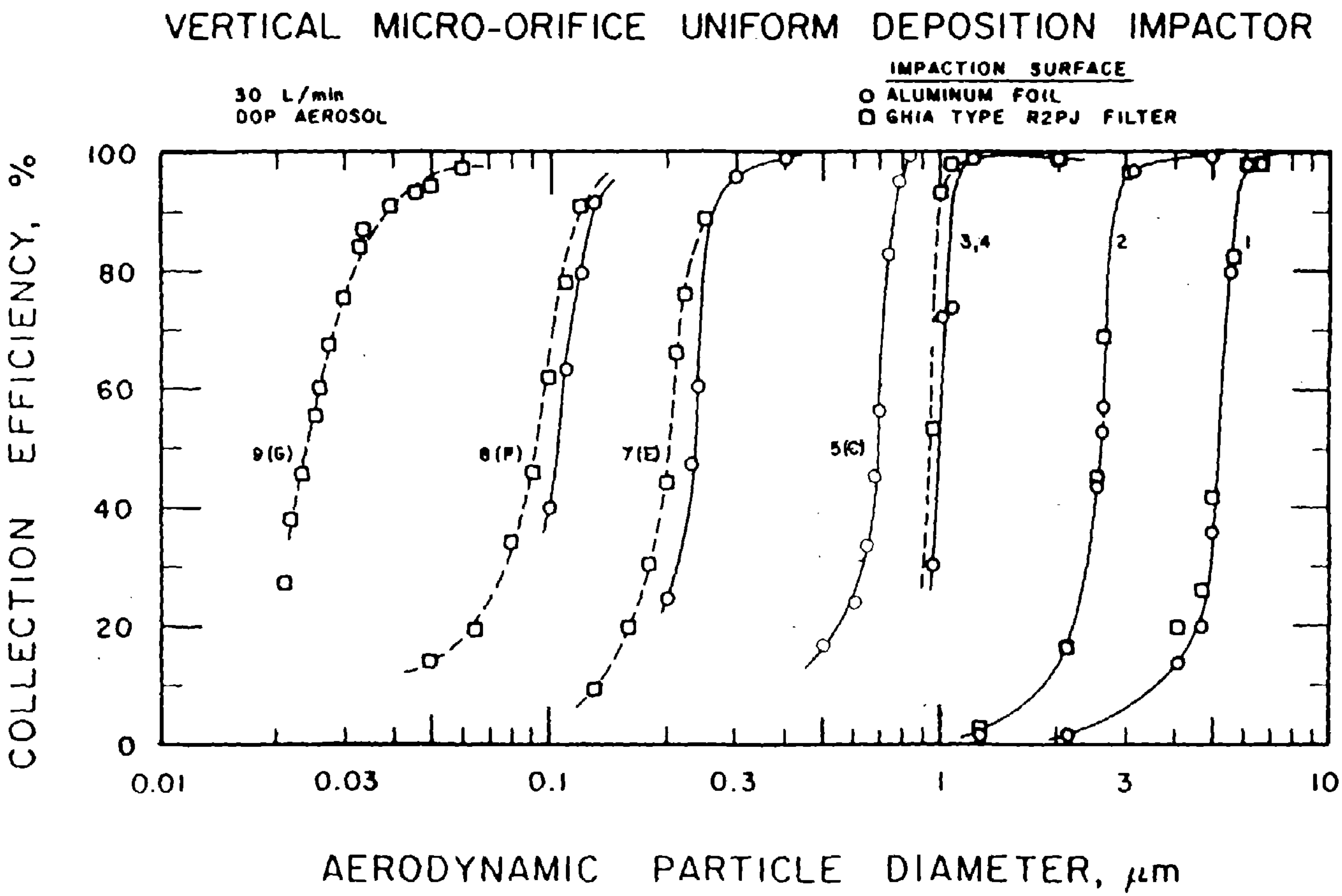


Figure 2.15 Calibration data for several stages of the MOUDI.

Table 2.5

MOUDI Design and Operating Parameters

Stage	Number of Nozzles	Nozzle Diameter, um	Cutsize, μm
1	3	8650	10.0
2	10	3410	4.9
3	10	2170	2.6
4	10	1170	1.0
5	80	467	0.70
6	900	69	0.23
7	2000	56	0.10

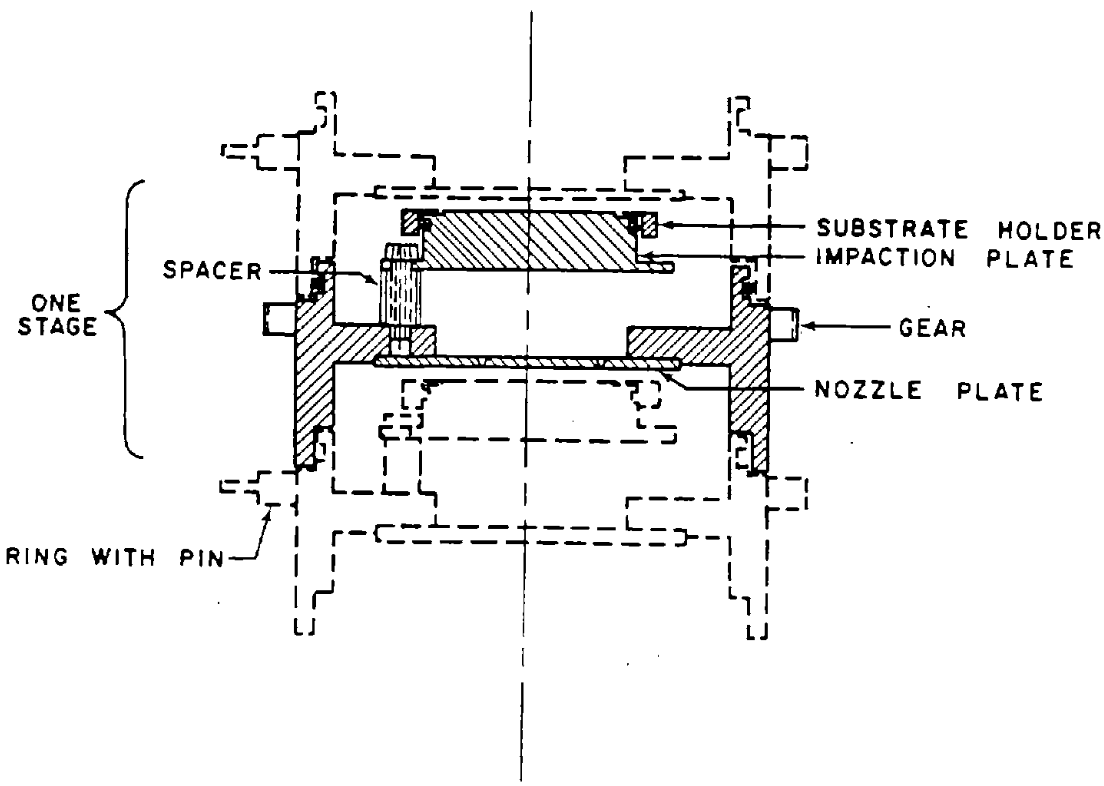


Figure 2.16 Schematic diagram of typical impactor stage.

CHAPTER 3

LABORATORY STUDIES

The objective of the laboratory studies was to determine the feasibility of using the MOUDI to separate, on the basis of particle size, diesel exhaust particles and coal dust from a mixed aerosol. A special test apparatus was constructed and tests were performed over a wide range of diesel exhaust and coal dust mixtures.

3.1 Experimental Test Setup

A laboratory testing apparatus was designed and built specifically for this project. This apparatus allowed for the generation, mixing, and sampling of diesel exhaust and coal dust. Diesel exhaust was mixed with coal dust that was generated with the fluidized bed dust generator (Marple et al., 1978). This mixture was then passed into a dilution system to decrease the mass concentration of the diesel exhaust particles to about 3 mg/m^3. The diesel exhaust aerosol concentration at a given engine operating condition, was kept constant while the concentration of the coal dust aerosol was varied to obtain different diesel exhaust particle to coal dust mixture ratios. In order to ensure a constant diesel exhaust particle concentration, the engine was run for at least one half hour before each test.

The test setup used in the combined diesel exhaust/coal aerosol experiments is shown in Figure 3.1. The system consists of four primary components, namely, a Caterpiller Type 3304 NA diesel engine, a TSI Model 3400 Fluidized Bed Aerosol Generator (TSI, Inc, St. Paul, MN), a dilution system, and the aerosol sampler. Diesel exhaust, at a flow rate of 16 L/min, was extracted from the engine exhaust manifold and combined with the coal dust aerosol. The flow rate was controlled by a metering orifice and valve. The diesel exhaust sampling tube was wrapped with heating tape from the exhaust manifold to the dilution system to prevent condensation. The coal dust was generated with the fluidized bed aerosol generator at a flow rate of 9 L/min. For each engine operating condition, the ratio of the diesel exhaust to coal dust aerosol concentration was adjusted by varying the coal dust concentration. The combined aerosol was then injected into a 7.6 cm-diameter dilution tunnel. Room air, at a flow rate of 800 L/min, was drawn into the tunnel and through a flow meter, a charcoal bed filter and a HEPA filter prior to the diesel exhaust/coal dust aerosol injection point. The diesel exhaust, coal dust and dilution air were turbulently mixed in the dilution tunnel where the aerosol dilution ratio was 33 to 1. A sample of the diesel exhaust/coal aerosol was isokinetically drawn from the tunnel at a flow rate of 30 L/min. The size distribution of this sample was obtained using the MOUDI. The mass concentration was also measured with photometers and filter samplers.

Classified coal dust containing no particles greater than 10 µm was used as the feed material in the fluidized bed dust generator. This coal dust was selected in an attempt to simulate the respirable fraction of coal dust aerosol. The size distribution of the coal dust was found to have a mass median diameter of approximately 2.5 µm with a geometric standard deviation of 2. On a mass basis, only about 2% of the dust was less than 1 µm. Thus, the size distribution of this test dust was similar to that reported in Section 2.3

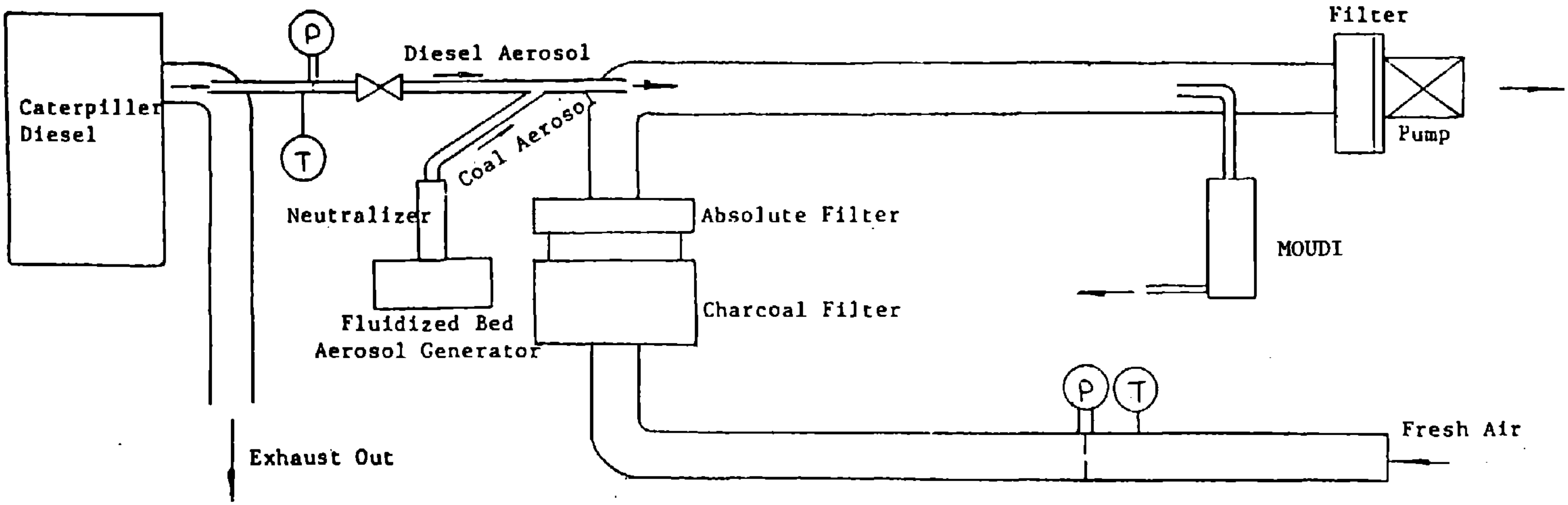


Figure 3.1 Schematic diagram of test setup used in the diesel exhaust/coal dust aerosol experiments.

for the respirable fraction of coal mine dust aerosols.

3.2 Diesel Exhaust Particle Loading in MOUDI

Two sets of experiments were conducted early in the feasibility portion of the program to investigate two potential problems when sampling diesel exhaust particles with the MOUDI. These were possible clogging of the small nozzles used in the MOUDI by the diesel exhaust particles and possible mass instability of the coating used on the impaction plates to prevent particle bounce when exposed to diesel exhaust.

The objective of the first test was to ascertain the degree of particle deposition in the micro-orifice nozzles of the MOUDI. Undiluted exhaust from a Volkswagon Rabbit diesel engine was used in this study. This engine has a swirl combustion system much like the Deutz engine. For this test only Stage 2, which has a 50% cutsize of 4.9 µm, Stage 7, which has a cutsize of 0.1 µm and an afterfilter were used. Stage 7, with 56 µm diameter nozzles, has the smallest nozzles in the standard MOUDI configuration and, consequently, the greatest likelihood of nozzle clogging due to particle deposition. The impaction plate of Stage 2 was heavily greased to ensure that no large particle would pass through to Stage 7. The impaction plate of Stage 7 was removed to eliminate any over loading problems. Particles passing through Stage 7 were collected by the afterfilter.

The pressure drop across Stage 7 was used as an indication of the degree of nozzle clogging. Pressure drop is very sensitive to clogging as the pressure drop across an orifice varies as the fourth power of the opening diameter. The pressure drop across Stage 7 was continuously monitored during the loading test.

The pressure drop across Stage 7 as a function of mass collected on the afterfilter is shown in Figure 3.2. The pressure drop increased from 1.655 psi to 1.922 psi or 16 % during the test. The total mass of diesel exhaust particles collected on the afterfilter was 19.3 mg. The results show that the pressure increased only 1.5% during the initial loading of 5 mg. At this loading the MOUDI could sample a diesel exhaust aerosol at a mass concentration of 3 mg/m^3 for 27 hours. Thus, while the data show the nozzle will clog, the degree of clogging is negligible during the duration of a typical test. Furthermore, the nozzles can be cleaned easily by ultrasonic cleaning in a soapy solution.

The coating mass stability test was conducted by passing filtered, undiluted, diesel exhaust through the MOUDI. The impaction plates were coated with Hercules Industrial F.D.A. Silicone Spray (Hercules Product Division, The Richardson Company, Alden, NY), which was the standard coating used in this project. Diesel exhaust was drawn through the impactor for 30 min. The coated impaction plates were weighed before and after the test with a Cahn Model 25 Automatic Electrobalance (Cahn Instruments, Inc, Cerritos, CA). No change in the coating mass on each impaction plate was observed.

3.3 Size Distribution Results

The MOUDI was used to measure the size distributions of the diesel exhaust/coal aerosol mixtures. For these laboratory tests, a 6 stage version

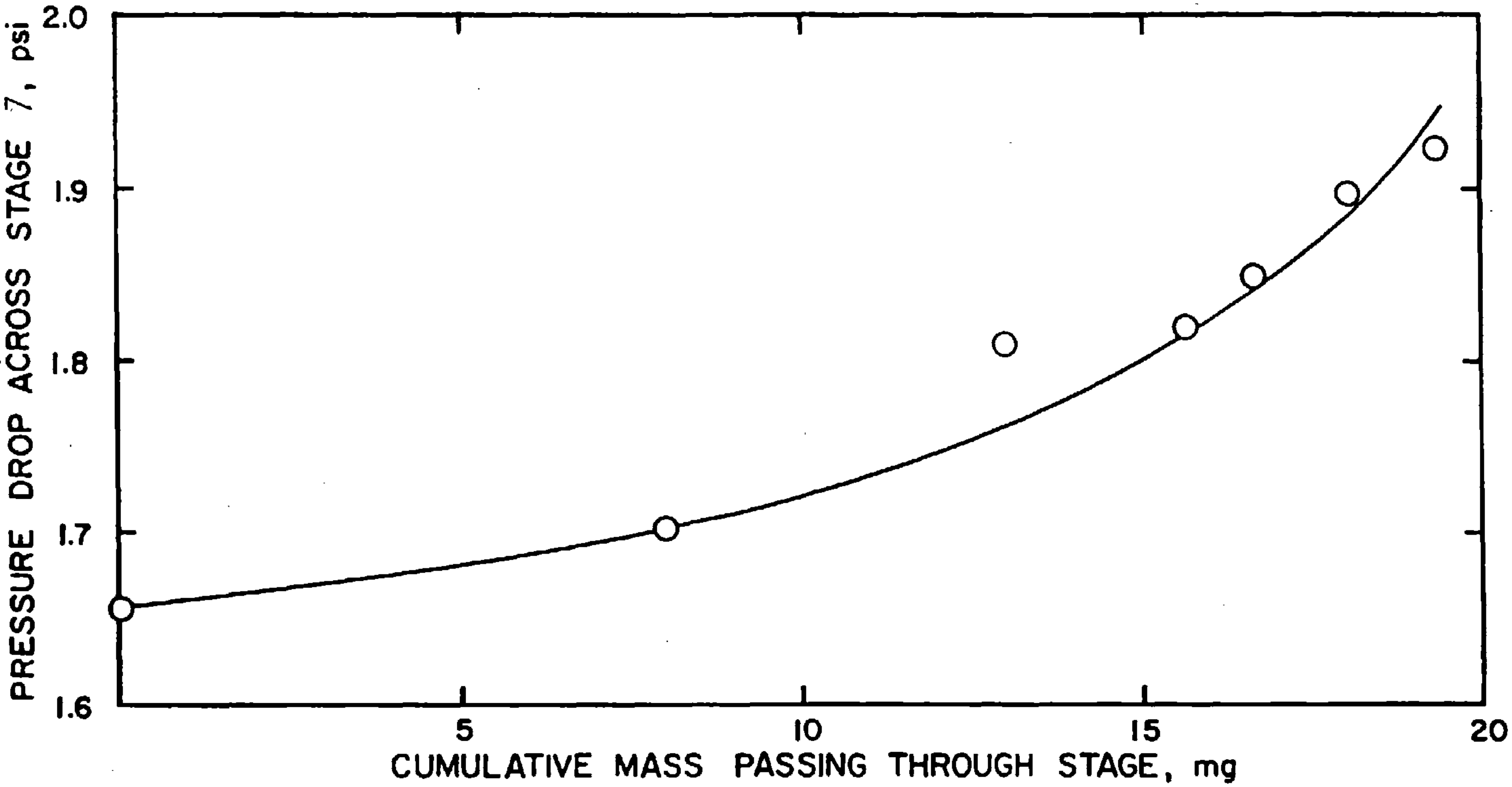


Figure 3.2 Pressure drop across Stage 7 as a function of the cumulative quantity of diesel exhaust aerosol passing through stage.

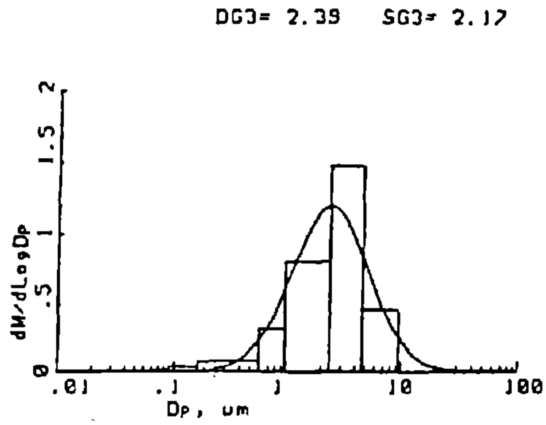
was used. The cutsizes of the stages were 0.10, 0.23, 0.70, 1.0, 2.6 and 4.9 µm. For the size distribution analysis, additional interval boundaries of 0.05 and 15 µm were assumed for the smallest size of the diesel exhaust particles and the largest size of the coal dust particles. Modal analysis was then used to obtain the lognormal size distribution of these aerosols.

Size distributions of 35 diesel exhaust and coal aerosol mixtures were obtained. These include 6 size distributions of pure diesel exhaust aerosols, 6 of pure coal dust aerosols, and 23 with the diesel exhaust mass fractions ranging from 2 to 95% of the combined aerosol. For the pure coal aerosol experiments, diesel exhaust particles were removed in a HEPA filter placed upstream of the point of mixing. Thus, the equivalent flow conditions were maintained to minimize differences in particle loss. The diesel exhaust particle size distribution was varied by performing tests with the Caterpillar Type 3304 NA diesel engine operating at conditions of half and full load at 1400 and 1800 RPM. Half and full load refer to brake mean effective pressures (BMEP) of 325 and 650 kPa at 1400 RPM and 310 and 620 kPa at RPM respectively. A General Electric DC dynamometer was used to impose the engine load. The measured mass median diameter (MMD) and geometric standard deviation (σ_g) for the diesel exhaust aerosol were found to range from 0.13 to 0.25 µm and 1.65 to 2.0 respectively. For coal dust the MMD and σ_g were found to vary from 2.3 to 3.1 µm and from 1.7 to 2.3 respectively. The variations in the size distributions of the coal dust aerosol resulted from the day to day variations in the operating conditions of the fluidized bed aerosol generator and the variability introduced by the sampling method.

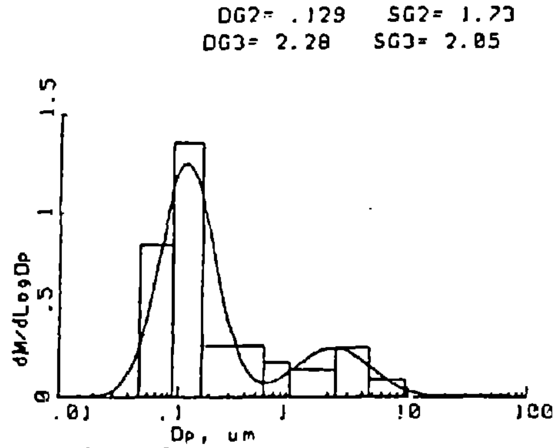
Two series of five typical mass size distributions are presented in Figures 3.3 and 3.4. Distributions are presented for pure coal and diesel exhaust aerosols plus various diesel exhaust/coal aerosol mixtures. All graphs are presented in mass weighted form, i.e. the area under any part of the curve is proportional to the mass concentration of particles in that size range. The particle diameter (D_p) is the aerodynamic particle diameter. The histograms in the graphs represent the experimental data. The lognormal size distribution curves were obtained by using "DISFIT", a size distribution fitting program. The MMD and σ_g for each mode are presented above the graph. DG2 and DG3 are the MMD'S for the submicrometer and supermicrometer modes, respectively. SG2 and SG3 are the corresponding σ_g's.

The data in Figure 3.3 were obtained with the diesel engine operating conditions of half load at 1400 RPM. The mass fraction of material less than 0.7 µm was 5% for the pure coal and 71% for the diesel exhaust aerosols. For the combined aerosol tests, mass fractions less than 0.7 µm were 78%, 26%, and 6.5%. The corresponding mass fraction of the diesel exhaust particles in the mixtures were 98%, 28%, and 3%, respectfully. Regardless of the diesel exhaust/coal aerosol mix, the data shows two distinct modes with a minimum occurring in the 0.7 to 1.0 µm size range.

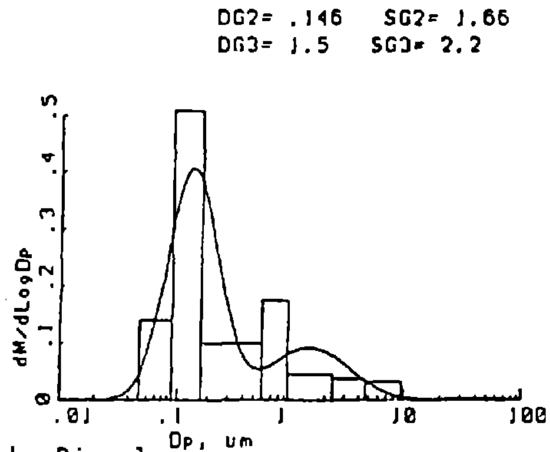
Figure 3.4 contains size distributions with the diesel engine operating at 1400 RPM with full load conditions. Figure 3.4a shows the bimodal size distribution of the pure diesel exhaust aerosol. This aerosol size distribution consists of two modes, namely, the accumulation and course particle modes. The MMD of the accumulation mode is 0.165 µm with a σ_g of 1.8. For the coarse particle mode, the MMD and σ_g were 2.5 µm and 2.1, respectfully. Size distributions for various combinations of the two aerosols



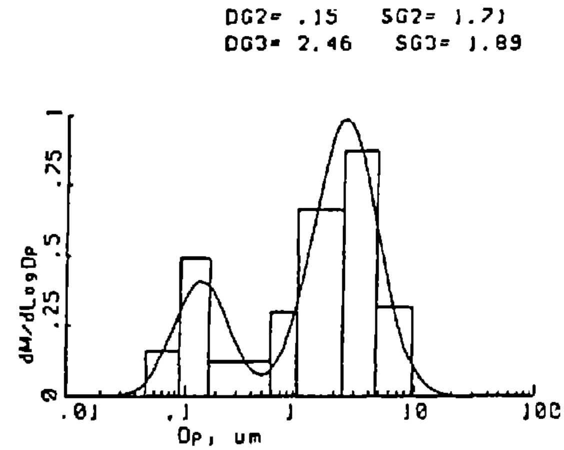
a. Coal



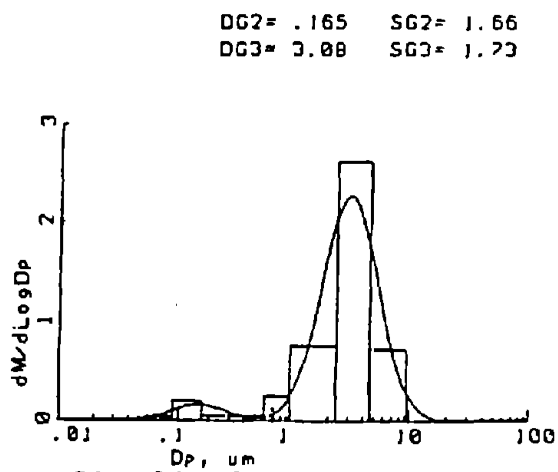
c. Diesel/coal mixture: high diesel fraction



b. Diesel

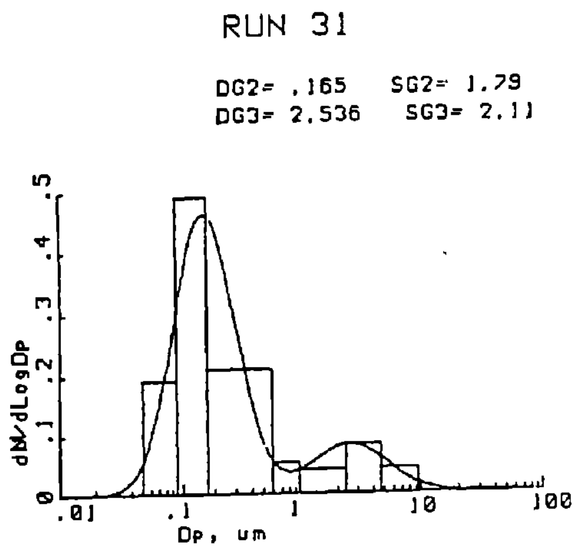


d. Diesel/coal mixture: medium diesel fraction

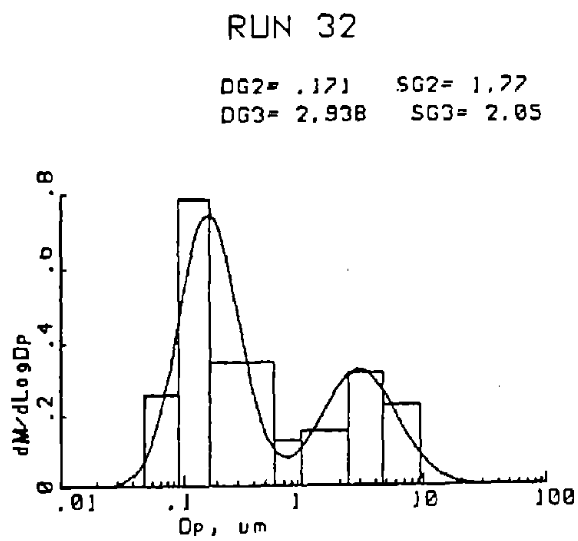


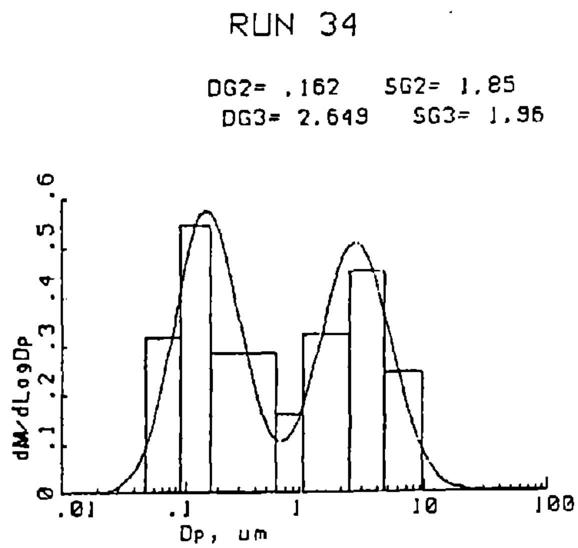
e. Diesel/coal mixture: low diesel fraction

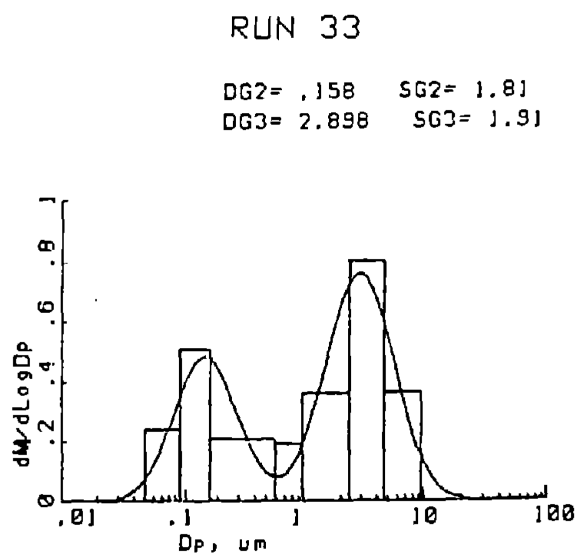
Figure 3.3 Measured and fit size distributions for pure coal, pure diesel exhaust and various mixtures of the two aerosols; diesel engine operating condition of half load at 1400 RPM.



a. Diesel only







b. Diesel/ coal mixtures

Figure 3.4 Size distribution of the diesel exhaust and diesel exhaust/coal aerosols for a diesel engine operating condition of full load at 1400 RPM.

are presented in Figure 3.4b. The mass fractions of diesel exhaust particles in the mixtures were 78%, 60% and 42%. The corresponding fraction of mass less then a particle diameter of 0.7 µm were 64%, 51% and 37%. As reported above, there is an excellent separation of the two aerosols in the 0.7 µm to 1.0 µm size range.

The size distribution of pure diesel exhaust aerosol in Figure 3.3b and 3.4a show that this aerosol is bimodal with the primary (accumulation)modes in the range of 0.146 to 0.165 µm and secondary (coarse) modes in the range of 1.5 to 2.5 µm. The existence of a bimodal distribution is discussed in Section 2.2. The mass in the larger mode is about 20% of the total mass.

While this larger mode is in the size range of dust aerosols, it should not present any significant problems in establishing the diesel exhaust aerosol fraction via size distribution analysis for three reasons. First, the mass fraction in the secondary mode typically ranges from 10 to 20% of the total diesel exhaust mass. By assuming a average value, of say 15%, the amount of mass in the secondary mode can be computed if the mass in the primary mode has been determined. Secondly, the mean diameter of the secondary mode is sufficiently greater than the primary mode so as to pose no problems in separating the two modes and more importantly, in separating the primary diesel exhaust mode from the coal (or dust) aerosol mode. This fact is clearly shown in Figure 3.3e where the diesel exhaust aerosol is only 2% of the total aerosol. Lastly, scrubbers are often used on diesel engines to reduce exhaust gas temperatures and particle emissions in underground mines. The coarse particle mode is presumably reduced in the scrubber, thereby, minimizing the interference with the dust particles. This hypothesis, however, needs to be experimentally verified.

CHAPTER 4

INSTRUMENTATION EVALUATION

Two photometers were investigated for suitability as aerosol monitors to measure the diesel exhaust particles and coal dust fractions of an aerosol mixture. These photometers were the GCA Model RAM-1 photometer (GCA Corp., Bedford, MA) and the Metrex Mineral/Diesel Photometer (Metrex Instruments Ltd., Brampton, Ontario, Canada). The light scattering response of both photometers was determined for both coal dust and diesel exhaust particles. The response of the GCA RAM-1 was determined theoretically while that of the Metrex photometer was obtained experimentally.

4.1 GCA RAM-1

The objective of this study was to determine the sensitivity of the GCA RAM-1 to particle size. The response of the RAM-1 to coal dust had been previously determined experimentally (Rubow and Marple, 1983; Marple and Rubow, 1984b).

The response of the GCA RAM-1 as a function of exhaust diesel and coal particle size was theoretically determined. The analysis computes the scattering of infrared radiation from particles in the view volume of the GCA RAM-1 using algorithms developed by Dave (1968, 1969). These algorithms are based on Mie scattering theory. The quantity of scattered radiation in a given direction is a function of the particle size, shape and index of refraction and the wavelength of the incident radiation. Wavelengths of 875 and 940 nm were used, as these are the mean wavelengths of the light emitting diodes used in the GCA MINIRAM and RAM-1 photometers, respectively. The wavelength of the light emitting diode used in the MINIRAM was included in this study to determine the influence of wavelength on the response of the RAM-1. The scattering intensity per unit particle mass was computed over the scattering angles of 45^o to 95^o. The particles were assumed to be spherical. For the case of diesel exhaust particles, calculations were performed for indices of refraction of 2.00-i1.00 and 1.95-i0.66 which are indices of refraction for graphite and amorphous carbon, respectfully. For coal particles, calculations were performed for indices of refraction of 1.8-i0.12 and 1.8-i0.38. Values within these limits were obtained by Bowman (1985) for ground coal dust and for respirable coal dust collected in an underground mine.

The light scattering data were computed on the basis of the equivalent spherical diameter. For the case of nonspherical particles (e.g. diesel exhaust and coal dust particles) particle shape factors must be used to convert the equivalent spherical diameter into the Stokes diameter or aerodynamic diameter. The conversion to aerodynamic diameter would also require knowledge of the particle density.

Figure 4.1 and 4.2 contain the theoretically determined scattering intensity per unit particle mass as a function of particle diameter. Scattering intensity data are presented in terms of arbitrary units. These data show the relative RAM-1 response rather than absolute response. In order to convert these data into the actual response (sensitivity) of the RAM-1, values for the incident infrared radiation intensity, the response of the

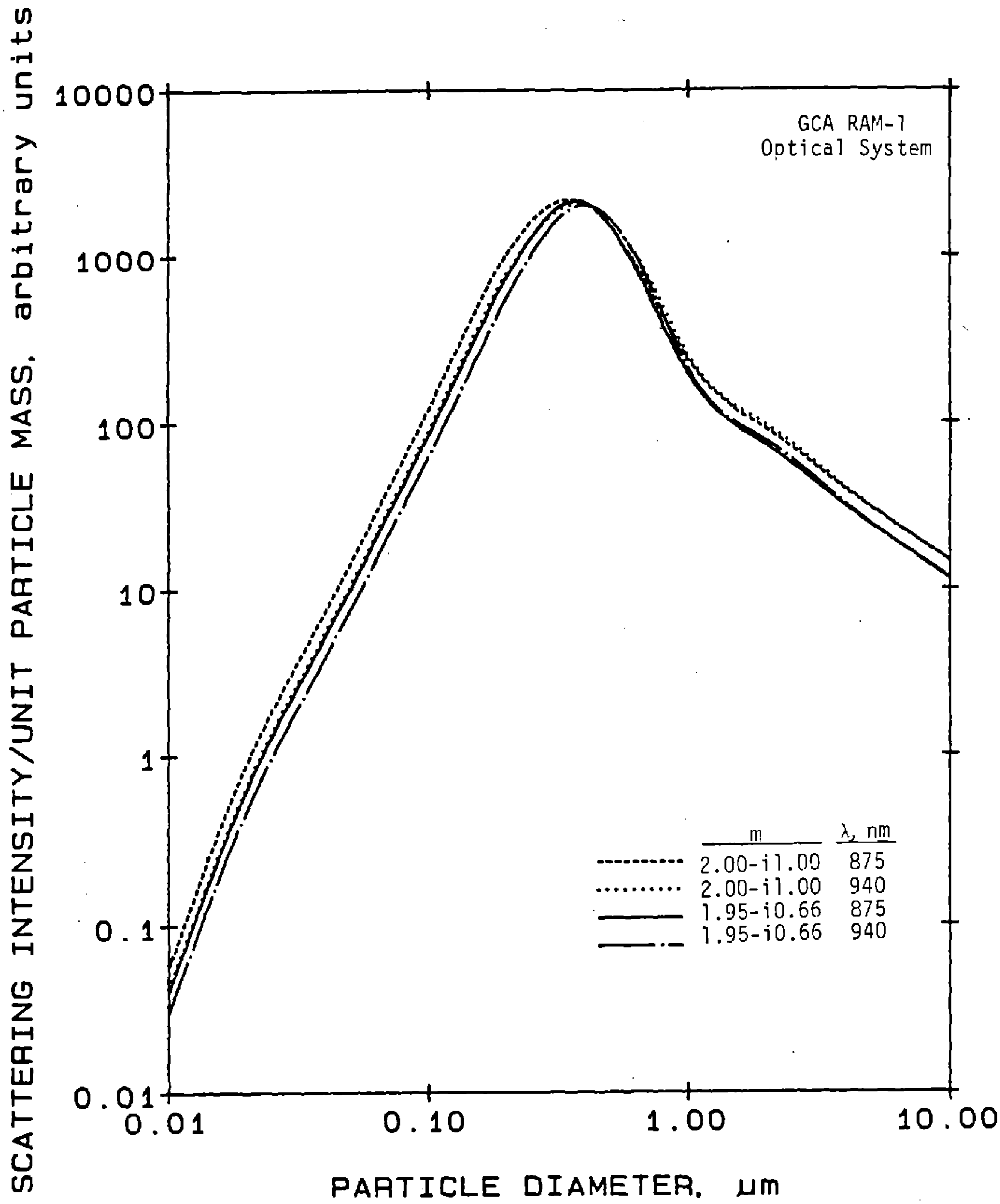


Figure 4.1 Theoretically predicted GCA RAM-1 response to diesel exhaust particles.

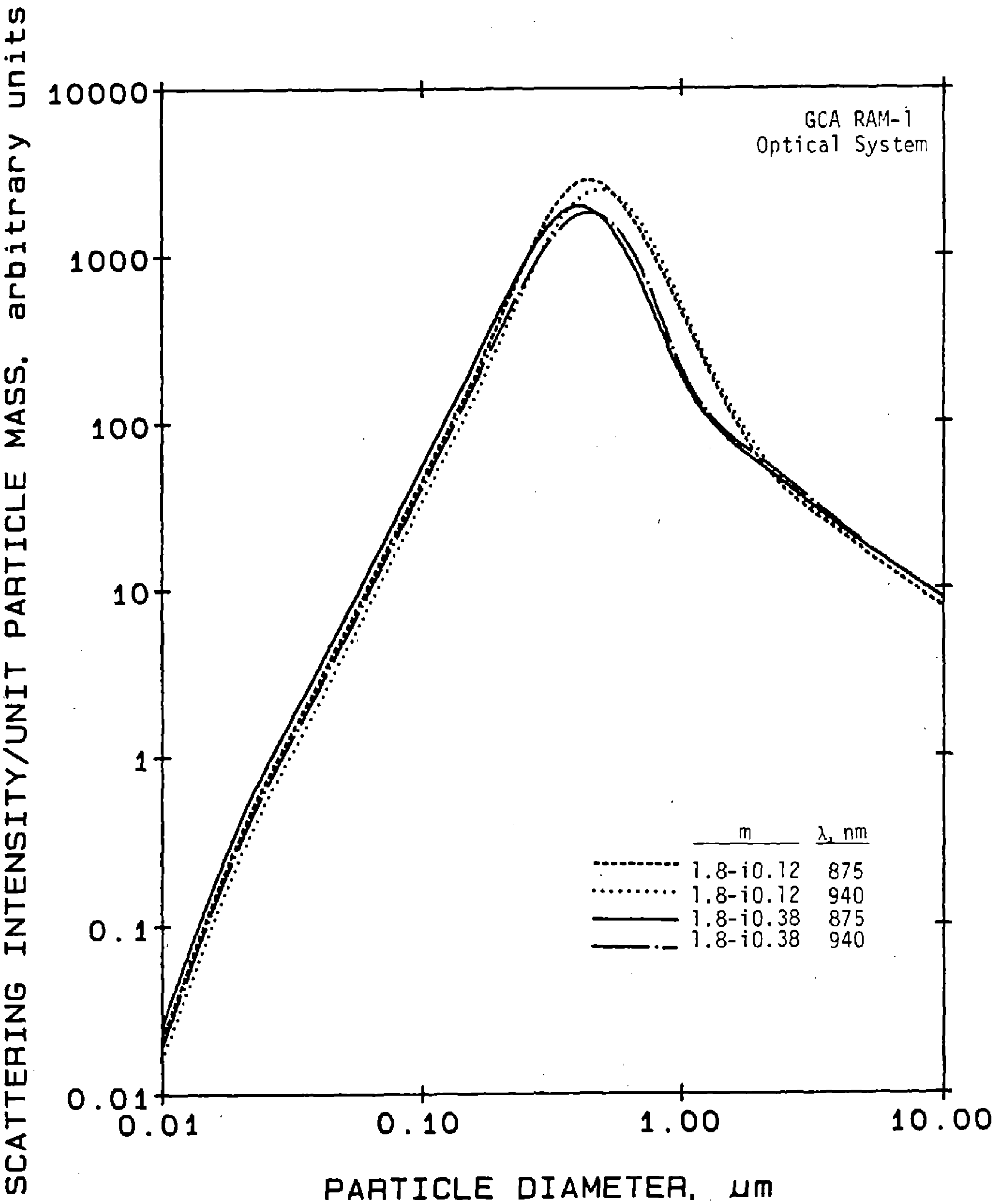


Figure 4.2 Theoretically predicted GCA RAM-1 response to coal particles.

photodetector, and the electronic gain in the RAM-1 circuitry would have to be known. The utility of these data is that the ratio of the data for any two particle sizes would be equivalent to that for the actual response.

Values for the theoretically determined scattering intensity per unit particle mass of diesel exhaust particles are presented in Figure 4.1. Results show the scattering to be highly dependent on particle size with a maximum scattering intensity occurring at approximately 0.4 µm. For smaller particles, the intensity decreases as the third power of particle diameter. For the limited variations in indices of refraction and wavelength, the scattering intensity varies by less than a factor of 2 for a given particle size in the submicrometer size range.

The theoretically determined scattering intensity per unit particle mass of coal dust particles for the GCA RAM-1 are presented in Figure 4.2 as a function of particle size. Results show the maximum scattering intensity occurs at approximately 0.4 µm. For smaller particles, the intensity decreases as the third power of particle diameter. For the various indices of refraction and wavelengths used, the scattering intensities vary by less than a factor of 2 for a given particle size as compared to the third order of magnitude variation with particle size.

The data in Figure 4.1 and 4.2 show the responses of the RAM-1 are similar for both coal and diesel exhaust particles. Responses to the two aerosols differ, at most, by a factor of 2. The relative difference is dependent on particle size.

4.2 Metrex Mineral/Diesel Photometer

An experimental evaluation of the response of the Metrex Mineral/Diesel Photometer to both coal dust and diesel exhaust particles was performed. This photometer was developed for the Canadian Centre for Mineral and Energy Technology, Energy, Mines and Resources by Metrex Instruments Ltd. (Metrex, 1984). The photometer distinguishes between the diesel exhaust particles and mineral dust by simultaneously monitoring the quantity of light scattered at two different light scattering geometries. The mineral matter is detected by light scattering at an average angle of 25 degrees while the diesel exhaust particles are detected at 90 degrees. Two light detectors are used, one for each set of scattering angles. Thus, the instrument can simultaneously measure the mass concentration of both the diesel exhaust and coal particles.

This photometer, like the GCA MINIRAM, is a passive sampler. Both contain no sampling pump, but instead rely on the convective air currents to transport the airborne particulate matter through the sensing volume.

The evaluation of the Metrex photometer proceeded in two phases. The first phase, which began in January, 1985 involved the evaluation of two prototype Diesel/Mineral Monitors. The responses of both units were found to be nonlinear with aerosol concentration and very erratic. These two units were returned to Metrex in April, 1985. One of the units was repaired and returned in September, 1985 for further evaluation.

During phase one, numerous tests were performed with the two Metrex photometers. Tests were conducted in a 0.012 m^3 test chamber specifically constructed for use in the diesel exhaust/coal aerosol experiments. A series of tests also were performed in an aerosol test chamber (Marple and Rubow, 1983a) using the same coal dust aerosols as used in the combined diesel exhaust/coal aerosol tests. In both sets of experiments two Metrex photometers, a GCA RAM-1 photometer and a filter sampler were used simultaneously to sample the test aerosol. These tests showed the response of both Metrex units to be nonlinear with aerosol concentration and very erratic. Conversations with the manufacturer revealed that modifications made to the units, just prior to shipment to the University of Minnesota, resulted in an electronics problem. The units were then returned to Metrex for repair.

Phase two involved evaluation of one repaired photometer. The study included zero stability tests and determination of the instrument response to coal dust and diesel exhaust particles.

The zero stability tests were performed by operating the instrument in a clean air hood. The air passing into the hood was drawn through HEPA filters. The zero response of the photometer was found to be unstable. The reading of the diesel exhaust indicator varied from 0.1 to 0.2. However, the response of the mineral dust indicator fluctuated at two different levels, i.e. reading between 0.7 to 1.0 about 2/3 of the time and 3.7 to 4.0 the remainder of the time. This oscillation between two ranges was also evident when responding to aerosols.

Tests with coal dust and diesel exhaust particles were conducted individually rather than with mixtures. The coal dust response tests were conducted in the aerosol test chamber with the coal dust aerosol produced with a TSI Model 3400 Fluidized Bed Aerosol Generator. This test series was initially intended to be exploratory, rather than a definitive calibration. Thus, the coal dust concentration was monitored with a GCA RAM-1 photometer rather than gravimetrically determined. The two photometers were operated adjacent to one another in the chamber. The coal dust concentration was varied from 6 to 17 mg/m^3. Through previous calibrations, the RAM-1 had been shown to respond linearly with mass concentration (Marple and Rubow, 1984). Furthermore, the response was within 20% of the gravimetrically determined concentration.

The responses of the mineral dust and diesel exhaust indicators in the Metrex unit are shown in Figure 4.3 as a function of the GCA RAM-1 photometer response. The responses of the mineral dust and diesel exhaust indicators were linear and approximately 1.5 and 0.05 times the RAM-1 response. For example, the responses of the mineral dust and diesel exhaust indicators were 23 and 0.8 mg/m^3, respectively, when the RAM-1 response was 15 mg/m^3.

The response of the Metrex photometer to diesel exhaust was determined by passing diluted and undiluted diesel exhaust through a 0.012 m^3 test chamber. The chamber contained the Metrex photometer and a gravimetric sampler. The chamber had a Plexiglas window to allow for viewing of the photometer displays. The diesel exhaust particle concentration was determined simultaneously through gravimetric analysis. The diesel engine test setup was as described in Section 3.1.

The response of the Metrex photometer to diesel exhaust was determined at mass concentrations of 0.76 and 25 mg/m^3. At the lower mass concentration, the response of the diesel exhaust indicator was 0.2 while the mineral

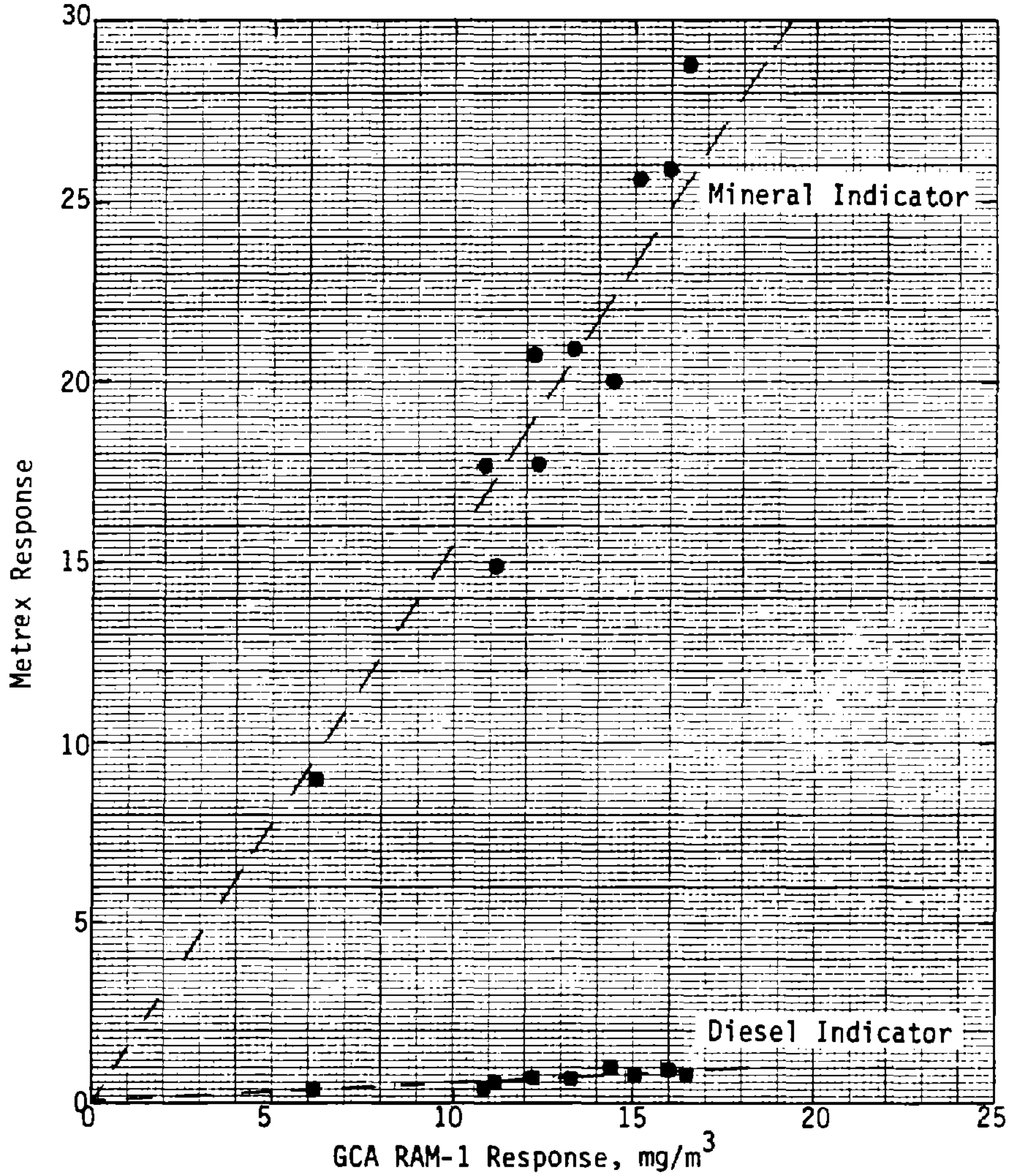


Figure 4.3 Response of Metrex photometer to coal dust.

indicator oscillated between 0.8 and 4.4. At a diesel exhaust concentration of 25 mg/m^3, the corresponding responses were 0.6 and 2.1, respectively. These results show that not only is the photometer very insensitive to diesel exhaust, but the mineral dust sensor is actually more sensitive.

Based on these results, no additional experiments were performed with the Metrex photometer. In conclusion, the unit has not performed as the manufacturer has intended. However, no conclusion can be drawn as to the soundness of the concept due to what are judged to be electronic problems with all units used in the evaluation studies.

CHAPTER 5

RECOMMENDED METHODS, INSTRUMENTS AND TEST PLAN FOR MEASUREMENT OF DIESEL EXHAUST AND MINERAL DUST PARTICLES IN UNDERGROUND MINES

The recommended instrumentation, sampling methodology, and field test plan are presented in this chapter. A review of various measurement techniques that could be used for time-integrated and real-time mass concentration measurements of the diesel exhaust and mineral dust components of underground mine aerosol is given followed by the recommended methods. Furthermore, a technique for determining the size distribution of the overall mine aerosol on the basis of aerodynamic size is given. The field test plan details the approach that the Bureau of Mines could use in an underground mine sampling program. The intent of this sampling program would be to verify the time-integrated test method recommended for determining the diesel exhaust particle concentration in the respirable aerosol as well as to measure the overall size distribution of the mine aerosol.

5.1 Recommended Measurement Methods

The objective of this contract is to the develop methods for determining respirable size diesel exhaust and mineral related particle mass concentrations and size distribution in underground mines. For the mass concentration measurements, a variety of techniques have been considered, including both time-integrated and real-time methods.

5.1.1 Time-Integrating Methods

The methods chosen must be capable of differentiating between diesel exhaust and mineral related particles in respirable dust. This differentiation might be accomplished either physically or chemically. For example, in the case of time-integrated measurements, filter samples of respirable dust might be collected and analyzed chemically to determine the mass fractions due to diesel exhaust and mineral dust sources. Such measurements have been made by Johnson (1985) using Raman scattering analysis to differentiate between carbon particles produced by diesel engines and other particles, including carbon particles produced by coal mining.

Alternatively, diesel exhaust and mineral dust particles might be differentiated by physical means. Size measurements made on diesel exhaust particles and mechanically generated dusts indicate significant differences in particle size. Typically diesel exhaust particles are found to be in the 0.1 to 0.5 μm diameter range while the mass median diameter of respirable dust aerosols are in the 2 to 5 μm size range. Physical differentiation based on size distribution measurements should be much less expensive than chemical analysis. Thus, this method is recommended for time-integrated measurements. In the developmental stages of this method, the complete particle size distribution must be measured. The specific device selected to make these time-integrated measurements is a MOUDI.

The MOUDI is recommended over other cascade impactors because of its ability to classify particles from less than 0.1 μm to 10 μm, high flow rate,

and high mass loading capabilities. Low pressure impactors are also capable of obtaining particle classification down to 0.1 µm. Particle classification in this size range is necessary due to the existence of diesel exhaust particles in this size range. However, the flow rate of low pressure impactors is typically 3 L/min compared to 30 L/min for the MOUDI. More importantly, the MOUDI has higher mass loading capabilities than low pressure impactors because the impactor substrates are rotated relative to the impactor nozzle, thereby collecting particles over a greater portion of the impaction substrate. Also, the possibility of particle bounce from overloaded impaction substrates is greater in low pressure impactors due to the much higher jet velocities used to achieve particle classification.

The MOUDI, described in Section 2.5, can be used to determine particle size distributions in the 0.05 to 10 µm diameter range and can resolve the particle size distribution of combustion-generated and mechanically-generated particles. From this size distribution, the diesel exhaust and mineral dust components can then be determined.

Laboratory experiments successfully showed that the separation of diesel exhaust and coal dust particles on the basis of size could be obtained with the MOUDI. The test results showed that the size distribution of the combined diesel exhaust/coal dust aerosol consisted of two distinct modes which could be separated at a particle diameter in the 0.7 to 1.0 µm size range. The diesel exhaust particles are primarily less than about 0.7 µm while the coal particles are greater than 0.7 µm. By use of the seven stage MOUDI with cut sizes ranging from 0.1 to 10 µm, sufficient data could be obtained to define the two modes. Although the MOUDI can be used with cut sizes lower than 0.1 µm, these smaller cutsizes are not necessary to define the diesel exhaust mode.

The MOUDI has been recommended as the device to be used during exploratory studies for determining the diesel exhaust and mineral dust concentrations in mine aerosols. This determination is made on by separating the mineral dust from the diesel exhaust particles on the basis of size. Once the point of separation, i.e. the particle size separating the size distributions of diesel exhaust and mineral dust particles has been determined, two simple parallel filter samplers could be used to made subsequent measurements on a time-integrated basis. Both would consist of a preclassifier, such as a cyclone or respirable impactor, to remove the nonrespirable particles. One sampler would also contain a second classifier with a cutsize corresponding to the point of separation between the diesel exhaust and mineral dust particles.

5.1.2 Real-Time Methods

Several real-time measurement techniques might be used to determine diesel exhaust and mineral dust particle concentrations. Evaluations of such techniques have, for the most part, been limited to conceptual rather than experimental studies because of limited access to these instruments. The instruments considered were the piezoelectric balance (Olin and Sem, 1971), the laser spectrophone (Faxvog and Raessler, 1979), long wavelength infrared adsorption developed by AVL (Krempl et al., 1985), the tapered element oscillating microbalance (Whitby et al., 1985), a method based on filter pressure drops which has been tested by Toyota and General Motors (Naguchi et al., 1981) and by Kittelson et al. (1983), GCA RAM-1 and MINIRAM photometers (GCA Corp., Bedford, MA; Marple and Rubow, 1984b), and the Metrex

Mineral/Diesel Photometer (Metrex Instruments Ltd., Brampton, Ont.; Metrex, 1984).

Except for the Metrex photometer, the real-time measurement techniques would all sense both diesel exhaust and mineral particles and would not be able to differentiate between them. However, if these devices are used in combination with a preclassifying inertial separator, the diesel exhaust and mineral particles might be easily separated. For example, if the GCA RAM-1 or MINIRAM photometer is placed downstream of a 0.7 µm cutsize separator, the separator should remove most of the particles in the mineral dust size range. Thus, the system should be capable of giving real-time measurements of the diesel exhaust component of the respirable particles. If two photometers were used, one with a 0.7 µm cutsize impactor, and one with a respirable dust preclassifier, the diesel exhaust and respirable mineral dust components of the aerosol might be monitored simultaneously. These measurements would, however, be subject to limitations imposed by the size distribution and composition dependence of photometers described below.

The piezobalance does not appear to be suitable for these measurements. Laboratory experiments (Marple and Rubow, 1981) indicate that it is very difficult to sense diesel exhaust particles with this type of sensor. Diesel exhaust particles do not bind to the surface of the piezoelectric crystal sufficiently well to change its natural frequency. Thus, the instrument underestimates the concentration of diesel exhaust particles.

Laser spectrophone devices have been used to sense diesel exhaust particles in real-time by a number of investigators (Faxvog and Raessler, 1979). Although these devices have shown promising results, they are extremely expensive and designed for relatively high mass concentrations, e.g. 2 to 20 mg/m^3. The estimated cost of such an instrument is in excess of $50,000. Thus, these devices would probably not be suitable for in-mine use.

The AVL long-wave length light adsorption photometer also has given promising results for the real-time measurement of diesel exhaust particles (Krempl et al., 1985). However, like the laser spectrophone, it is large, expensive and applicable to the measurement of high mass concentrations. Thus, this technique would not be suitable for in-mine applications.

The tapered element oscillating microbalance has been shown to be capable of making real-time measurements of diesel exhaust particle concentrations under highly transient conditions (Whitby et al., 1985). Although this device is considerably more compact and less expensive than the two optical devices mentioned above, it is probably still too expensive to be used in a mine. The price of this instrument is about $20,000.

Measurements based on filter pressure drop have been shown to be relatively accurate under laboratory conditions (Naguchi et al., 1981, Kittelson et al., 1983). The pressure drop across a filter is monitored as it loads with diesel exhaust particles. The rate of increase in pressure drop gives the cumulative mass collected. Such a system, combined with an inertial preclassifier, might be used to monitor diesel exhaust particle concentrations in mines. In principle, such measurements could be made with a relatively inexpensive device. It might be worthwhile to encourage development of such an instrument. No manufacturer offers a commercial version of the instrument.

GCA RAM-1 and MINIRAM photometers are relatively portable and inexpensive devices that may be used for sampling diesel exhaust particles and other respirable dusts. However, the responses of these instruments are sensitive to particle size (Section 4.1) and composition (Marple and Rubow, 1984b). Although this particle size and composition dependency makes these instruments less attractive, they still may be useful in a semi-quantitative, real-time mode.

The Canadian Metrex Mineral/Diesel Photometer is designed to make simultaneous real-time measurements of particles in the diesel exhaust size range and particles in the mineral dust size range. In principle, the Metrex photometer can distinguish between the diesel exhaust particles and the mineral dust by monitoring the quantity of light at two different light scattering geometries. The instrument is described in more detail in Section 4.2. In principle, such an instrument might be quite attractive, although it may still have particle size and composition dependence. The applicability of this instrument has yet to be experimentally verified (Section 4.2).

Based on these considerations, the real-time packages selected for further consideration are the inertial preclassifier followed by a GCA photometer and the Metrex Mineral/Diesel Photometer if the electronic problems can be resolved. These real-time measurement methods deserve further consideration, but have not yet reached the stage of development to be considered as fully recommended methods.

The GCA RAM-1 and MINIRAM photometers, as currently configured, are designed to monitor the respirable dust concentration in the underground mine environment. Both use laser diodes as the light source. The RAM-1 has an integral pump, whereas, the MINIRAM is a passive sampler with an optional pump attachment available. The RAM-1 uses a 10 mm nylon cyclone as the preclassifier to remove the larger nonrespirable particles, while the MINIRAM optically senses only the respirable fraction.

These devices could be used in conjunction with a simple inertial classifier, for example, an impactor, cyclone or virtual impactor, to exclude the larger mechanically generated particles from its sensing volume. Thus, the device would only detect diesel exhaust particles.

5.2 Test Plan for Field Sampling

The field test plan details the sampling protocol recommended when using the MOUDI in underground coal mine sampling programs. The MOUDI is used to obtain the overall size distribution of the combined diesel exhaust/coal dust aerosol. From this size distribution, the diesel exhaust and coal dust components can be determined.

The objective of the field sampling program is to measure the overall size distribution of airborne diesel exhaust and coal dust particles with the MOUDI and then to determine the degree of particle size separation between the diesel exhaust and coal aerosol modes. In addition, the location of and variation in the point of separation between the two modes is to be determined. The particle size distribution should be measured in a number of locations within a number of mines to verify that the modes of the diesel exhaust and coal particles can be separated under a wide variety of mine conditions. The mines should include coal mines using diesel-powered equipment to determine if the two modes can be found, nondiesel-powered coal mines to determine whether or not there is a natural coal particle size mode in the less than 0.7 µm diameter range, and diesel-powered noncoal mines to again check whether or not the size distributions are also separated into two modes.

Using the MOUDI in a coal mine may be difficult since the flow rate through the MOUDI is 30 L/min and a permissable pump with this flow rate does not exist. It is therefore recommended that the pump to placed in a clean air intake or some other suitable safe location and vacuum lines run to the MOUDI for these tests.

The procedures for sample preparation and use of the MOUDI in a mine are as follows:

1. Coat 37 mm aluminum foil impaction substrates with silicone spray using a mask to coat only the central 33 mm of the foil.
2. Dry silicone in oven at 150^{o} F for 1 hr to ensure complete evaporation of solvents.
3. Preweigh foil using microbalance and mount on impaction plate.
4. Preweigh 37 mm afterfilter using microbalance and mount in MOUDI filter holder.
5. If a nonpermissable pump is used with the MOUDI in a coal mine, the pump will have to be placed in a clean air intake with a vacuum line connected to the impactor.
6. The flow rate through the MOUDI is 30 L/min which can be determined by monitoring the pressure drop across the MOUDI with the pressure gage provided with the MOUDI.
7. Alternate stages of the MOUDI must be rotated during a test to minimize particle bounce from overloaded impaction deposits.
8. A typical test may last about 1 hr for respirable mass concentrations on the order of 2 mg/m^3.
9. Post weigh impaction substrates and afterfilter.
10. Data reduction and analysis is same as for any conventional impactor.

CHAPTER 6

FIELD STUDIES

The objective of the field study was to determine if the diesel exhaust and coal dust particles could be separated on the basis of particle size. Tests were conducted in both diesel- and electric-powered underground coal mines so that aerosol size distribution could be measured with and without the presence of diesel exhaust particles. These data can then be used to determine the fraction of submicrometer diameter size coal and diesel exhaust particles in respirable aerosol and to determine if a distinction can be made between respirable coal dust and diesel exhaust particles on the basis of particle size. Thus, these measurements will be a check on measurements made in the laboratory.

All tests were performed with Dr. Bruce Cantrell of the Twin Cities Research Center (TCRC). This portion of the contract was implemented by providing technical support to the Bureau of Mines. The data presented in this chapter reflect the work performed by the University of Minnesota. Data gathered by Cantrell will be published separately by the TCRC (Cantrell et al., 1986).

6.1 Instrumentation and Test Procedures

Two types of experiments were conducted. The first utilized the MOUDI to obtain the overall size distribution of the diesel exhaust and coal dust aerosols. Two identical MOUDI's were used in the field sampling so that size distributions could be obtained simultaneously at two locations in the mine. Each mode of the resulting bimodal size distribution was analyzed using the DISFIT size distribution program to obtain the mass median diameter, MMD, and geometric standard deviation, σ_g, of the mode.

The second set of experiments involved collecting size classified particle samples for elemental analysis. For each test, two samples were obtained. The first consisted of respirable particles greater than 0.7 µm and the other particles less than 0.7 µm. Quantitative elemental analysis was then performed on each sample using neutron activation analysis. The objective of these tests was to determine the fraction of coal, rock dust and diesel exhaust particles in the particle size fractions less than and greater than 0.7 µm.

The sampler consisted of a respirable impactor followed by two 0.7 µm cutsize MOUDI stages and an afterfilter. The particle cutsize was 0.7 µm for both stages. The second stage was used to collect those particles larger than 0.7 µm which may not be collected on the first stage as a result of particle bounce and other nonideal effects. Thus, three samples were obtained, two consisting of respirable particles greater than 0.7 µm and the other consisting of particles less than 0.7 µm. The particle collection characteristics of the respirable impactor approximate the ACGIH respirable dust criteria (Marple, 1978). A description of the respirable impactor used in these tests is given by Marple and Rubow (1984b). The sample flow rate was 30 L/min. The impaction substrates were 37 mm diameter Nuclepore filter material that contained no pores. The impaction substrate was coated with Vaseline to prevent particle bounce. Vaseline was used instead of silicone because it has a low elemental background. The afterfilter was a Gelman type P5PJ037 Zeflour filter. The collected particle samples were analyzed using neutron activation to determine the elemental composition of particles in each size range. In addition, samples of the diesel fuel, coal and limestone, which was used as a rock dust, were collected and subjected to neutron activation analysis. Based on the elemental analysis of each of the three bulk materials, the fractions of diesel exhaust, coal and limestone in each of the aerosol samples split at 0.7 µm could be determined. The analysis was performed using source apportionment methods. This technique would then serve as an independent method to determine if the diesel exhaust/coal aerosol mixtures can be separated at 0.7 µm.

6.2 Mine Description

Tests were performed in three mines. Two utilized diesel-powered equipment while the third exclusively used electric power. The third mine was included as a control to obtain the submicrometer size distribution of coal and rock dust without the presence of diesel exhaust particles. The three mines are identified as 1, 2 and 3 with Mines 1 and 2 utilizing diesel-powered equipment. The two diesel mines are located in the western U. S. while Mine 3 was an eastern mine.

The field studies in the two diesel-powered mines were conducted jointly with Mr. Joseph Cocalis of NIOSH. This joint project resulted from similar test objectives between this contract and the Bureau of Mines's contract with NIOSH.

Schematic diagrams of the test sections in each of the three mines are presented in Figure 6.1. Each diagram shows the location of the working faces, feeder breaker, beltway, and pathway of mine ventilation airflow.

The sampling sites in all three mines are also shown in Figure 6.1. Four sites were used, namely the intake (I), the primary return (R), along the beltway (B) and adjacent to the main haulage way (H). The beltway sites were located 30 m away from the feeder breaker. In Mines 1 and 3 the beltway was located in the secondary return. The beltway was in the secondary intake for Mine 2.

Sampling in the return was performed with and without rock dusting occurring at the face.

6.3 Particle Size Distribution Results

Table 6.1 summarizes the tests conducted in the three field trips. This table contains the number of sampling days at each mine and the number of tests performed at each location. A total of 28 size distribution tests were performed in the two diesel-powered mines while 17 were obtained in the electric-powered mine. Nine aerosol samples were collected for elemental analysis in the diesel-powered mine while four were collected in the electric-powered mine.

A summary of each size distribution test performed is given in Table 6.2. The test number, mine number, mine equipment type, date, time and sampling site are listed for each test run. Tests were conducted at four different types of sites representing a total of 9 different mining activities. In particular,

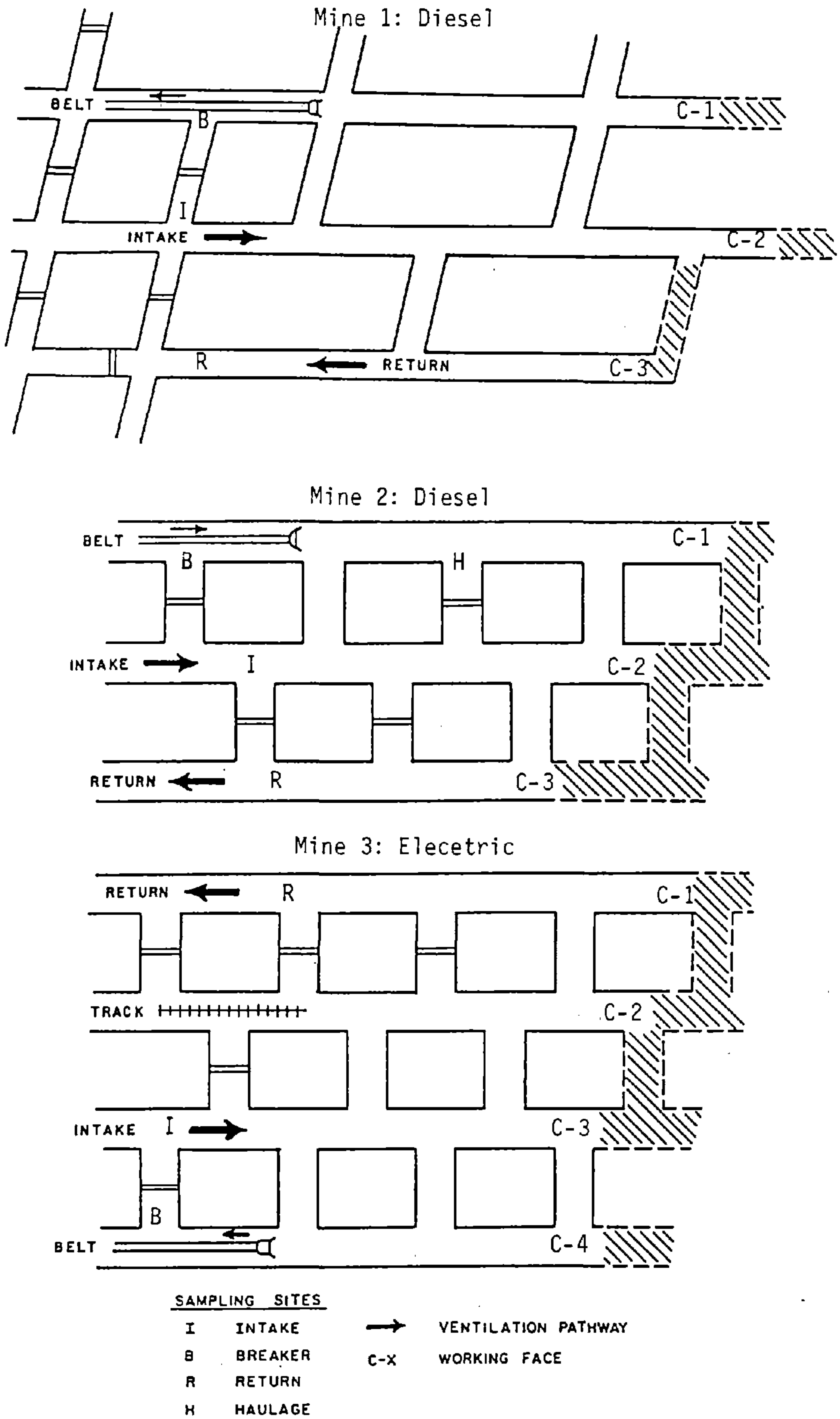


Figure 6.1 Schematic diagram of the test sections in three underground coal mines.

Table 6.1

Summary of Tests Performed
in Continuous Mining section
of Underground Coal Mines

Mine	Equipment Power Source	Number of Sampling Days	Type of Test	Number of Tests Performed at Mine Location: Intake	Belt/Breaker	Haulage	Return	Total Number of Tests
1	Diesel	3	SD	1	6	-	3	10
			NA	1	3	-	-	4
2	Diesel	4	SD	4	2	9	3	18
			NA	1	-	4	-	5
3	Electric	3	SD	3	7	-	5	15
			NA	-	4	-	-	4

SD = Aerosol size distribution test using MOUDI impactor

NA = Aerosol sample collected for neutron activation analysis

Table 6.2

Summary of Size Distribution Tests
Performed in Three Coal Mines

Test Number	Mine	Mine Equipment	Date	Sample Time, Hr	Sampling Site
WI-1	1	Diesel	5-17-85	12:32-13:32	Intake[1]
WB-1	"	"	5-15-85	10:10-11:00	Breaker[2]
WB-2	"	"	"	12:00-13:00	Beltway[3]
WB-3	"	"	5-16-85	09:50-11:00	"
WB-4	"	"	"	11:20-12:20	"
WB-5	"	"	"	13:01-14:01	"
WB-6	"	"	5-17-85	10:36-11:36	"
WR-1	"	"	5-16-85	09:57-10:19	Return[10]
WR-2	"	"	"	11:19-11:39	Return[9]
WR-3	"	"	"	13:15-13:45	"
UI-1	2	"	2-17-86	10:35-14:45	Intake[1]
UI-2	"	"	2-18-86	09:25-14:15	"
UI-3	"	"	2-19-86	09:28-11:28	"
UI-4	"	"	2-20-86	08:38-10:38	"
UB-1	"	"	2-17-86	11:10-12:12	Beltway[5]
UB-2	"	"	"	13:00-14:25	"
UH-1	"	"	2-18-86	09:25-10:28	Haulage Way[7]
UH-2	"	"	"	10:49-11:40	Haulage Way[6]
UH-3	"	"	"	12:33-14:33	"
UH-4	"	"	2-19-86	08:32-09:52	"
UH-5	"	"	"	11:32-12:33	"
UH-6	"	"	"	13:23-14:15	"
UH-7	"	"	2-20-86	08:32-09:22	"
UH-8	"	"	"	10:07-11:30	"

Table 6.2 continued

Test Number	Mine	Mine Equipment	Date	Sample Time, Hr	Sampling Site
UH-9	2	Diesel	2-20-86	12:32-13:32	Haulage Way[6]
UR-1	"	"	2-19-86	12:36-12:56	Return[8]
UR-2	"	"	2-20-86	11:18-11:23	"
UR-3	"	"	"	12:41-12:51	"
PI-1	3	Electric	3-25-86	11:26-14:45	Intake[1]
PI-2	"	"	3-26-86	09:43-13:43	"
PI-3	"	"	3-27-86	09:12-13:12	"
PB-1	"	"	3-25-86	10:41-11:13	Beltway[4]
PB-2	"	"	"	12:47-14:47	Beltway[3]
PB-3	"	"	3-26-86	12:07-14:07	"
PB-4	"	"	"	14:28-15:28	"
PB-5	"	"	3-27-86	11:01-12:01	"
PB-6	"	"	"	12:17-13:17	"
PB-7	"	"	"	13:33-14:33	"
PR-1	"	"	3-26-86	10:44-10:54	Return[9]
PR-2	"	"	"	11:20-11:25	Return[8]
PR-3	"	"	3-27-86	09:19-09:29	Return[9]
PR-4	"	"	"	09:49-09:59	Return[11]
PR-5	"	"	"	10:17-10:27	Return[9]

[1] Primary intake to section

[2] Adjacent to feeder breaker in secondary return

[3] Adjacent to beltway in secondary return

[4] Adjacent to beltway in secondary return - rock dusting intake

[5] Adjacent to beltway in secondary intake

Table 6.2 continued

[6] Adjacent to haulage way and down wind of beltway - hauling coal

[7] Adjacent to haulage way and down wind of beltway - no hauling

[8] Primary return during normal mining operation with trickle dusting

[9] Primary return during normal mining operation with no trickle dusting

[10] Primary return during rock dusting at face

[11] Primary return - no mining but ventilation fans at face turned on

tests were conducted with and without the presence of rock dust in order to ascertain the additional affect of rock dust on the coal and diesel exhaust size distributions. Tests were performed in a wide variety of mining conditions in order to obtain a wide variation in the diesel exhaust aerosol fraction and overall aerosol mass concentrations. In particular, samples were obtained in the return airway to determine if the diesel exhaust aerosol mode would be obscured by a very high fraction of coal or rock dust. Duplicate tests were conducted to determine the variability in the aerosol size distribution.

The length of each test, as determined from the sampling times presented in Table 6.1, ranged from 5 min to 4 hr. Tests in the intake varied from 1 to 4 hrs with most lasting 4 hrs. The sampling time in the beltway and haulage way was usually 1 hr. The return tests ranged from 5 to 20 min. No tests were conducted over an entire shift. The sampling period was set by the anticipated quantity of mass collected in the MOUDI, which was related to the mining activity, and to obtain a representative aerosol sample for each sampling location. The tests at the beltway, return and haulage way were structured to encompass a period of continuous mining activity.

The measured size distributions from all tests are presented in Appendix A. All particle size analysis is on the basis of aerodynamic equivalent diameter. In determining the aerosol size distribution, a lower particle size limit of 0.05 µm was assumed for the diesel exhaust particles collected on the afterfilter. Based on inlet sampling efficiency considerations, an upper size limit of 25 µm was assumed for the particles collected on the first stage of the MOUDI for the data collected in Mine 1. The MOUDI was used with a preimpactor stage for tests in Mines 2 and 3. The cutsize of the preimpactor was 18 µm. As was described in Section 3.3, the histograms represent the experimental data. The lognormal size distribution curves were obtained from the size distribution analysis performed by DISFIT. The MMD and σ_g of each mode are presented in Table 6.3.

The data obtained during tests PB-3 to PB-7, PR-1, PR-3 and PR-4 show a concentration spike in the 0.05 to 0.10 µm size range. This range corresponds to the particles collected on the afterfilter. Since no material was collected on the last two stages of the MOUDI, the data resulting from material collected on the afterfilter are thought to be erroneous. The same MOUDI was used for all tests performed at the return and beltway sites. The data obtained on 3-25-86, i.e. Tests PB-1 and PB-2, showed no significant material collected on the last two stages of the MOUDI or the afterfilter. However, tests performed on the two subsequent days, 3-26-86 and 3-27-86, i.e. tests PB-3 to PB-7 and some of the return samples show material collected on the afterfilter. The particles collected on the filter probably entered the MOUDI through a very small air leak between stage 7 and the afterfilter since no particles were found on the impaction substrates for Stages 6 and 7.

Typical size distributions measured in Mine 2, a diesel-powered mine, are presented in Figure 6.2. Data are shown for sampling sites in the primary intake and return, along the beltway, and in the main haulage way. The overall mass concentrations for these four tests were 0.40, 127.0, 1.93 and 1.68 mg/m^3. The ratio of the mass of material less than 0.7 µm diameter to the total mass was 30%, 1.2%, 4.7% and 45%, respectively. For the return data presented in Figure 6.1a, the fraction of mass for particles less than 0.7 µm

Table 6.3

Modal Parameters of Size Distributions Measured in Three Coal Mines

Test Number	Diesel Mode		Dust Mode	
	MMD, μm	σg	MMD, μm	σg
WI-1	0.15	2.10	10.3	3.02
WB-1	0.20	1.92	15.9	2.81
WB-2	0.17	1.72	16.3	3.78
WB-3	0.21	2.00	7.1	2.10
WB-4	0.15	1.70	8.6	2.67
WB-5	0.17	3.22	8.9	2.27
WB-6	0.18	1.80	15.0	2.50
WR-1	0.17	1.60	29.1	2.87
WR-2	0.22	1.70	9.9	2.50
WR-3	0.18	1.80	13.6	2.43
UI-1	0.13	2.50	6.79	1.70
UI-2	0.15	1.90	7.50	1.75
UI-3	--	--	5.78	2.17
UI-4	0.17	1.65	6.78	1.80
UB-1	0.15	1.60	7.41	2.83
UB-2	0.12	2.00	6.63	2.56
UH-1	0.16	1.60	3.28	2.51
UH-2	0.15	1.80	5.61	2.51
UH-3	0.15	1.80	5.61	2.51
UH-4	0.14	1.80	7.57	2.63
UH-5	0.09	3.00	5.79	2.65
UH-6	0.11	2.70	5.38	2.60
UH-7	0.15	1.67	8.63	3.07
UH-8	0.14	1.80	10.22	3.44

Table 6.3 continued

Test Number	Diesel Mode MMD, μm	Diesel Mode g	Dust Mode MMD, μm	Dust Mode g
UH-9	0.14	1.80	6.50	2.20
UR-1	0.17	1.80	7.55	1.90
UR-2	0.18	1.50	6.31	1.90
UR-3	0.18	1.70	6.02	2.00
PI-1	0.20	2.30	4.89	2.44
PI-2	0.21	2.54	3.80	1.85
PI-3	--	--	--	--
PB-1	--	--	4.65	1.87
PB-2	--	--	7.73	1.88
PB-3	--	--	8.71	2.31
PB-4	--	--	9.04	2.29
PB-5	--	--	9.47	2.14
PB-6	--	--	9.01	2.12
PB-7	--	--	9.01	2.14
PR-1	--	--	6.42	2.09
PR-2	--	--	5.73	1.98
PR-3	--	--	5.53	2.02
PR-4	--	--	5.75	1.94
PR-5	--	--	5.98	2.01

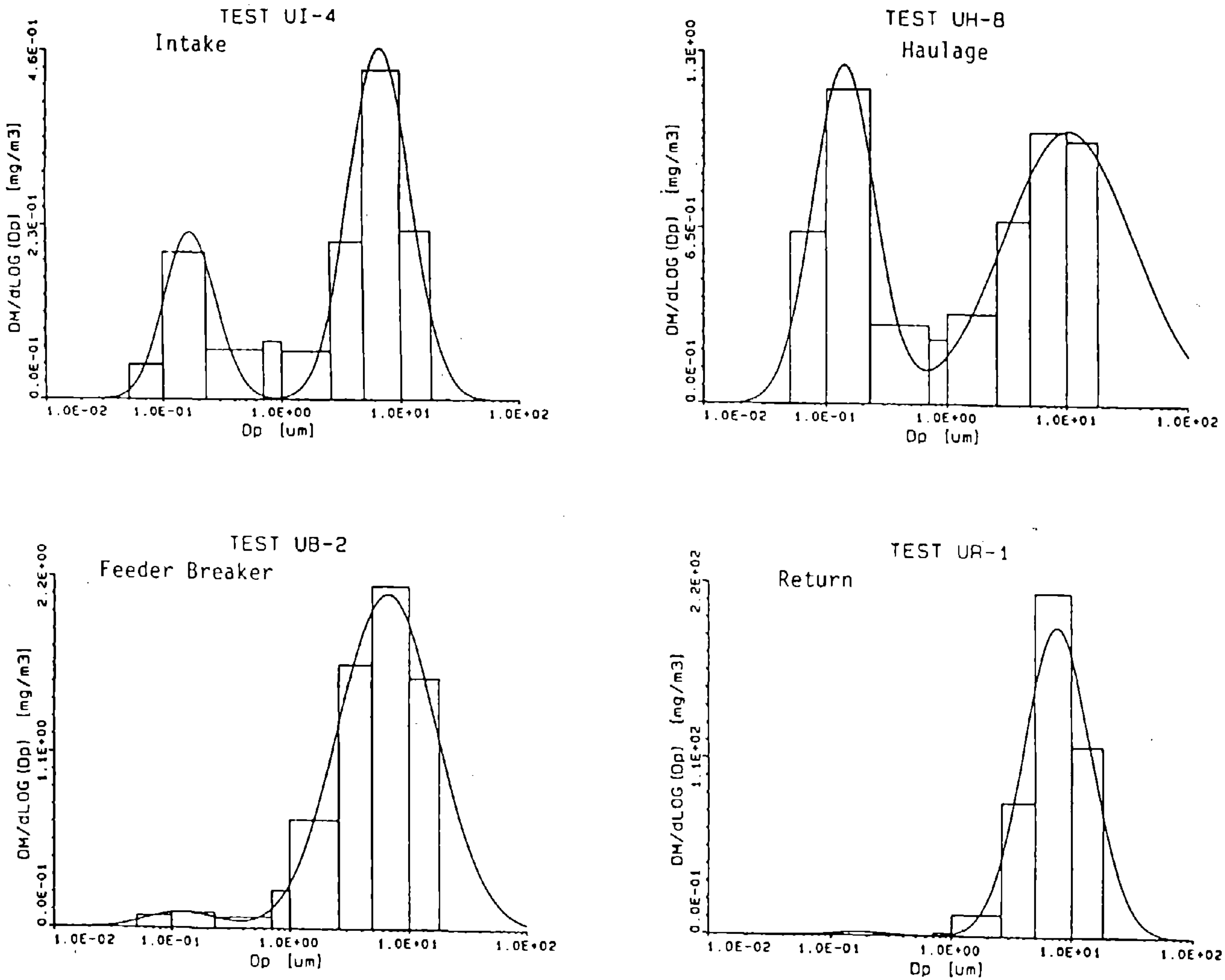


Figure 6.2 Typical particle size distributions measured at several locations in mine 2, a mine using diesel-powered equipment.

is only 1.2% of the total mass which makes the mode difficult to observe. However, on an expanded scale, the small particle mode is clearly separated from the large particle particle mode. The extremely high concentration in the return occurred during a rock dusting operation. These results show that, regardless of the sampling location, the mass concentration, or the ratio of particle was less than 0.7 µm to the total mass, there is clear separation between the two modes. The minimum exists in the 0.7 to 1.0 µm size range.

Typical size distributions measured in Mine 3 are presented in Figure 6.3. This mine exclusively utilized electric-powered equipment. Data are presented for sampling sites located in the intake, the return, and along the beltway. These size distributions show that essentially no mine generated aerosol is less than 0.7 µm. The aerosol in this range measured in the intake is most likely the background aerosol found in the outdoor air used for mine ventilation as this mass concentration is typical of that found in the ambient environment. The mass concentration in this mode is 0.01 mg/m^3, which is insignificant relative to typical mine aerosol mass concentrations.

When interrupting the data presented in Figure 6.2 and 6.3, note that different ordinate scales are used on each graph. In Figure 6.2, the scales for the return, beltway, and haulage way are 480, 4.8 and 2.8 times greater than that of the intake scale. In Figure 6.3 the scales for the return and the beltway are 210 and 100 times greater than for the return.

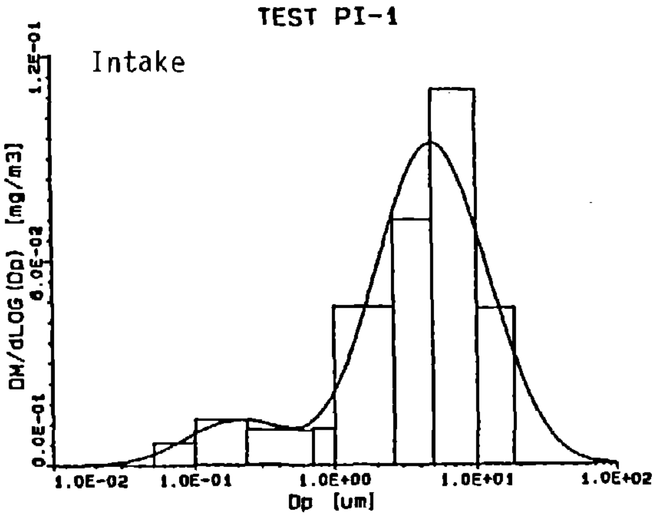
A composite graph showing typical size distributions as measured near the beltway is presented in Figure 6.4. A typical size distribution from each of the three mines is presented. The coarse particle modes, i.e the coal dust modes, are nearly identical for the three mines. Furthermore, the diesel exhaust particle modes are nearly identical. The size distribution from the electric mine clearly shows the absence of any mode in the submicrometer particle size range.

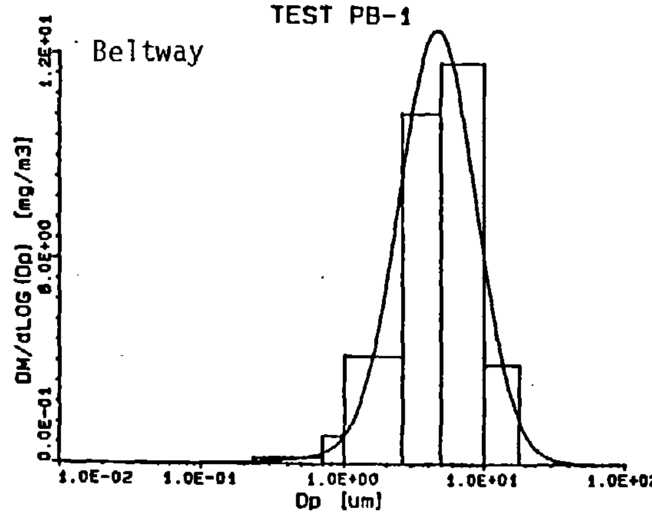
Table 6.4 summarizes the aerosol mass concentration data. The mode labeled "Fine" consists of aerosol less than 0.7 µm. The "Coarse" particle mode is all particles greater than 0.7 µm. This distinction is made at 0.7 µm as the minimum between the two modes occurs in the vicinity of 0.7 µm. In particular, the data show that the mass less than 0.7 µm relative to the total mass is 1.3% for Test PB-1, a test at the beltway in the electric-powered mine. In the diesel-powered mine, this ratio of fine to total particle mass typically ranged from 26% to 51% for the beltway and haulage way sites.

In summary, the data obtained from these three mines show that, regardless of the fraction of diesel exhaust in the aerosol, the aerosol size distribution is bimodal. Furthermore, the diesel exhaust mode is clearly separated from the dust particle mode, with the minimum between the two modes occurring in the 0.7 to 1.0 µm size range.

6.4 Neutron Activation Results

Chemical mass balance (CMB) model source apportionment analysis is being developed for application to the mining environment by Cantrell. This analysis will serve as a reference analysis method to validate the findings of the MOUDI measurements, i.e. diesel exhaust and coal dust can be separated on the basis of particle size. The CMB requires measurements of the chemical and elemental





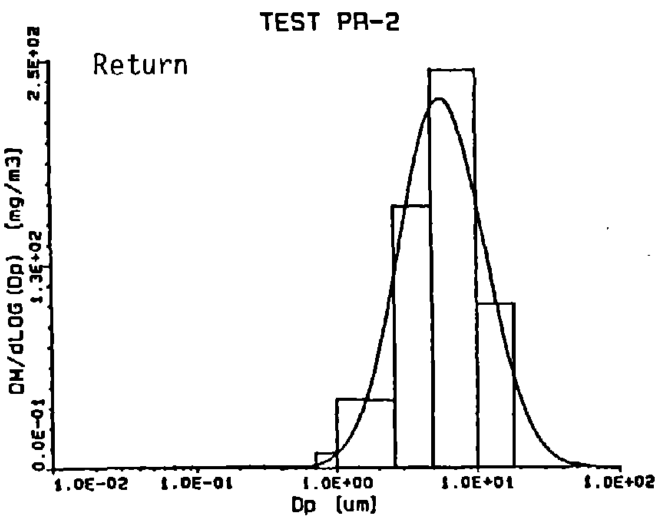


Figure 6.3 Typical particle size distributions measured at three locations in Mine 3, an electric-powered mine.

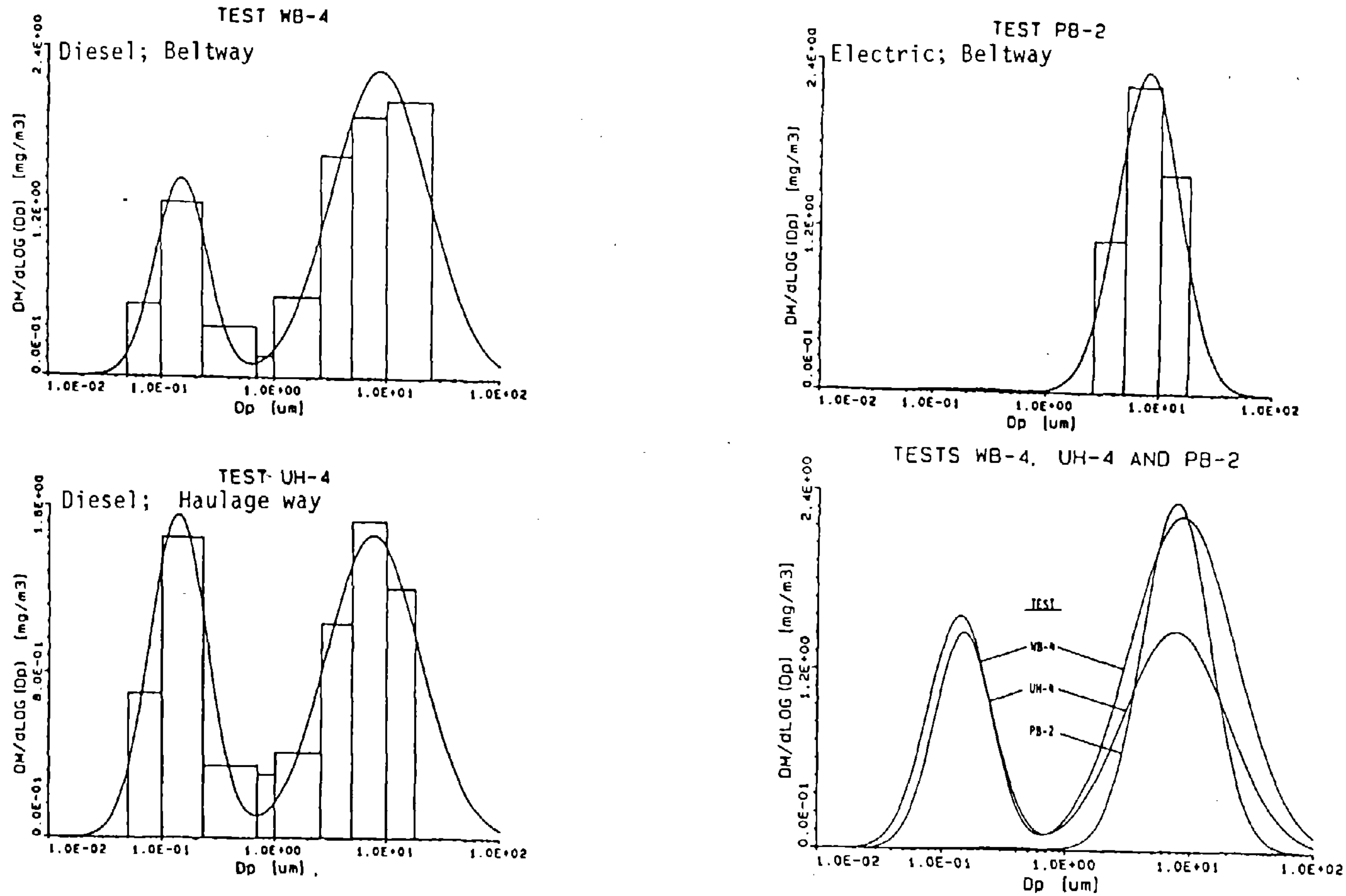


Figure 6.4 Comparisons of typical size distributions measured in all three mines.

Table 6.4

Summary of Aerosol Mass Concentration
Measured in Three Mines

Test Number	Aerosol Mass Concentration, mg/m^3 Total[1]	Fine[2]	Coarse[3]	Ratio Fine/Total
WI-1	**	0.23	**	--
WB-1	5.57	1.26	4.31	0.23
WB-2	2.51	1.09	1.42	0.41
WB-3	**	**	1.49	--
WB-4	2.91	0.72	2.19	0.25
WB-5	5.25	0.83	4.42	0.16
WB-6	2.66	1.45	1.21	0.54
WR-1	75.5	0.79	74.7	0.010
WR-2	**	**	10.3	--
WR-3	50.0	0.69	49.3	0.014
UI-1	**	**	0.74	--
UI-2	**	**	0.14	--
UI-3	**	**	0.17	--
UI-4	0.40	0.12	0.29	0.30
UB-1	**	0.11	**	--
UB-2	1.93	0.09	1.84	0.047
UH-1	0.58	0.15	0.43	0.26
UH-2	1.75	0.79	0.96	0.45
UH-3	1.61	0.78	0.83	0.48
UH-4	2.20	0.91	1.30	0.41
UH-5	3.77	1.96	1.81	0.52
UH-6	4.00	2.08	1.92	0.52
UH-7	1.19	0.50	0.69	0.42

Table 6.4 continued

Test Number	Aerosol Mass Concentration, mg/m³ Total[1]	Fine[2]	Coarse[3]	Ratio Fine/Total
UH-8	1.68	0.75	0.92	0.45
UH-9	1.51	0.72	0.79	0.48
UR-1	127.3	1.49	125.8	0.012
UR-2	13.3	1.81	11.5	0.14
UR-3	15.6	1.05	14.6	0.067
PI-1	0.10	0.01	0.09	0.10
PI-2	0.08	0.02	0.06	0.25
PI-3	**	**	**	--
PB-1	8.75	0.11	8.64	0.013
PB-2	**	0.01	**	--
PB-3	1.15	0.05	1.10	0.043
PB-4	1.66	0.20	1.46	0.12
PB-5	**	**	0.92	--
PB-6	**	**	1.00	--
PC-7	**	**	1.35	--
PR-1	23.1	0.35	22.7	0.015
PR-2	168.2	0.65	167.5	0.004
PR-3	**	**	24.4	--
PR-4	**	**	8.12	--
PR-5	**	**	34.1	--

1 Total measured aerosol

2 Particle diameters less than 0.7 μm

3 Particle diameters greater than 0.7 μm

** Incomplete data

components of both source and aerosol materials. These measurements were provided by instrumental neutron activation analysis.

Table 6.1 lists the aerosol samples obtained for the neutron activation analysis. In addition to the aerosol samples, samples of the coal, rock dust and diesel fuel were also submitted for analysis.

All results from the neutron activation analysis have not been received. Cantrell will conduct the data analysis using a source apportionment technique. The results from these three field trips will be reported by the TCRC in a separate publication.

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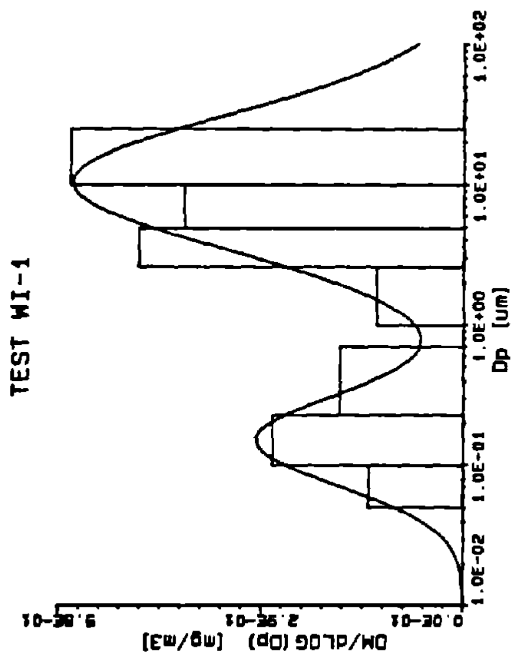
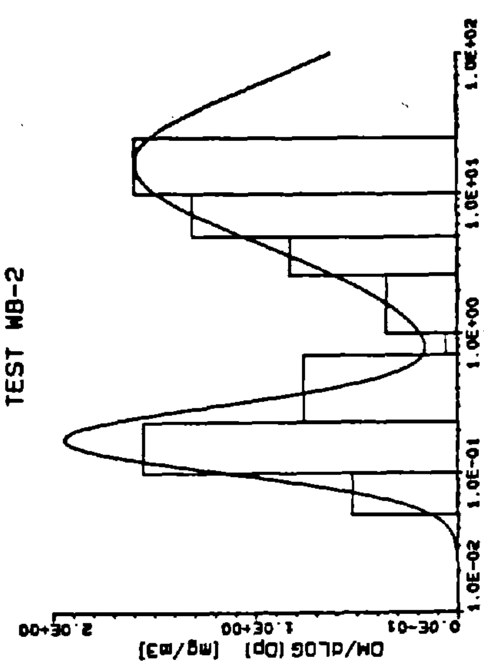
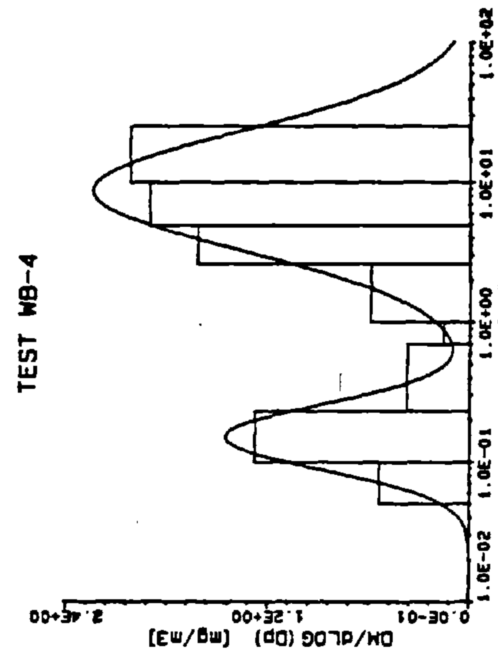
APPENDIX A

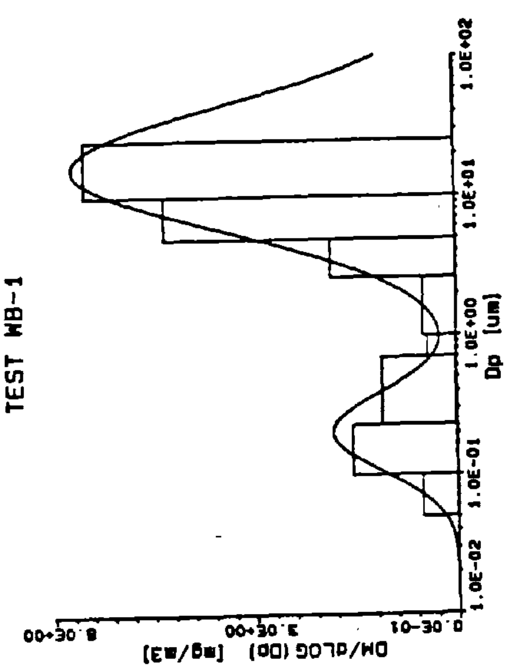
Particle Size Distribution Graphs from Field Trips

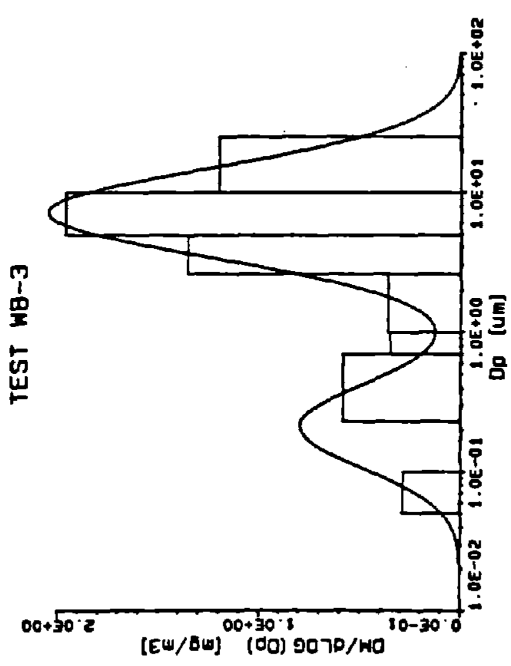
Size distribution graphs from data obtained during the field sampling portion of this contract are presented. The test number on each graph corresponds to that given in Tables 6.2 to 6.4. The graphs are arranged in the order listed in these tables.

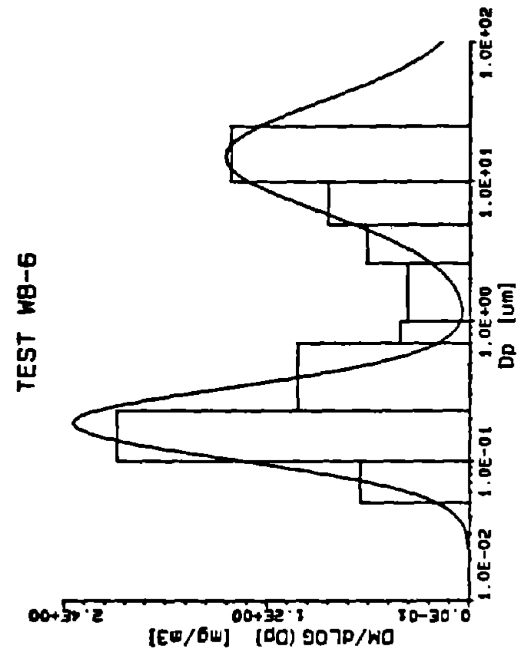

TEST WI-1
1.0E-02
1.0E-01
1.0E+00
1.0E+01
1.0E+02
Dp [um]
0.0E-01
DM/dLOG(Dp) [mg/m3]

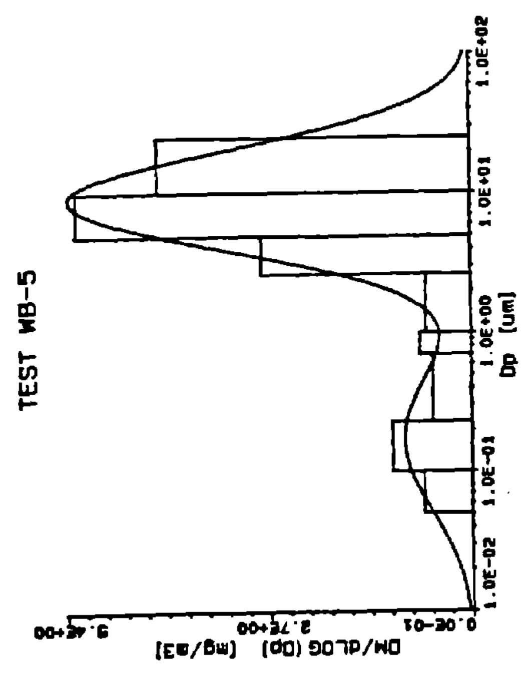

TEST WB-2
DM/dLOG (Dp) [mg/m3]
0.0E-01
1.0E+00
2.0E+00
1.0E-02
1.0E-01
1.0E+00
1.0E+01
1.0E+02
Dp [um]

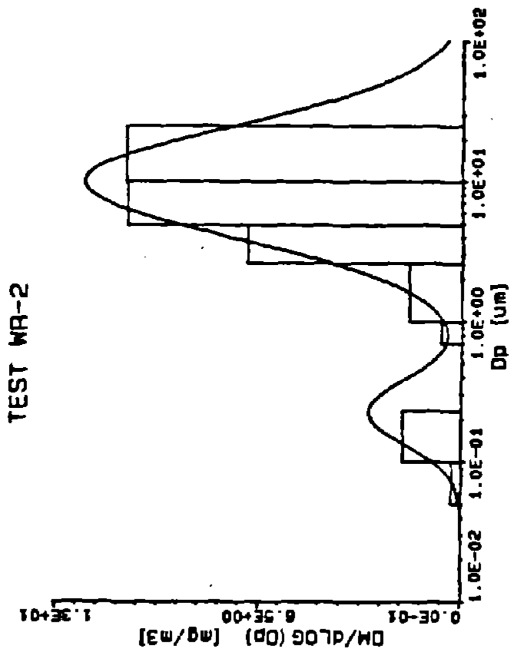

TEST WB-4
DM/dLOG (Dp) [mg/m3]
0.0E-01
1.2E+00
2.4E+00
1.0E-02
1.0E-01
1.0E+00
1.0E+01
1.0E+02
Dp [um]

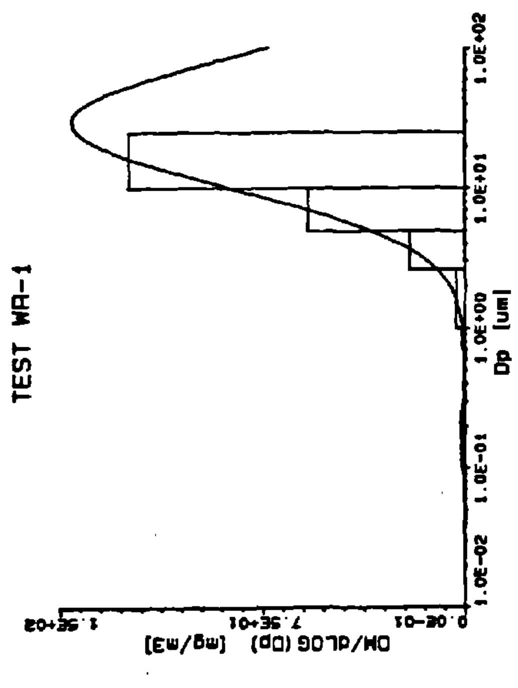

TEST WB-1
DM/dLOG (Dp) [mg/m3]
0.0E-01
3.0E+00
6.0E+00
1.0E-02
1.0E-01
1.0E+00
1.0E+01
1.0E+02
Dp [um]

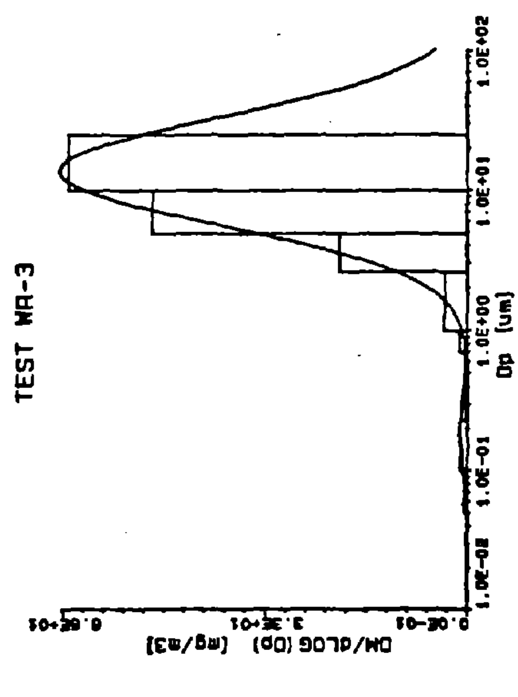

TEST WB-3
DM/dLOG (Dp) [mg/m3]
0.0E-01
1.0E+00
2.0E+00
1.0E-02
1.0E-01
1.0E+00
1.0E+01
1.0E+02
Dp [um]


TEST WB-6
DM/dLOG (Dp) [mg/m3]
0.0E-01
1.2E+00
2.4E+00
Dp [um]
1.0E-02
1.0E-01
1.0E+00
1.0E+01
1.0E+02

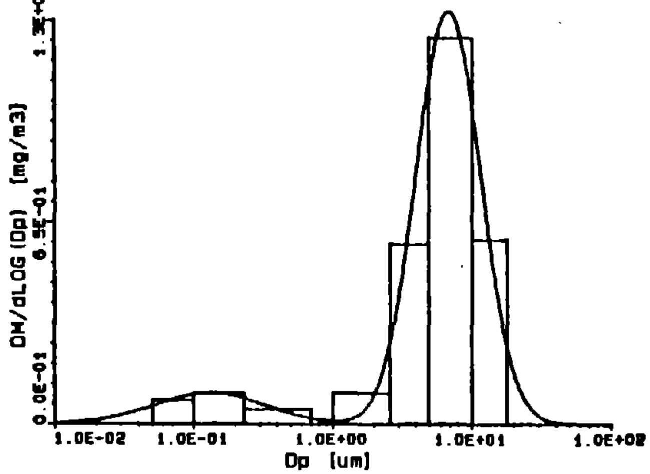

TEST WB-5
DM/dLOG (Dp) [mg/m3]
0.0E-01
2.7E+00
5.4E+00
Dp [um]
1.0E-02
1.0E-01
1.0E+00
1.0E+01
1.0E+02


TEST WA-2
DM/dLOG(Dp) [mg/m3]
0.0E-01
6.5E+00
1.3E+01
1.0E-02
1.0E-01
1.0E+00
1.0E+01
1.0E+02
Dp [um]

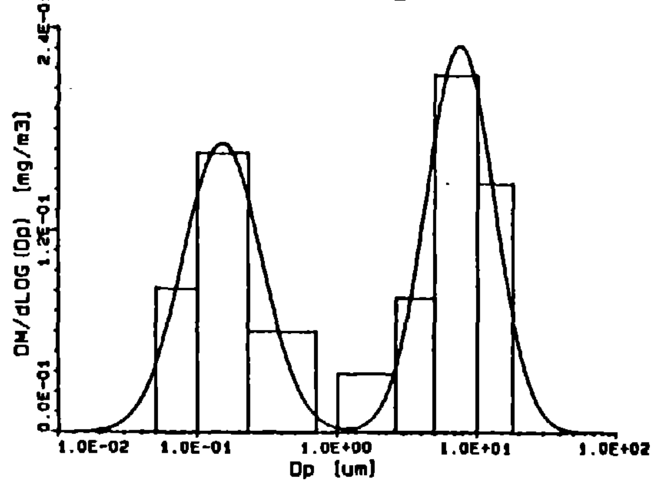

TEST WA-1
DM/dLOG(Dp) [mg/m3]
0.0E-01
7.5E+01
1.5E+02
1.0E-02
1.0E-01
1.0E+00
1.0E+01
1.0E+02
Dp [um]


TEST WA-3
DM/dLOG(Dp) [mg/m3]
0.0E-01
3.3E+01
6.6E+01
1.0E-02
1.0E-01
1.0E+00
1.0E+01
1.0E+02
Dp [um]

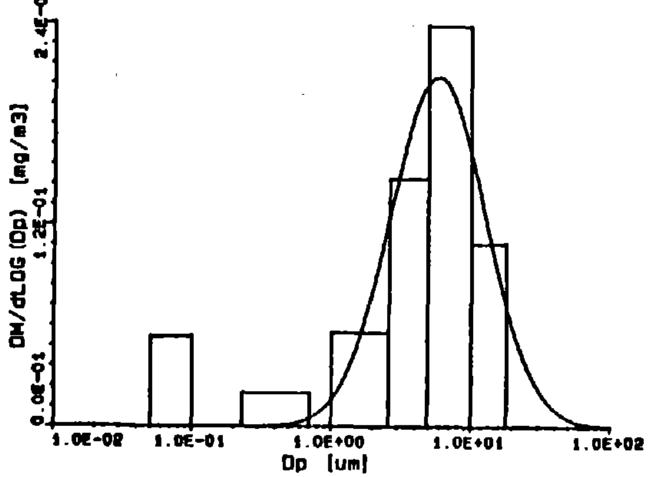
TEST UI-1



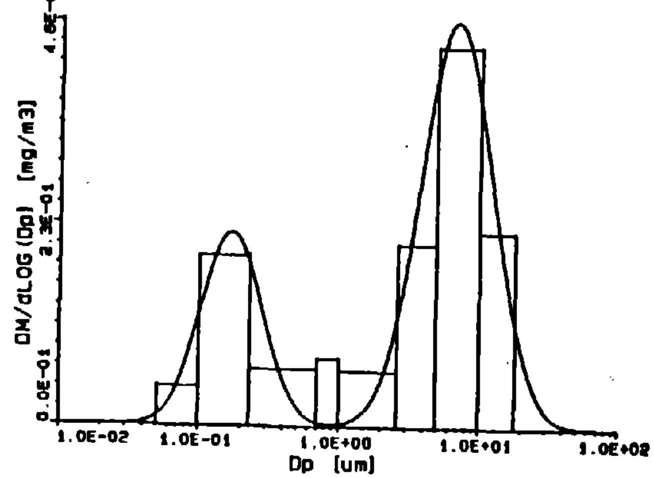
TEST UI-2

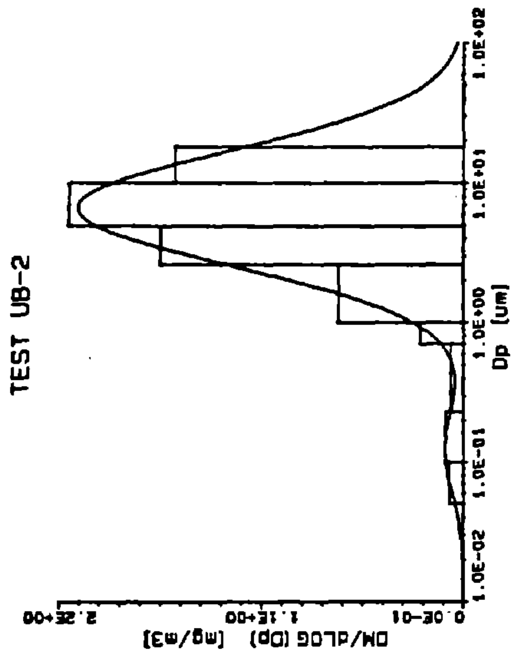


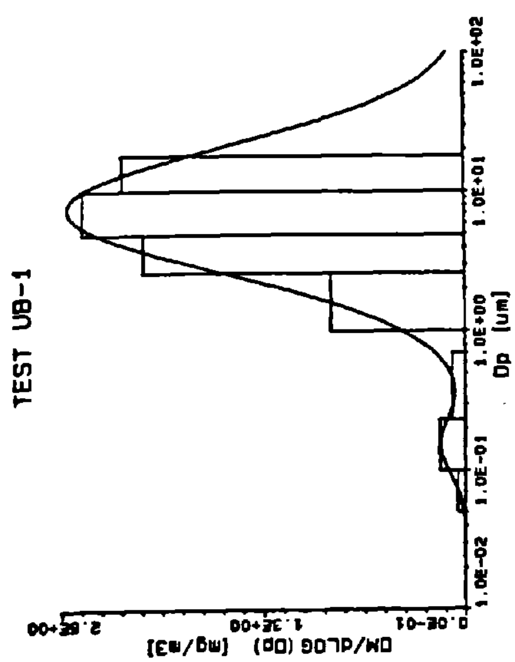
TEST UI-3

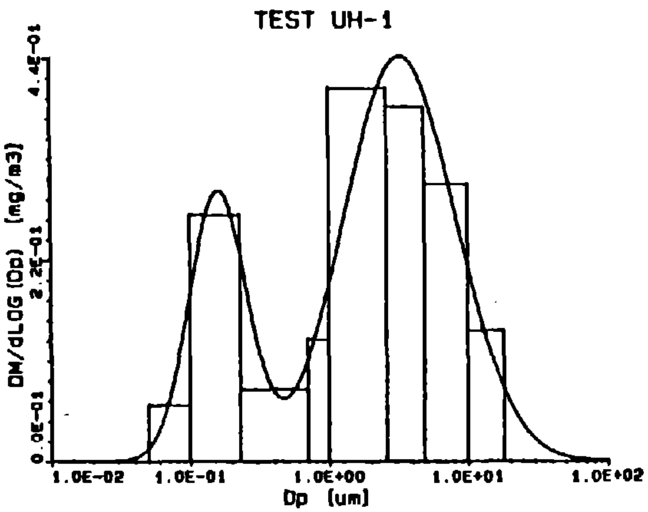


TEST UI-4

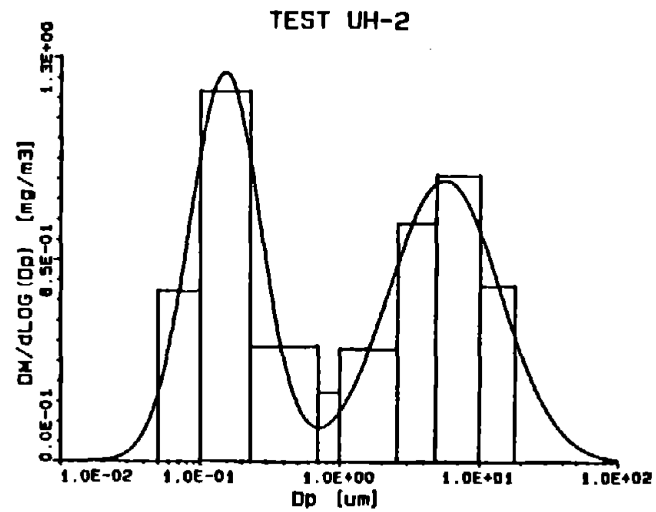



TEST UB-2
Dp [um]
1.0E-02
1.0E-01
1.0E+00
1.0E+01
1.0E+02
DM/dLOG (Dp) [mg/m3]
0.0E-01
1.1E+00
2.2E+00

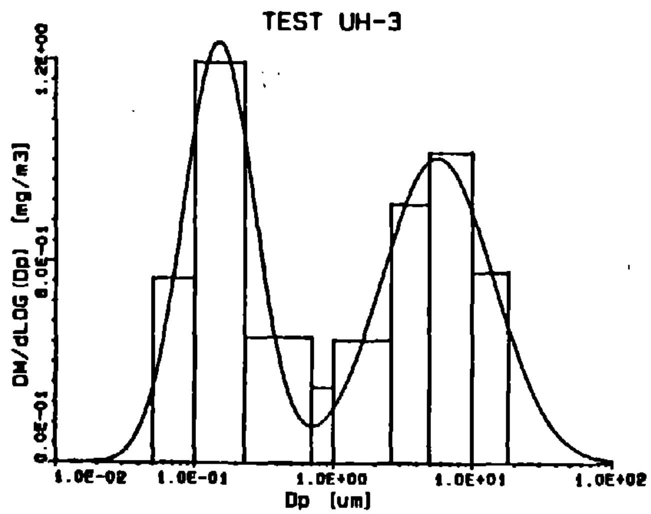

TEST UB-1
Dp [um]
1.0E-02
1.0E-01
1.0E+00
1.0E+01
1.0E+02
DM/dLOG (Dp) [mg/m3]
0.0E-01
1.3E+00
2.6E+00



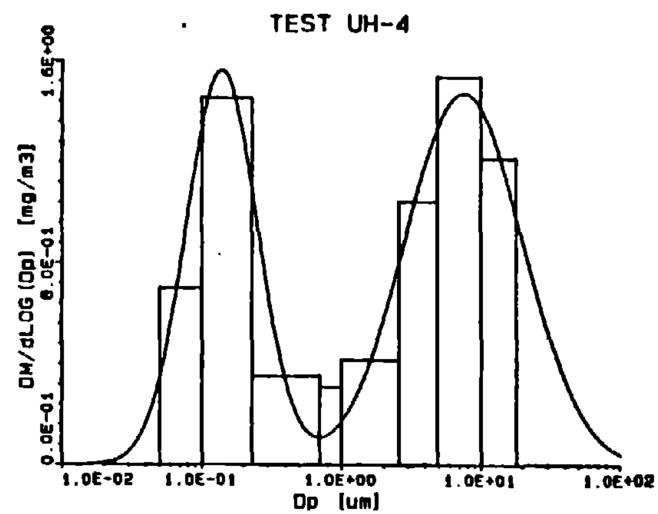
TEST UH-1
DM/dLOG (Dp) [mg/m3]
0.0E-01
2.2E-01
4.4E-01
1.0E-02
1.0E-01
1.0E+00
1.0E+01
1.0E+02
Dp (um)



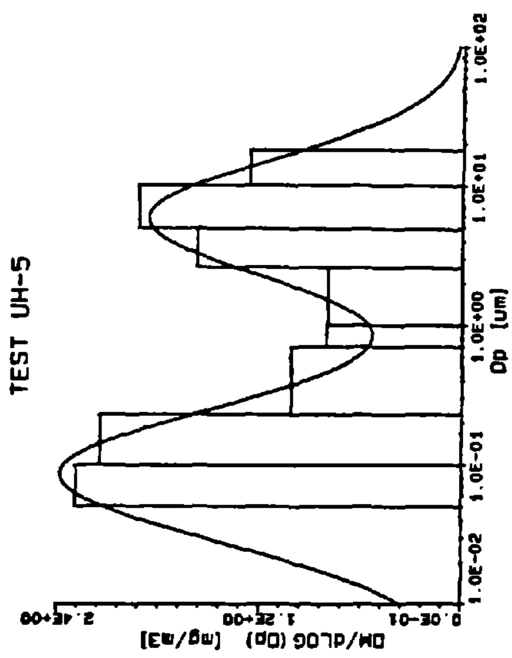
TEST UH-2
DM/dLOG (Dp) [mg/m3]
0.0E-01
6.5E-01
1.3E+00
1.0E-02
1.0E-01
1.0E+00
1.0E+01
1.0E+02
Dp (um)



TEST UH-3
DM/dLOG (Dp) [mg/m3]
0.0E-01
6.0E-01
1.2E+00
1.0E-02
1.0E-01
1.0E+00
1.0E+01
1.0E+02
Dp (um)



TEST UH-4
DM/dLOG (Dp) [mg/m3]
0.0E-01
8.0E-01
1.6E+00
1.0E-02
1.0E-01
1.0E+00
1.0E+01
1.0E+02
Dp (um)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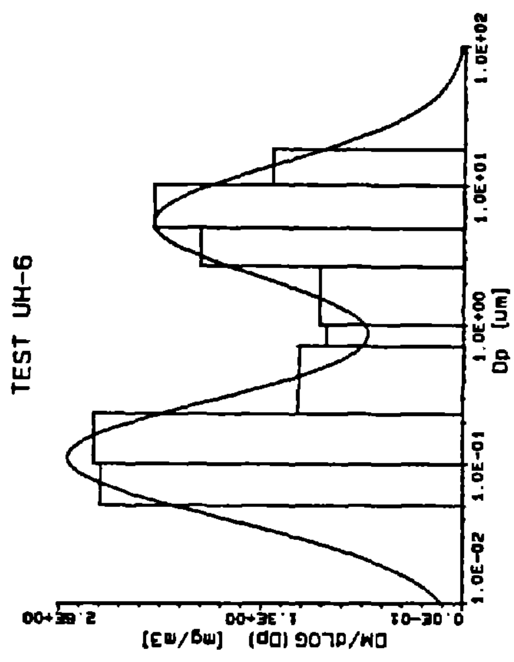
DM/dLOG (Dp) [mg/m3]
Dp [um]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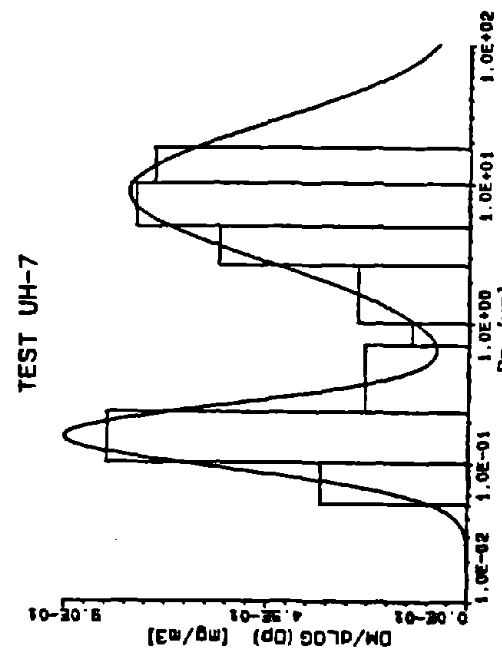
DM/dLOG (Dp) [mg/m3]
Dp [um]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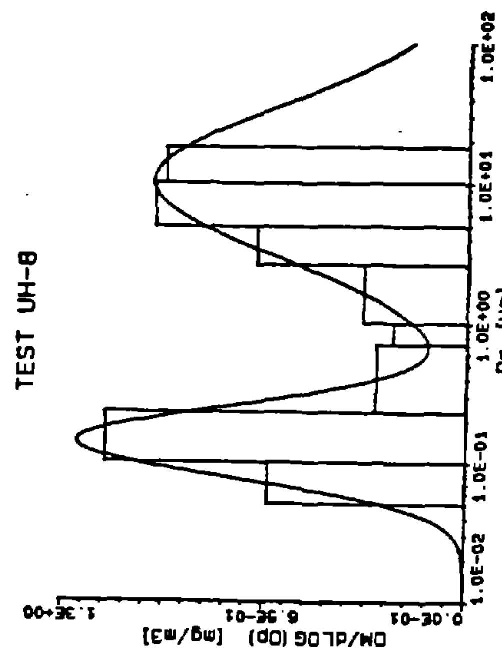
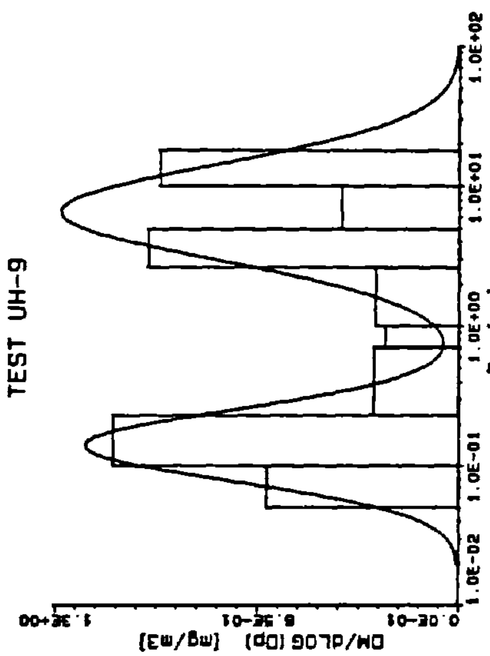
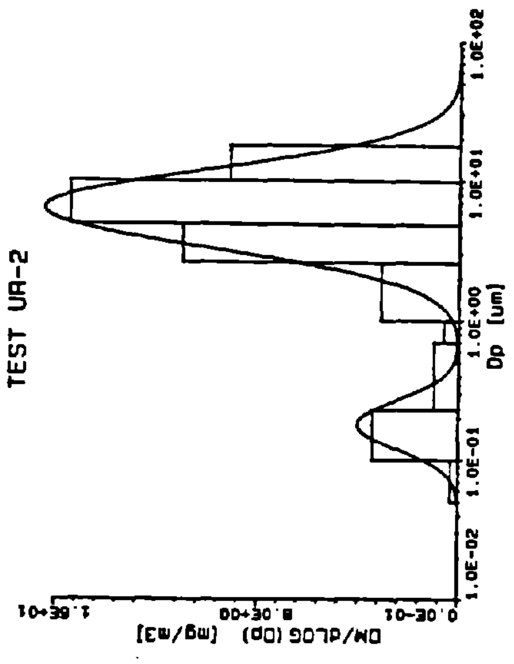
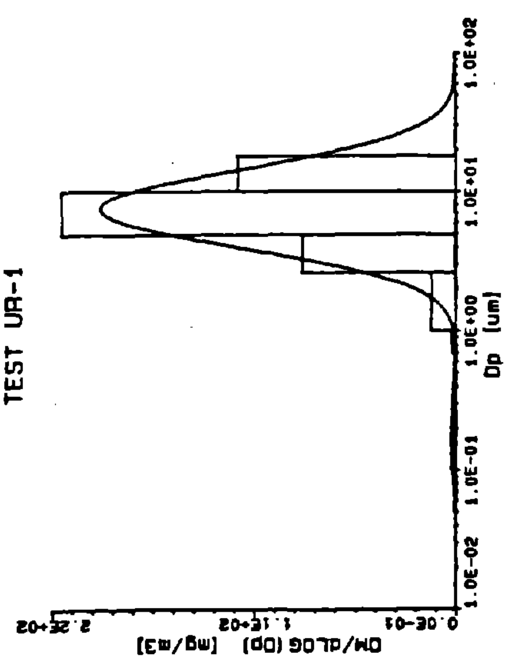
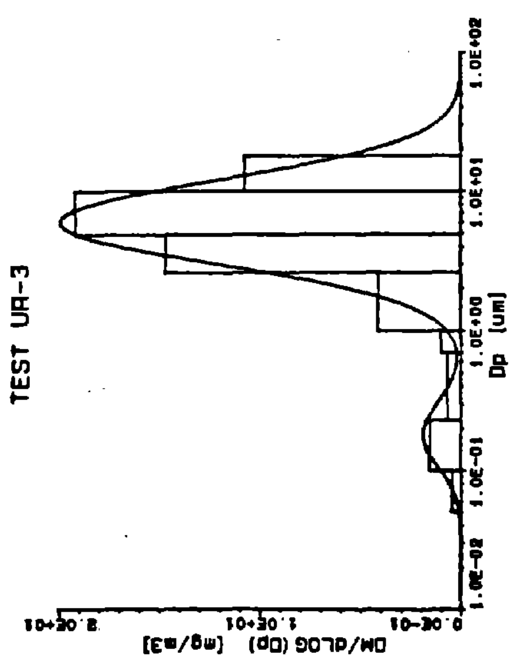
DM/dLOG (Dp) [mg/m3]
Dp [um]

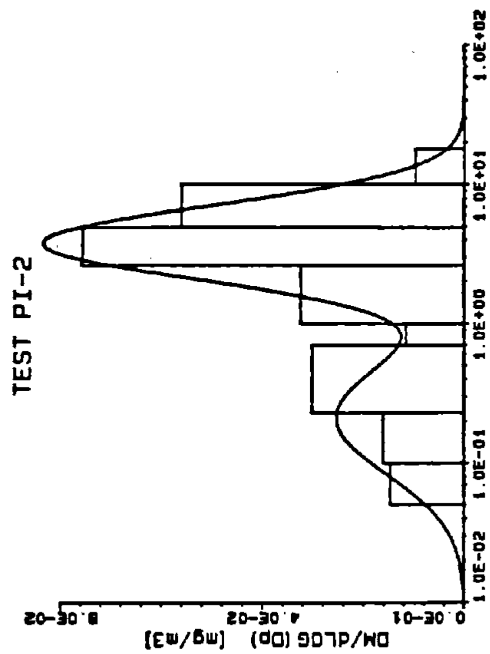

TEST UH-8
DM/dLOG (Dp) [mg/m3]
Dp [um]

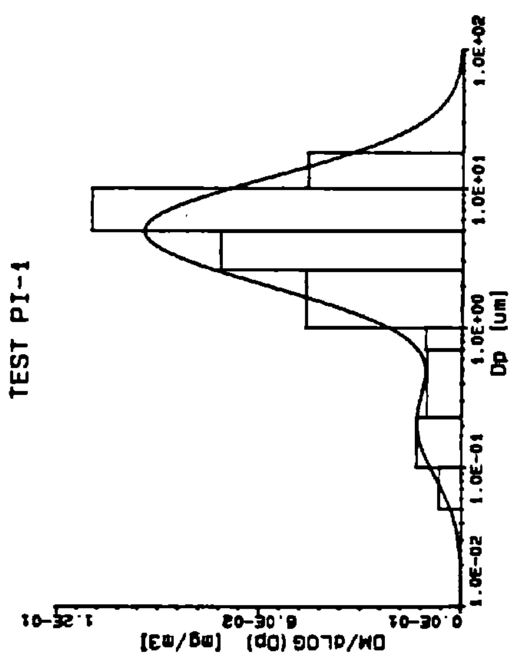

TEST UH-9
1.0E-02
1.0E-01
1.0E+00
1.0E+01
1.0E+02
Dp [um]
DM/dLOG(Dp) [mg/m3]

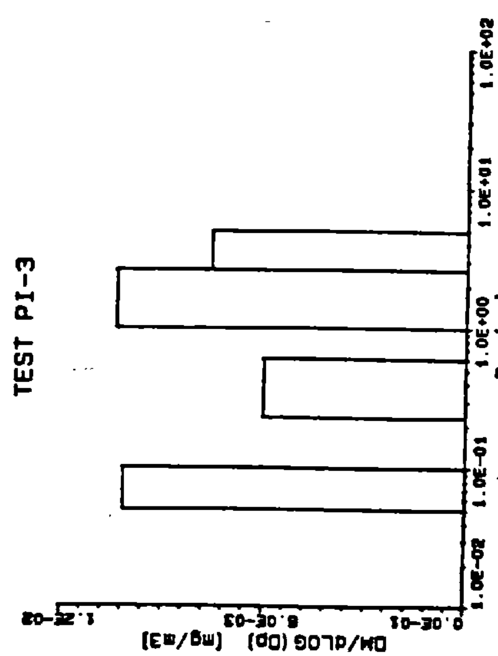

TEST UR-2
DM/dLOG(Dp) [mg/m3]
0.0E-01
8.0E+00
1.6E+01
1.0E-02
1.0E-01
1.0E+00
1.0E+01
1.0E+02
Dp [um]


TEST UR-1
DM/dLOG(Dp) [mg/m3]
0.0E-01
1.1E+02
2.2E+02
1.0E-02
1.0E-01
1.0E+00
1.0E+01
1.0E+02
Dp [um]

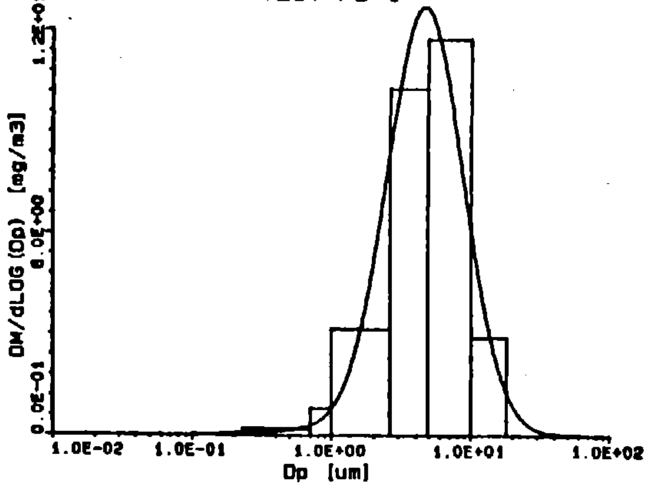

TEST UR-3
DM/dLOG(Dp) [mg/m3]
0.0E-01
1.0E+01
2.0E+01
1.0E-02
1.0E-01
1.0E+00
1.0E+01
1.0E+02
Dp [um]


TEST PI-2
DM/dLOG (Dp) [mg/m3]
0.0E-01
4.0E-02
8.0E-02
Dp [um]
1.0E-02
1.0E-01
1.0E+00
1.0E+01
1.0E+02

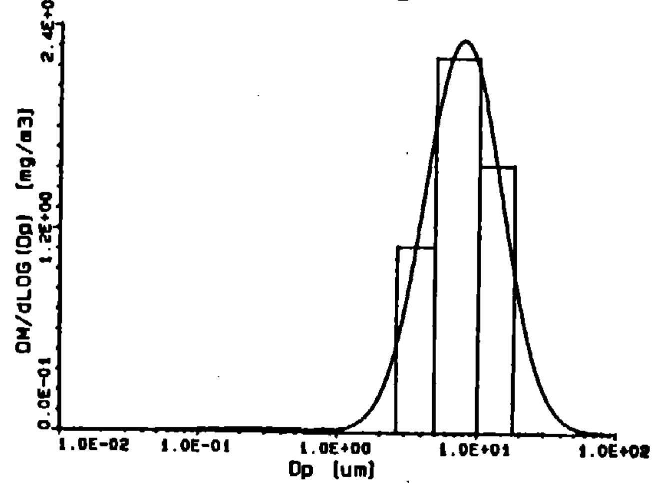

TEST PI-1
DM/dLOG (Dp) [mg/m3]
0.0E-01
6.0E-02
1.2E-01
Dp [um]
1.0E-02
1.0E-01
1.0E+00
1.0E+01
1.0E+02


TEST PI-3
DM/dLOG (Dp) [mg/m3]
0.0E-01
6.0E-03
1.2E-02
Dp [um]
1.0E-02
1.0E-01
1.0E+00
1.0E+01
1.0E+02

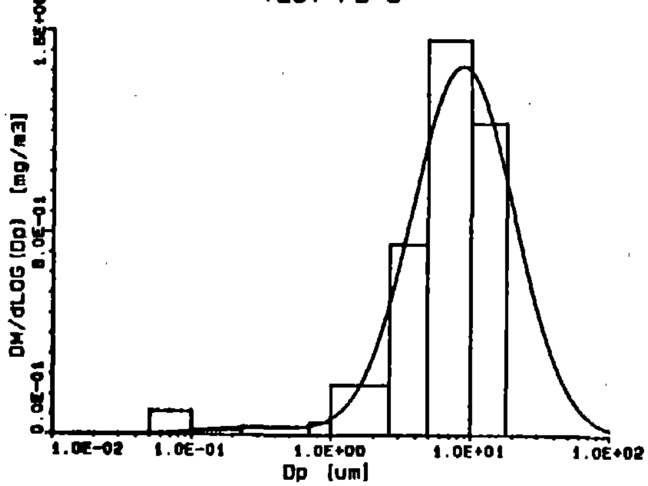
TEST PB-1



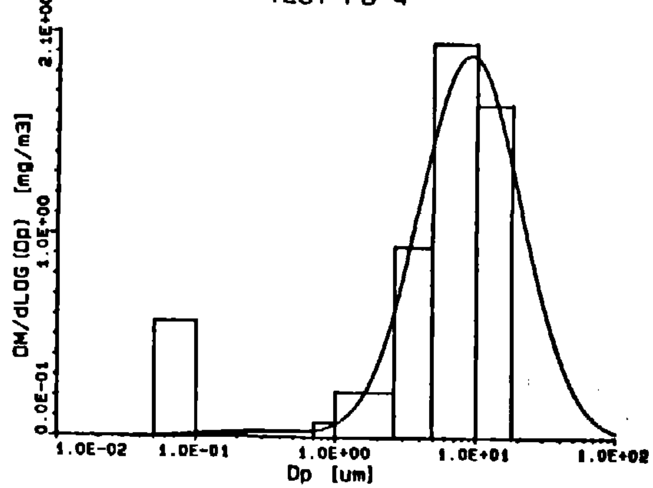
TEST PB-2



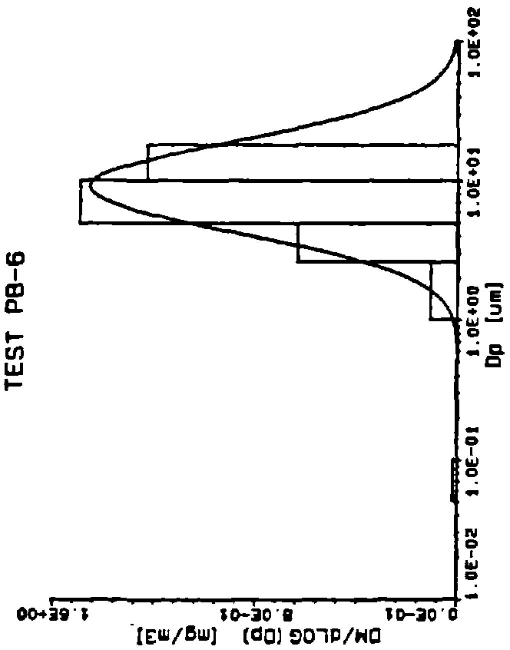
TEST PB-3



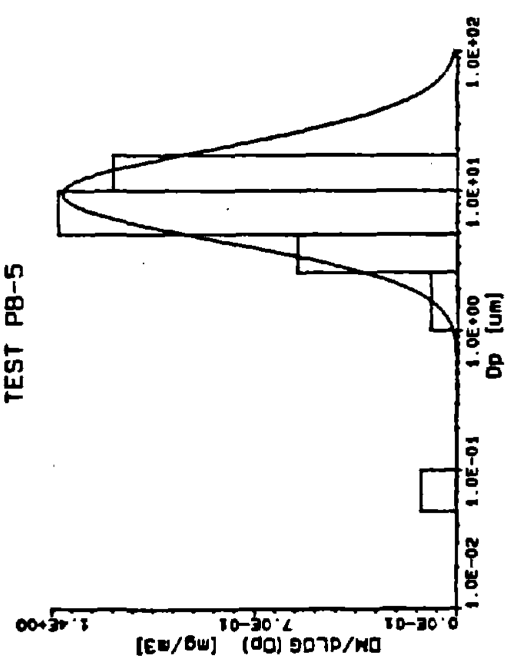
TEST PB-4



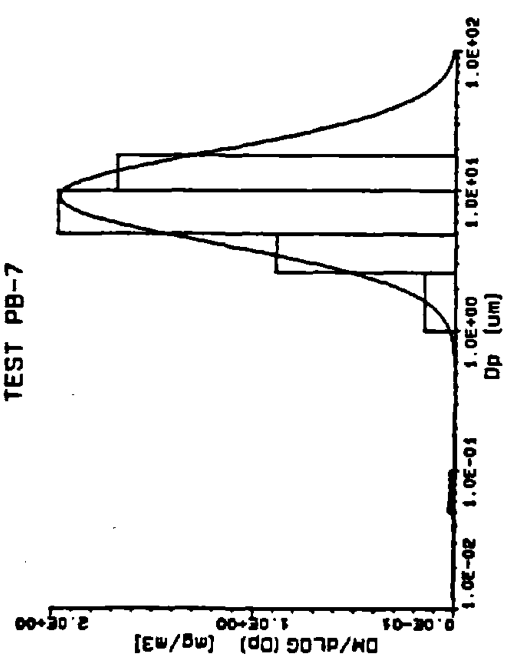
TEST PB-6



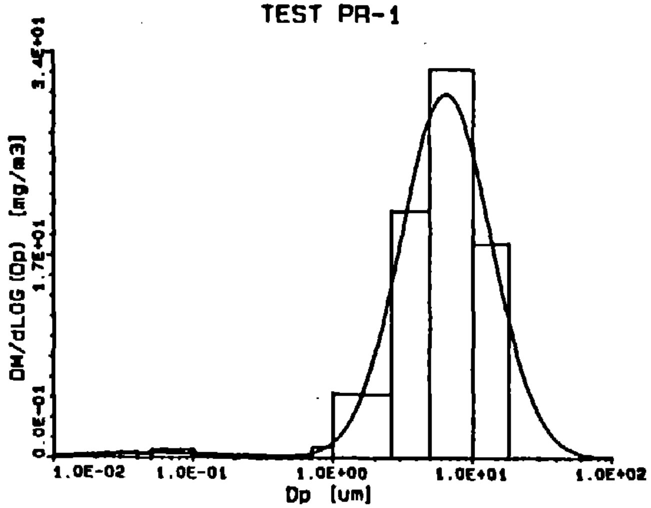
TEST PB-5



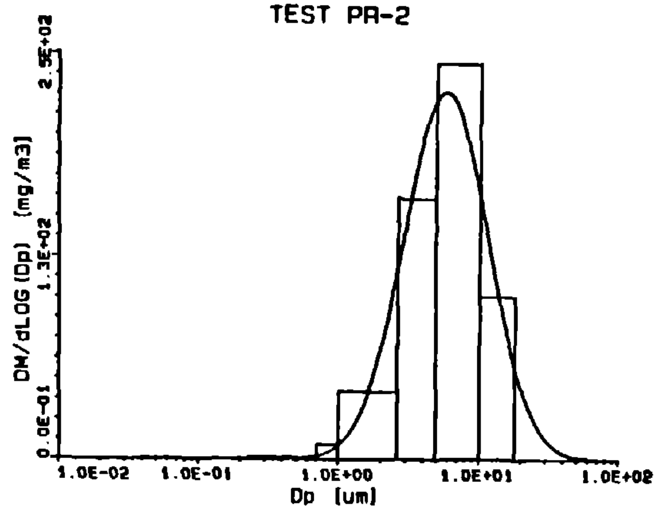
TEST PB-7



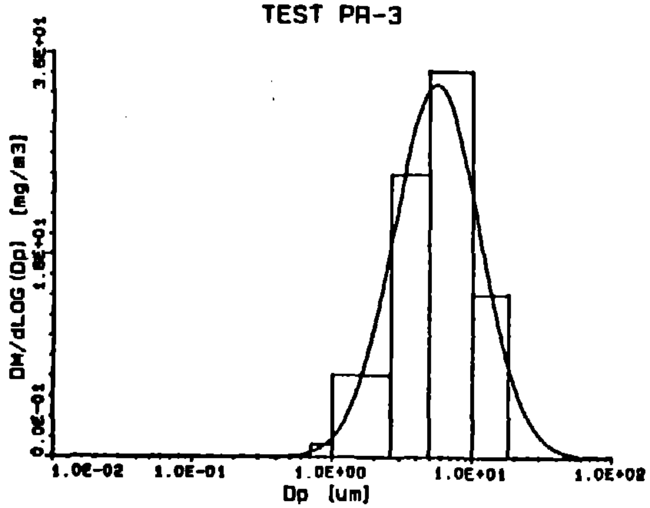
TEST PA-1



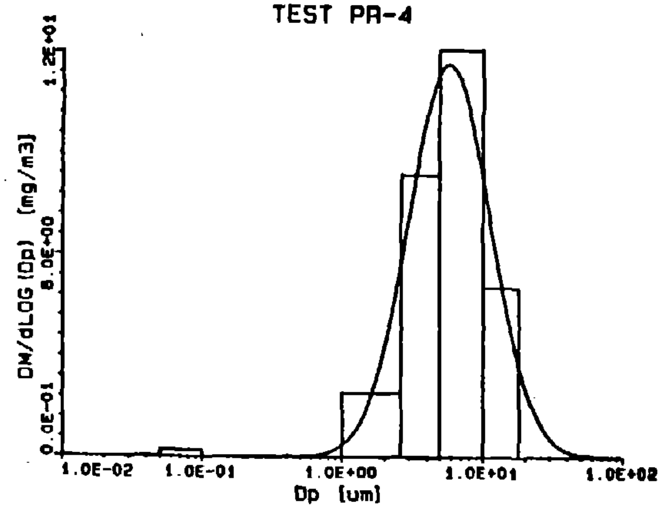
TEST PA-2



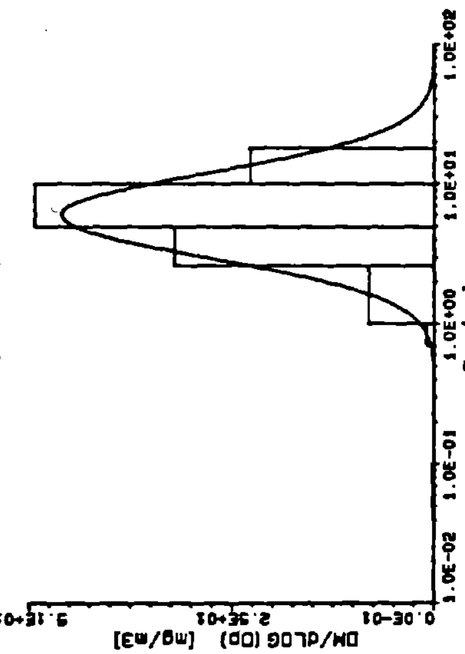
TEST PA-3



TEST PA-4



TEST PA-5



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UNIVERSITY OF MINNESOTA
TWIN CITIES

Department of Mechanical Engineering
125 Mechanical Engineering
111 Church Street S.E.
Minneapolis, Minnesota 55455

October 20, 1987

Mr. Kenneth Williams
U. S. Bureau of Mines
Cochrans Mill Road
P. O. Box 18070
Pittsburgh, PA 15236

Dear Ken:

Enclosed are the letters requested by NTIS granting us permission to use copyrighted materials in the final report for contract number J014022.

I have also enclosed copies of the letters requesting permission as those letters indicate the figures and tables that I have reproduced in the final report. Seven figures and five tables used in Chapter 2 were reproduced from copyrighted materials.

Please contact me at (612) 625-8354 if you have any questions.

Sincerely,

Ken

Kenneth L. Rubow
Research Associate and Manager,
Particle Technology Laboratory

enc.

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October 13, 1987

Mr. Kenneth L. Rubow
Research Associate and Manager
Particle Technology Laboratory
University of Minnesota
Department of Mechanical Engineering
125 Mechanical Engineering
111 Church Street S.E.
Minneaplis, Minnesota 55455

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UNIVERSITY OF MINNESOTA
TWIN CITIES

Department of Mechanical Engineering
125 Mechanical Engineering
111 Church Street S.E.
Minneapolis, Minnesota 55455

October 5, 1987

Professors B. Y. H. Liu and V. A. Marple:
University of Minnesota
125 Mech. Eng.
Minneapolis, MN 55455

Dear Drs. Liu and Marple:

I am writing to obtain written permission to reproduce two figures and five tables from the book entitled "Aerosols in the Mining and Industrial Work Environments", edited by B. Y. H. Liu and V. A. Marple. This book was published in 1983 by Ann Arbor Science Publishers and is currently out of print.

The figures and tables in question are as follows:

- Figure 2 on page 367
- Figure 1 on page 426
- Tables I and II on page 400
- Table III on page 401
- Table V on page 403
- Table IX on page 470

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Should you have any questions, please contact me at (612) 625-8354.

Sincerely,

Kenneth L. Rubow

Kenneth L. Rubow
Research Associate and Manager,
Particle Technology Laboratory

OK
V A Marple
10/6/87

O.K.
BYH Liu
10/6/87

UNIVERSITY OF MINNESOTA
TWIN CITIES

Department of Mechanical Engineering
125 Mechanical Engineering
111 Church Street S.E.
Minneapolis, Minnesota 55455

September 20, 1987

Ms. Ginger Joa
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Dear Ms. Joa:

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The four figures are all of the size distribution of diesel exhaust particulate matter. One figure is from the 1979 publication - SAE No. SAE/PT-79/17 authored by P. J. Groblicki and C. R. Begeman. Two figures are from the 1979 publication - SAE Paper No. 780787, Transaction of SAE authored by D. B. Kittelson, D. F. Dolan, R. B. Diver, and E. Aufderheide. The fourth figure is Figure 6 from the 1984 publication - SAE Paper No. 840362 authored by C. P. Fang and D. B. Kittelson.

Please contact me at (612) 625-8354 if you have any questions.

Sincerely,

Kenneth L. Rubow
Research Associate and Manager,
Particle Technology Laboratory

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G

UNIVERSITY OF MINNESOTA
TWIN CITIES

Department of Mechanical Engineering
125 Mechanical Engineering
111 Church Street S.E.
Minneapolis, Minnesota 55455

September 20, 1987

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The figure in question is Figure 1 on page 136 of the book entitled "Sulfur in the Atmosphere". The book was published by Pergamon Press in 1978.

Atmospheric Environment

Please contact me at (612) 625-8354 if you have any questions.

Sincerely, 12

Kenneth L. Rubow

Kenneth L. Rubow
Research Associate and Manager,
Particle Technology Laboratory

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October 14, 1987

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