MONITORING AND MEASUREMENT OF IN-MINE AEROSOL: DIESEL EMISSIONS

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ABSTRACT

Extensive use of diesels in the mining industry has given rise to questions concerning the exposure of miners to diesel aerosol emissions. Answering such questions accurately depends on the type of mine and the measurement methods that can be employed. In metal and nonmetal mines, measurement of the carbonaceous diesel particulate fraction of respirable dust aerosol is accomplished using common sampling techniques and laboratory analysis. In coal mines, measurement is complicated by the carbonaceous nature of the coal. In such cases, special sampling and analytical techniques must be used to distinguish between diesel and respirable coal dust aerosol.

The objective of this Bureau of Mines paper is to review some of the techniques that can be used to measure the diesel particulate fraction of respirable aerosol in the mine environment. In addition, the regulatory requirements for respirable dust in U.S. mines and the physical and chemical characteristics of diesel aerosols are reviewed in the larger context of ambient aerosol in the mine. Current regulatory and experimental measurement protocols for respirable mine aerosols are discussed. These include the use of filtration, inertial impaction, and optical detection methods. In each case, the methodology is evaluated for the information that can be derived from the technique about the diesel fraction of the measured aerosol.

Concluding the paper are recommendations on the use of dichotomous samplers to derive qualitative information on exposure to diesel aerosol in a mine. Also discussed are some of the Bureau's current research plans with regard to measurement of diesel emissions aerosol.

INTRODUCTION

Extensive use of diesels in the mining industry has given rise to questions concerning the exposure of miners to diesel aerosol emissions. Primary among these is, To what mass concentration levels of diesel aerosol are miners exposed? A secondary, but important, question being posed is, What fraction of the measured respirable aerosol originates from diesel equipment in the mine? Answering such questions accurately depends on the type of mine under consideration and the aerosol measurement methods that are employed.

This paper reviews the problems associated with monitoring and measurement of the diesel component of mine aerosol. It focuses on the instrumentation used to determine the contribution that diesel emission aerosols make to respirable aerosol concentrations in the mine environment. The paper summarizes regulatory requirements for respirable aerosol in U.S. mines. The physical and chemical characteristics of diesel aerosols are also discussed in relation to their effect on the methods used to both monitor and measure the diesel fraction of respirable mine aerosol. The paper then reviews both those measurement methods currently used to monitor respirable dust in mines and those used for mine aerosol research. In each case an attempt is made to summarize the type of information that the technique can provide on the diesel fraction of the respirable aerosol as measured.

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REGULATORY REQUIREMENTS—METAL AND NONMETAL

The Mine Safety and Health Administration (MSHA) regulates health and safety conditions and practices in metal and nonmetal mines and mills under the authority of the Federal Mine Safety and Health Act of 1977 (*1*).[5] The specific regulations are found in the Code of Federal Regulations, title 30 (*2*). Standards in these regulations for airborne contaminants and physical agents were adopted from the 1973 recommended threshold limit values (TLV's) of the American Conference of Governmental Industrial Hygienists (ACGIH) (*3*). Compliance with these regulations is determined by the collection of environmental samples by MSHA inspectors.

For respirable dust, a sample is collected on a filter after the aerosol has passed through a cyclone preclassifier at a flow rate of 1.7 L/min. The TLV for respirable dust containing quartz is determined by collecting a respirable dust sample, analyzing for quartz content,[6] and calculating the TLV using the formula:

$$\frac{10 \text{ mg/m}^3}{\text{percent respirable quartz} + 2},$$

when the quartz content (percent respirable quartz) is greater than 1 pct (*3*). The resultant TLV is expressed in milligrams per cubic meter. For a given exposure level the magnitude of the toxicity is proportional to the quartz content (*4*). The factor 2 in the denominator of the TLV formula ensures that dust exposures will not be excessively high when the quartz content is less than 5 pct and effectively limits the dust concentration to 5 mg/m³ when no quartz is present in the sample.

In 1983 MSHA proposed to revise many of the existing health regulations (*5*). Included in these revisions was a proposed change in the respirable dust standard. The proposed new standard, which is still undergoing review, is 100 µg/m³ of respirable quartz.

REGULATORY REQUIREMENTS—COAL

In 1970 a mandatory respirable dust standard of 3.0 mg/m³ was established for underground coal mines under the Federal Coal Mine Health and Safety Act of 1969. This standard was subsequently lowered in 1972 to 2.0 mg/m³. Mandatory dust standards for surface work areas of underground coal mines and surface mines also became effective in 1972. These regulations were continued under the Federal Mine Safety and Health Act of 1977 (*6*), which amended the 1969 coal act and merged coal and noncoal regulations into one law. In the 1969 act, "concentration of respirable dust" was defined as a measurement made with a Mining Research Establishment (MRE) Casella model 113A sampling instrument shown in figure 1 or such equivalent concentration measured with another device. This instrument was designed to have a sampling efficiency equivalent to the respirable response curve specified by the British Medical Research Council (BMRC) and shown in figure 2. The 1977 act changed the definition "concentration of respirable dust" to be the "average concentration of respirable dust measured with a device approved by the Secretary (of Labor) and the Secretary of Health Education and Welfare." The device approved for measuring respirable dust uses a Dorr-Oliver 10-mm nylon cyclone, sampling at 2 L/min, to remove the nonrespirable fraction of dust samples. Measurements made with this device are converted to equivalent MRE concentrations by multiplying by an accommodation factor of 1.38 (*7*). Specific regulations detailing the collection of respirable dust samples by mine operators are found in the Code of Federal Regulations, title 30, (*2*).

From the BMRC sampling efficiency curve of figure 2, it can be seen that all aerosol less than about 7 µm aerodynamic diameter are included in the definition of respirable dust. As a result, diesel emissions aerosol, which are mostly in this size range (*8*), are a major component of the aerosol sampled for compliance measurement of respirable dust in a coal mine. This diesel component of the sampled aerosol can affect the measurement in several ways. It can contribute out of proportion to its actual concentration to the measured respirable aerosol in a mine because the accommodation factor used to correct compliance measurements overcorrects for aerosols less than 1 µm. Also, for mines with quartz concentrations greater than the minimums specified by the current regulations, the diesel component can dilute the collected respirable aerosol sample leading to a false low concentration for the quartz fraction of the mineral dust portion of the aerosol.

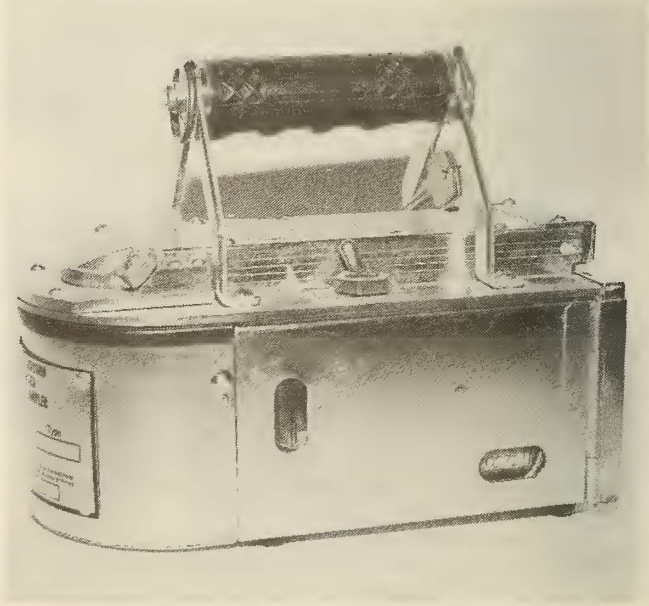

Figure 1.—MRE gravimetric dust sampler.

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[5] Italic numbers in parentheses refer to items in the list of references at the end of this paper.

[6] Quartz content is determined by X-ray diffraction after the filter has been weighed.

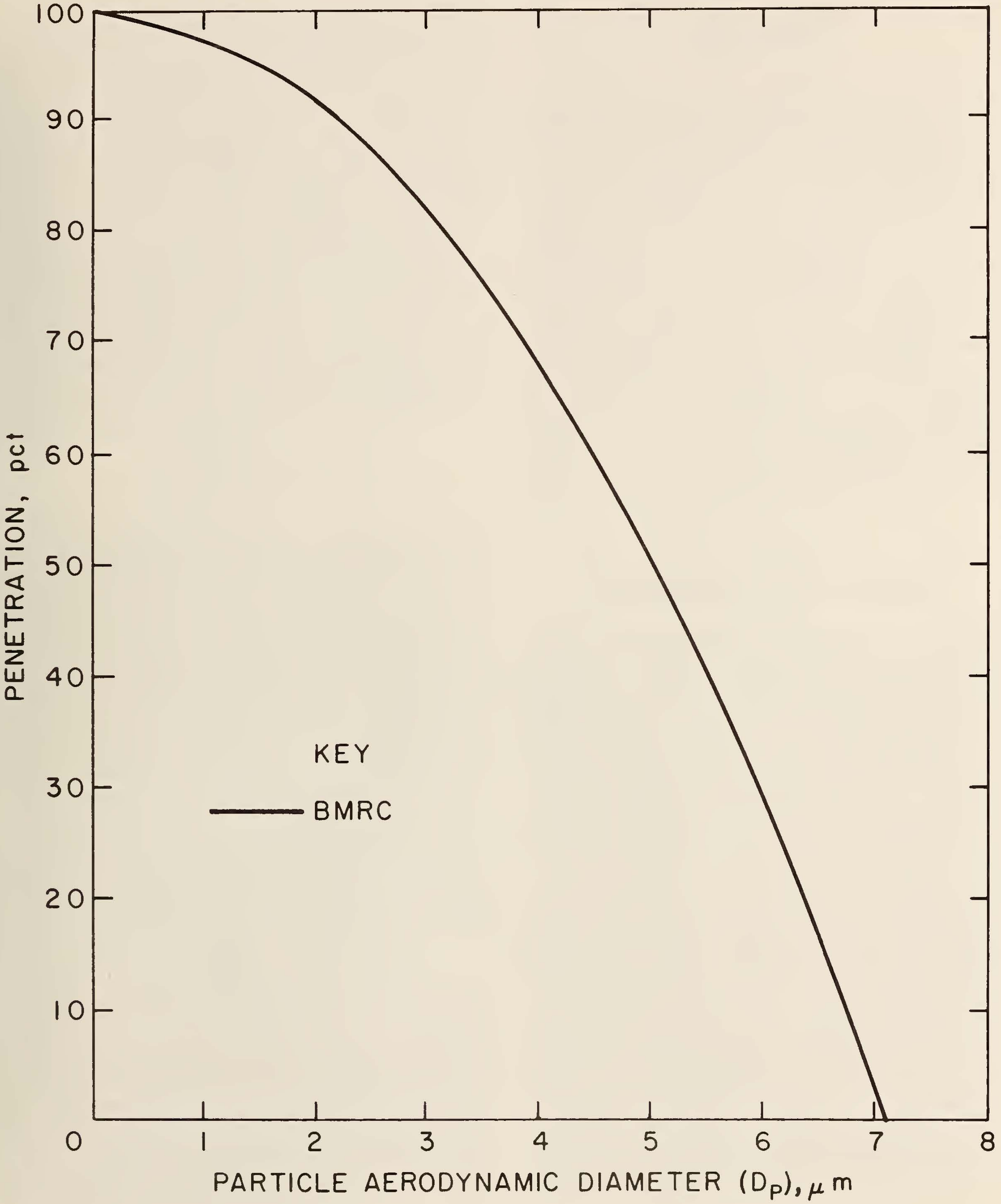

Figure 2.—BMRC respirable penetration curve.

REVIEW OF MINE AEROSOL CHARACTERISTICS

To this point in the discussion, the terms dust, dust aerosol, diesel emissions aerosol, and diesel aerosol have been used loosely. More properly, the terms dust or particulate refer to finely divided material wherever it is found. The term aerosol refers to such finely divided material suspended in air. When referring to air suspensions of particulates, the proper terminology is aerosol. In a mine, sources of such aerosols include mining activities in the face area; e.g., drilling, operation of continuous mining machines, conventional mining methods, etc.; materials handling procedures such as use of breaker heads on conveyor roads; and the diesel-powered equipment necessary to perform these tasks. Secondary sources of aerosol include dust entrainment during load-haul-dump operations, dust reentrainment from floor and walls caused by mine traffic, and dust from special procedures such as rock dusting. Aerosols from each of these sources have size distributions, chemical properties, and trace element compositions that are characteristic of the source emission or parent material from which the aerosol is formed. These characteristics are briefly discussed in the following subsections.

AEROSOL SIZE RANGES

Mine aerosols arise from a variety of sources and, as shown in figure 3, the shape of the aerosol size distribution can be influenced by these sources. The figure also displays the physical mechanisms such as condensation and coagulation that transfer aerosol mass from one size to another. There are three distinct aerosol size ranges that can be identified from features in measured size distributions. The smallest of these, from 0.001 to 0.08 μm, is the Aitken nuclei range, which contains primary aerosol from combustion sources, such as diesel engines, and secondary aerosol formed from coagulation of primary aerosols to form chain aggregates. The next size range, from 0.08 to approximately 1.0 μm, termed the accumulation range, contains emissions in this size range plus aerosol accumulated by mass transfer through coagulation and condensation processes from the nuclei range. The last range, 1.0 to approximately 40 μm, is termed the coarse-aerosol range. Aerosols within this size fraction are generally the result of mechanical processes such as a rock fracture and bulk material handling. Mineral dust aerosol reentrained by mine haulage vehicles during the load-haul-dump cycle is an example of an in-mine emission that will contribute aerosol to this size range.

For convenience, the Aitken nuclei and the accumulation range are combined in a single "fine" aerosol range. A division is usually made between this range and the "coarse" aerosol at 1.0 μm. This distinction is possible because sources of aerosol in the two ranges are usually different, and the coarse-aerosol range contains very little mass transferred from the accumulation range by coagulation. Respirable aerosol, as defined by the penetration efficiency curve of figure 2, include aerosols from about 10 μm and down in size. The respirable aerosol size range therefore includes a portion of the coarse aerosol range and all of the accumulation and nuclei aerosol ranges.

MODAL STRUCTURE AND GRAPHICAL DISPLAY CONVENTION

In each of the ranges mentioned, the size distribution of mine aerosol can exhibit a maximum, or mode, which takes its name from the size range in which it occurs. Hence, the maximum in the accumulation particle range is termed the accumulation particle mode. Figure 4 presents a typical size distribution of aerosol mass concentration measured near a feeder-breaker conveyor head in a diesel-equipped mine. Here the modal character of the size distribution is discernible even though the nuclei mode is suppressed compared with the accumulation mode. In contrast, figure 5 shows a mass size distribution measured near a feeder-breaker conveyor in an all-electric-equipped mine. Here the accumulation mode is much smaller than the coarse particle mode. Taken together the figures indicate that diesel aerosols make a strong contribution to accumulation mode aerosol in a diesel-equipped mine. In both figures, the mass concentration histograms are plotted as $\Delta C/\Delta(\log D_p)$ versus D_p on a log scale, where ΔC is the concentration in each size interval and D_p is the aerosol's aerodynamic diameter. Using this convention, the area of each block of the histogram is proportional to the fraction of the mass concentration in the indicated aerosol size interval.

CHEMICAL AND ELEMENTAL ANALYSIS TECHNIQUES FOR DIESEL AEROSOL

Another distinguishing characteristic of mine aerosol is its chemical nature including the distribution of trace elements. In a diesel-equipped mine, diesel emission and mineral dust aerosol are mixed and are not separated when collected using a simple filter sampler. In metal and nonmetal mines, determining the amount of the diesel fraction on such a filter sample is relatively straightforward. A common analysis method relies on combustion techniques to determine the total combustible fraction as a measure of the mostly carbon diesel aerosol in the sample (*9*). For coal mine aerosol samples such analysis is not applicable since both types of aerosol involved are primarily carbon.

To determine the diesel fraction of mixed carbonaceous aerosol from collected samples requires rather complicated and relatively expensive analytical procedures. Two such procedures have been developed under Bureau sponsorship. These are analysis using Raman spectroscopy and chemical mass balance (CMB) modeling. The first, by Johnson (*9*), is measurement of diesel and coal fractions of particulate matter using Raman spectral parameters. The second method is source apportionment based on the elemental analysis of both the collected aerosol and the source of the aerosol. For diesel-equipped mines the primary sources are the coal and diesel aerosol emissions. CMB analysis permits relating of elements or chemical components in an aerosol sample to those same components in the sources of the aerosol. The model is based on the following assumptions, summarized by Watson (*10*):

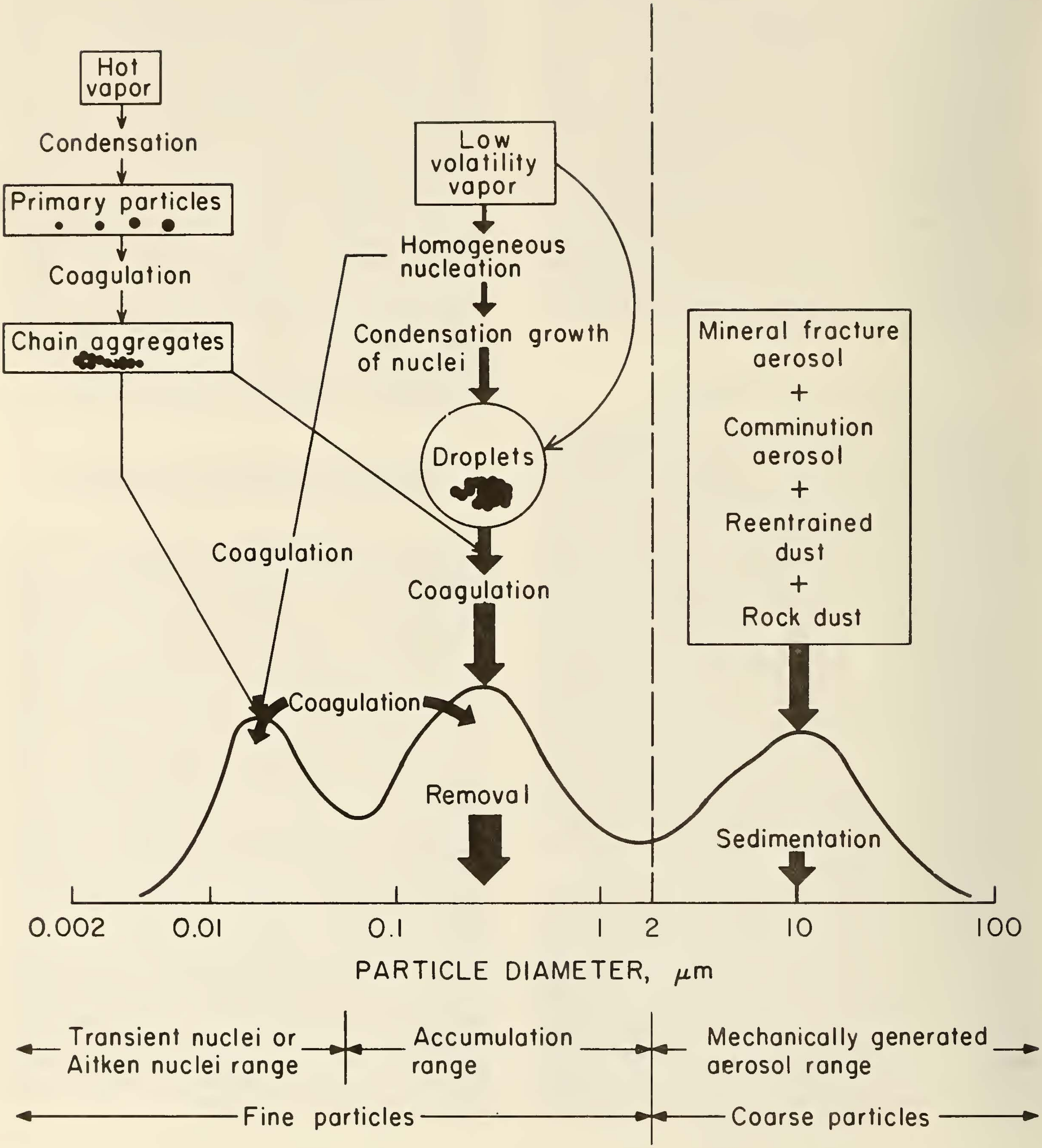

Figure 3.—Summary of in-mine aerosol characteristics exhibiting the modal character of the size distribution and the conventional terminology for their description.

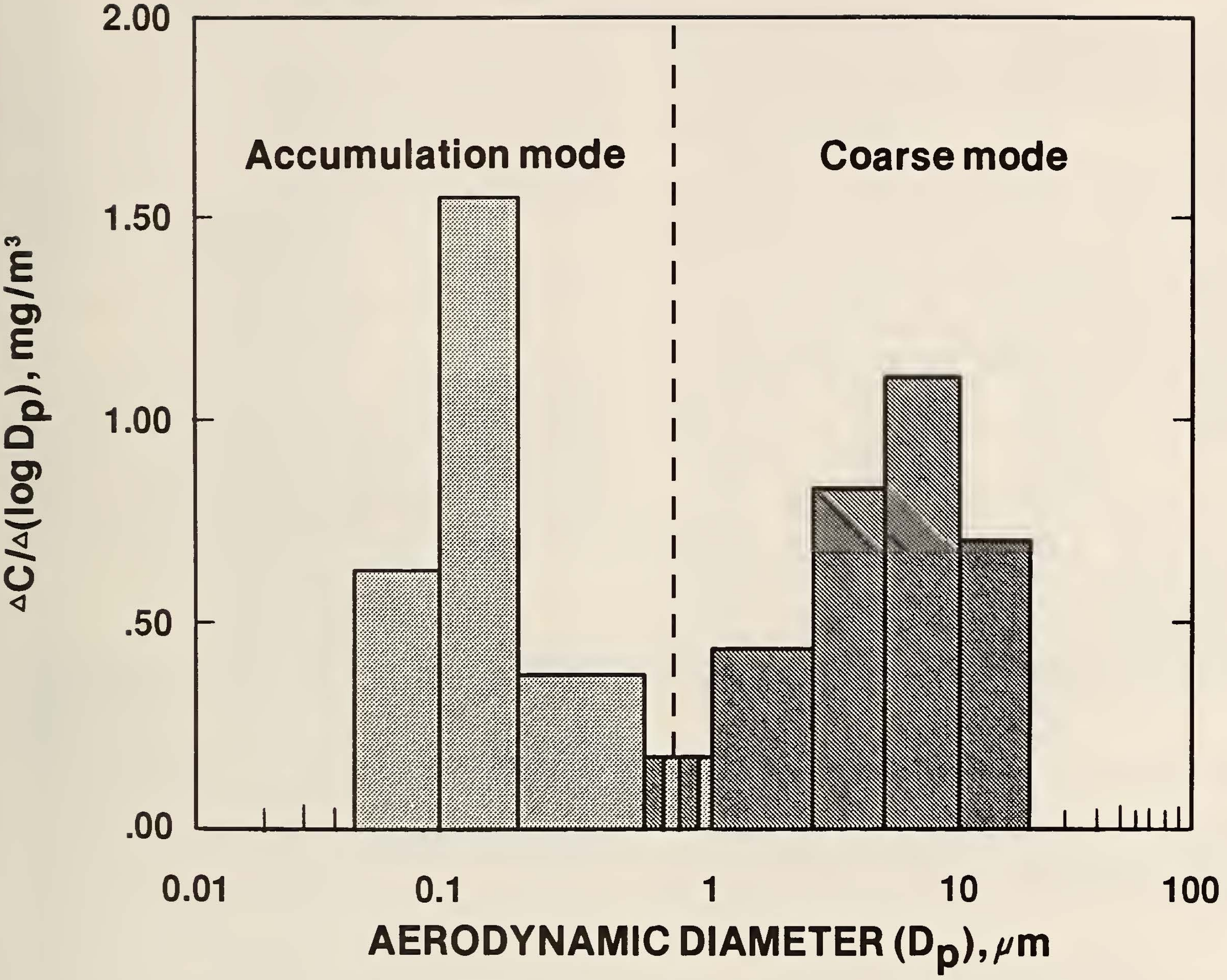

Figure 4.—Mass size distribution collected at a breaker site in a diesel-equipped coal mine.

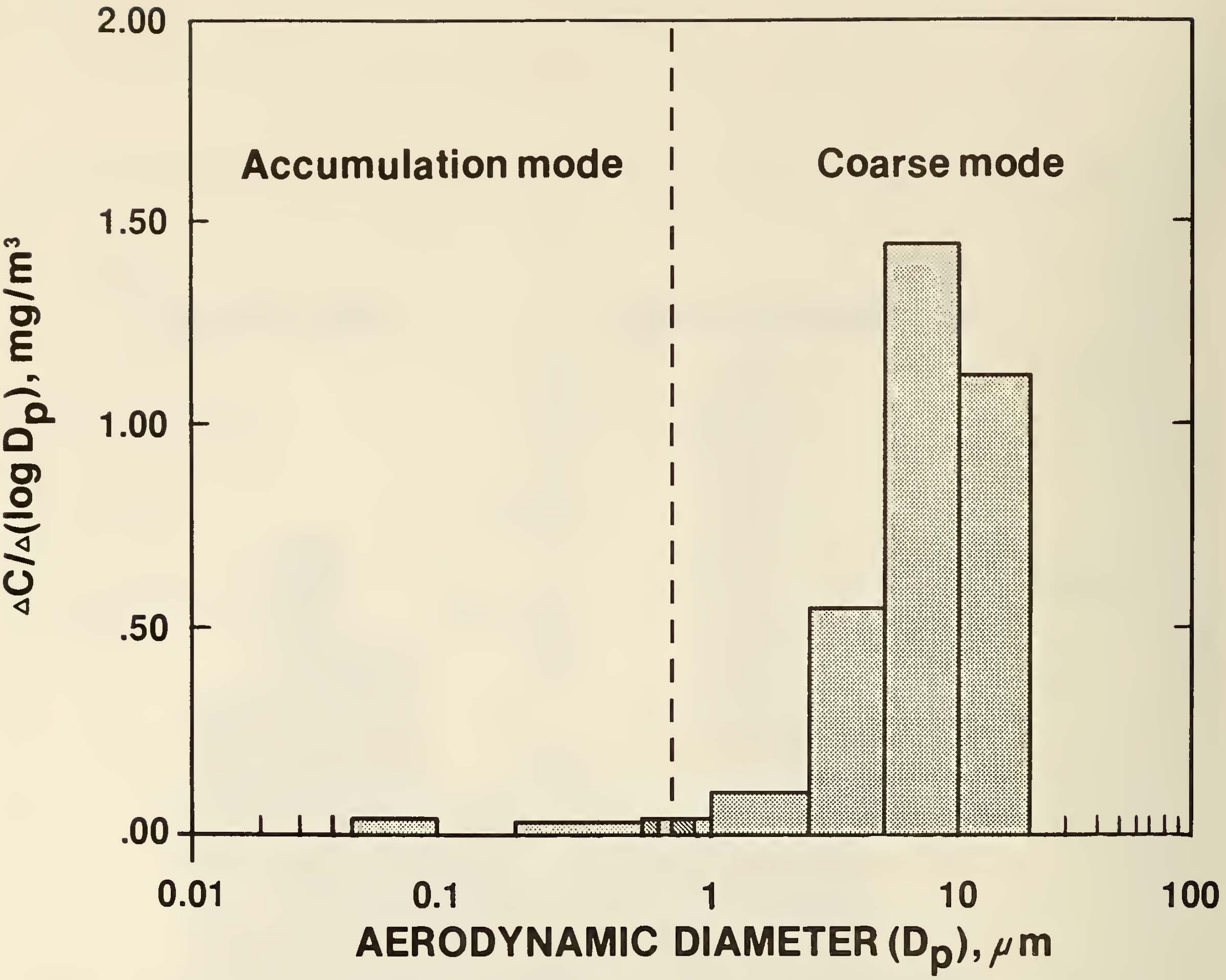

Figure 5.—Mass size distribution collected at a breaker site in an all-electric-equipped coal mine.

1. Compositions of elemental and chemical components of source emissions are constant.
2. Components do not react with each other.
3. p identified sources contribute to aerosol concentrations in the sample, i.e., they add linearly.
4. The number of sources, p, is less than or equal to the number of components, n.
5. The compositions of all p sources are linearly independent of each other.

The model is expressed as

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

Here, C_i, is the mass concentration of the i^{th} elemental or chemical component of the sample, in μg/m³, a_{ij} is the fractional amount of component i in emissions from source j, and S_j is the total contribution of source j to the sample. Apportionment of the source is achieved by first characterizing the aerosol sources, obtaining values for a_{ij}, then analyzing the aerosol in the sample for the same components and, finally solving for the S_j. A least squares regression analysis is used to determine the S_j of the overdetermined system of equations expressed by equation 1.

DIESEL AEROSOL MEASUREMENT TECHNIQUES

An aerosol measurement can be separated into two parts: (1) collection or confinement of the aerosol into a specific location and (2) application of an analysis method that is specific for the aerosol characteristic of interest. Commercially available instruments used to perform such measurements on diesel aerosol emissions in a mine can be grouped in two categories: (1) instruments that provide an integrated sample of the mine aerosol for subsequent analysis and (2) those that provide continuous or quasi-continuous direct measurement of aerosol in the mine environment. It should be remembered that each of the instruments discussed in these categories was designed for specific functions that are not necessarily compatible with measurement of diesel emissions in the mine.

MEASUREMENTS WITH COLLECTED AEROSOL SAMPLES

These techniques depend on collection of sufficient aerosol mass for gravimetric or other analysis. The length of sampling time depends on the sensitivity of the analysis method and the rate at which air is sampled. Two such measurement systems applicable to the measurement of the diesel fraction of collected aerosol are discussed here. The first is the personal cassette filter sampling system and the second is the Bosch smoke meter.

Filter Sampler

The personal cassette sampling system is used for respirable dust compliance monitoring. It is a filter following a cyclone that acts as an aerosol preseparator. Analysis of the collected samples to complete the measurement protocol consists of determining the change in weight of the filter and yields the mass concentration of respirable aerosol at the sampling site. This, however, provides no information on the diesel component of the aerosol sample. This information may be obtained using either Raman or CMB analysis. Although these techniques show promise for yielding the required information, they are costly and are as yet in the research stage. As such they cannot be relied on for definitive analysis of samples containing diesel aerosols. Another drawback for these methods is high cost per sample. Until these problems are resolved, other, more indirect, methods must be used to estimate diesel aerosol concentration in mine aerosol.

Smoke Meter Measurements

The Bosch smoke meter utilizes filter reflectance as a method of measurement. It consists of two components: a manual, spring-operated piston pump for collecting sample aerosol on a filter and a separate optical reader consisting of a light source and a sensor. In practice, a clean filter is inserted into the pump and a sample of the exhaust is collected, a process that takes about a minute. The filter is removed and a reflectance measurement is made of the filter using the optical reader.

The Bosch meter does not provide direct measurements of diesel aerosol mass concentration. Instead, readings are given as Bosch units. Approximate, empirical methods are available for converting Bosch units to mass concentration. One such relationship (*11*) is given by the following equation:

$$C = A \ln(10/(10-B_n))^{1.206}. \tag{2}$$

Here C is the concentration, in mg/m^3, B_n is the Bosch number, and A is en empirical coefficient. A suggested value for A is about 500 to 600 mg/m^3. In other work, Homan (*12*) has provided means for converting Bosch readings to other smoke meter readings.

Athough the Bosch meter is not a continuous, real-time monitor, it can provide smoke concentration estimates every few minutes and can be used for in-mine, tailpipe measurements where the only source of carbon in the measured aerosol is diesel aerosol. For example, it can be used to evaluate relative engine condition, as it affects aerosol emissions, by sampling the exhaust with the engine running at full load and comparing the result with prior measurements from the same engine or those from another engine operating at the condition under test. Engine condition could be tracked over time with a Bosch meter to determine when emissions are excessive and engine maintenance required.

The instrument could also conceivably be used for soot measurements in the workplace. When no other dusts are present, or have been removed from the sample air, and when the diesel soot is diluted by mine ventilation, the only operational modification would be the need for sufficient pump cycles to obtain an adequate filter sample for the optical reader. Even if other dusts are present, the instrument may conceivably be used because the light absorption characteristics of some mineral dusts may not interfere significantly with light absorption by soot carbon.

CONTINUOUS PHOTOMETRIC MEASUREMENTS

A number of photometric instruments are available from different manufacturers for real-time, continuous monitoring of dust aerosols. These are of two types: the first utilizes light scattering to detect aerosol and the second employs light absorption.

Light Scattering Instruments

The GCA RAM-1 and MINIRAM, Sibata P5, TM-digital, and Simslin II all use a light source to illuminate the dust aerosol and a light sensor to measure the scattered light, which can then be related to the mass concentration of the aerosol. There are many differences among these instruments. For example, some are certified for underground coal mine use. All, except the TM-digital and the MINIRAM, use a pump for air movement through the instrument. Various means, such as cyclones or optical techniques, are used to provide output proportional to the respirable dust concentration. These light scattering aerosol monitors have been characterized in the laboratory for different dusts by Kuusisto (*13*), Marple (*14*), Keeton (*15*), and Williams (*16*). Except for the work by Keeton, none of the laboratory research has involved diesel exhaust particulate. In all cases the relationship of instrument response to aerosol concentration is not simple but depends on particle size, particle composition, and on instrument design and manufacturing differences. Usually these instruments must be calibrated to the specific dust being monitored, although this is not necessary for cases where only relative measures are needed and the particle properties do not change significantly during the measurement period.

Most of the Bureau's work with real-time, photometric instruments has been with the GCA RAM-1 and MINIRAM devices. Because they were initially designed for use in the mine environment, versions can be certified for underground coal mine use and can be operated with the Dorr-Oliver 10-mm cyclone to measure respirable dust. The RAM is a light-scattering aerosol monitor of the nephelometric type; i.e., the instrument continuously senses the combined scattering from the cloud of particles within its sensing volume. The instrument uses a pulsed gallium-arsenide light-emitting source that generates a narrow-band emission centered at 875 nm. Radiation scattered by airborne particles in the view volume is collected over an angular range of approximately 45° to 95° from the forward direction by means of a silicon light detector.

The fraction of incident light per unit particle mass collected by the RAM-1 detector can be estimated as a function of aerosol size using a Mie scattering calculation for spherical aerosols with an index of refraction close to that measured for carbon. Figure 6 shows the results of such a calculation for an index of refraction (n)=2.0-i1.0 and a monochromatic incident light wavelength of 875 nm. The key feature to note is the dramatic decrease in scattered light with a decrease in aerosol size from 0.2 to 0.05 µm. To scatter an appreciable amount of light, most of the diesel aerosol would need to be greater than 0.1 µm. Because of insufficient time for coagulation, laboratory measurements of diesel aerosol size yield smaller values than this for some engine operating conditions. In these cases, the RAM would not seem to be a reliable instrument for diesel aerosol monitoring.

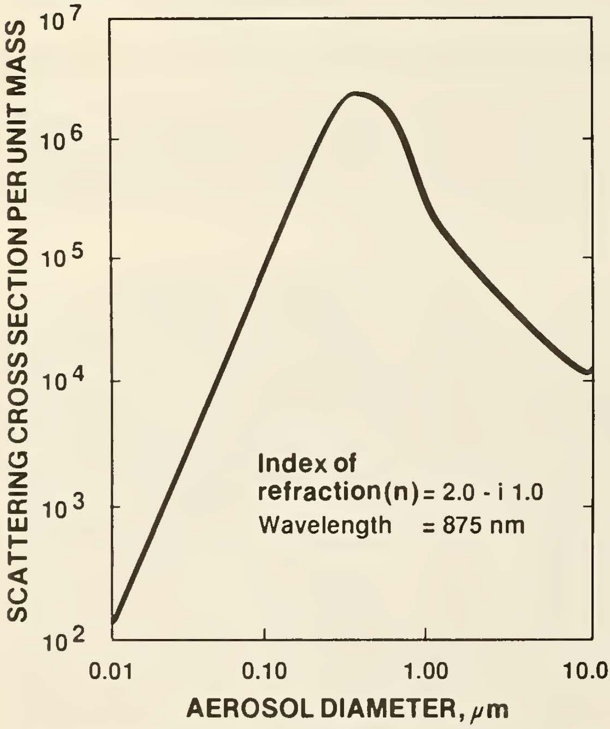

Figure 6.—Theoretically predicted mass sensitivity of GCA RAM-1 to carbon aerosol.

In-mine experience with these monitors for mineral dusts is extensive, but little published data are available for diesel aerosol. The National Institute for Occupational Safety and Health (NIOSH) (*17*) has obtained correlations of 92 pct between coal mine MINIRAM measurements and a gravimetric sampler fitted with an intake impactor to restrict penetration of particles larger than 1 µm. Analysis of the collected sample was accomplished using respirable combustible dust (RCD) measurements. This successful comparison between diesel aerosol and the response of a RAM type instrument holds promise that it might be used to monitor diesel aerosol in a coal mine environment. Response of the RAM-1 and MINIRAM to diesel aerosol in the laboratory has also been reported by Zeller (*18-19*). Figure 7 shows the recorded response during these tests of two MINIRAM's and three RAM's for diesel exhaust aerosol from a Caterpillar 3304 engine operated at different combinations of steady-state speeds and loads. The exhaust was diluted, about 25:1, with clean air prior to measurement. The mass concentrations are from simultaneously collected filter samples.

Data shown in figure 7*A* exhibit five distinct trends indicating that each instrument responds differently to diesel aerosol. This instrument bias is normal and has been observed by Marple (*14*) for rock and coal dusts. Manufacturing tolerances are the sources of these differences in instrument response functions. Figure 7*B* shows these same data adjusted for instrument bias by multiplying the instrument responses by a value that is constant for each instrument. The data now lie on a line with only moderate scatter attributed to imprecision or random error.

In the case of the RAM's, the manufacturer provides internal adjustments to compensate for instrument bias. All the results in figure 7 were obtained with the instruments adjusted according to the factory calibration, which is based on a standard silica dust. An alternative to this procedure would be to expose the instruments to a known concentration of diesel aerosol and determine a new internal adjustment specifically for diesel aerosol. If this had been done for these tests, then it is expected that the instrument responses would appear as depicted in figure 7*B* without any need for a mathematical adjustment of the data.

Light Absorption Instruments

Opacity meters are widely used as continuous monitors for diesel emissions, but their sensitivity is not adequate for measuring soot concentrations diluted by mine ventilation. Standardized calibration and operating procedures for several commercial instruments are given in the SAE Handbook (*20*). As with the Bosch meter, opacity smoke meters do not provide output directly proportional to mass concentration. Instead the output is percent opacity, which is related to mass concentration by

$$N = 100(1-\exp(-KL)).$$

Here, N is the opacity, in pct, K is the extinction coefficient, in units of reciprocal length, and L is the path length in units of length. K is the parameter that is directly related to diesel aerosol concentration.

Bureau staff have had considerable experience with the Celesco model 107 opacity meter used in the diesel emissions test facility (*18*). Representative data from a portable in-line meter are displayed in figure 8. The results are ad-

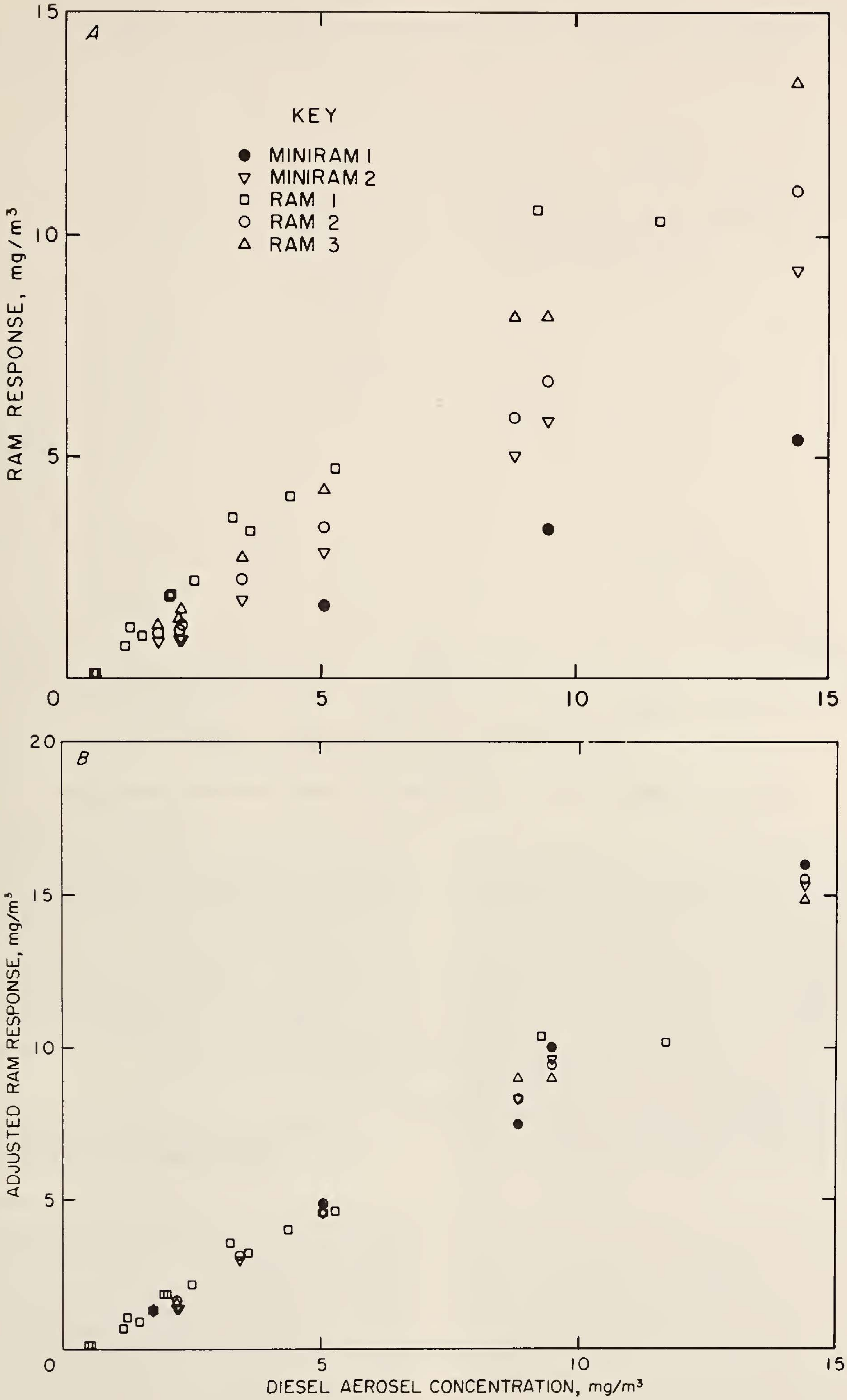

Figure 7.—RAM and MINIRAM response to diesel soot. *A*,actual instrument response; *B*, same data adjusted for instrument bias.

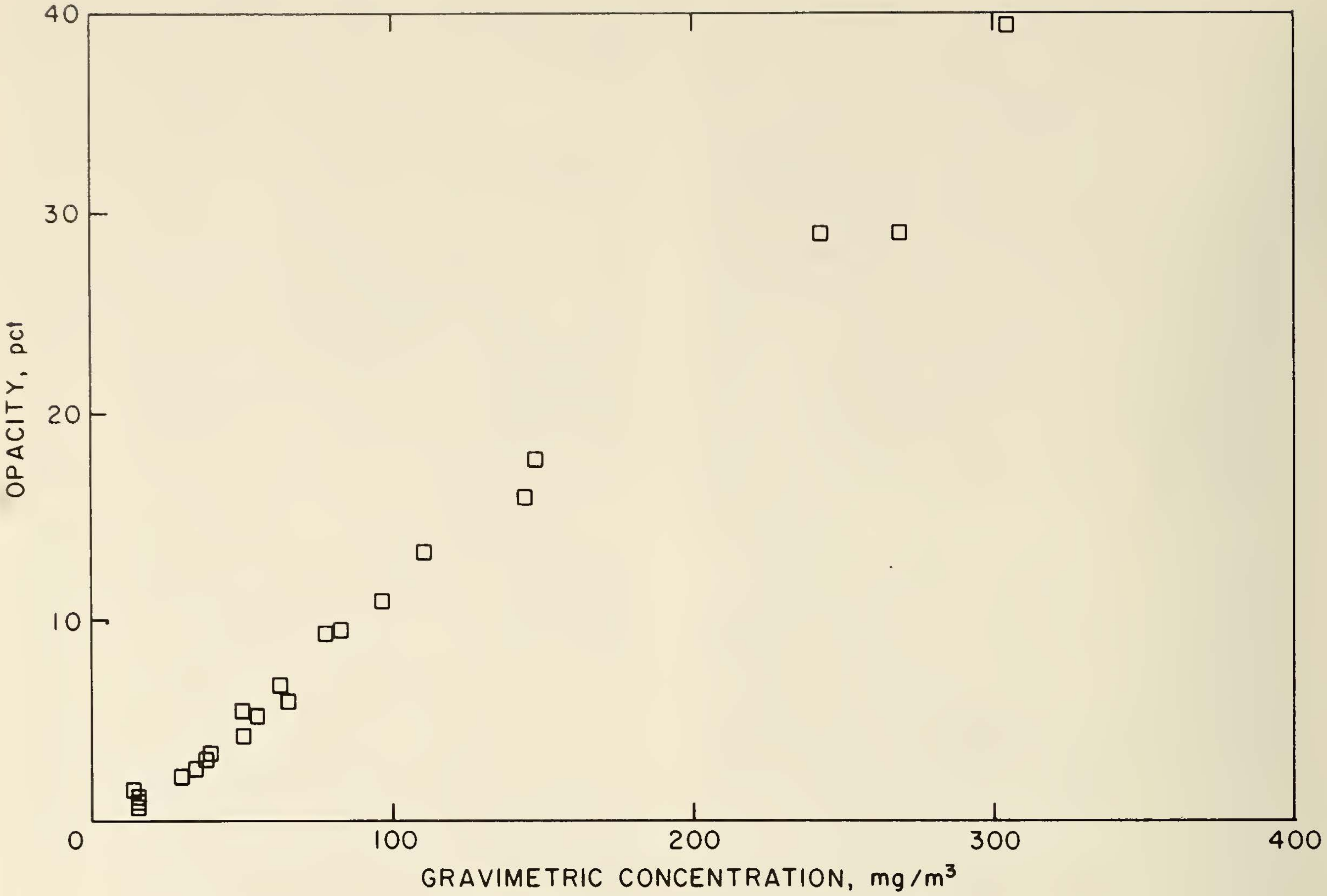

Figure 8.—Comparison of opacity with gravimetrically measured aerosol concentration.

justed to standard conditions of 75 ° F and 1 atm. The apparent linearity of the opacity data with gravimetric measurements is typical of this instrument for a wide range of engine operating conditions. However, close examination of the data labeled solid plus volatiles in figure 9, shows that the opacity meter underestimates aerosol concentration at concentrations, below about 80 mg/m^3, with the magnitude of the underestimation increasing as soot concentration decreases. The response of most optically based instruments, including opacity meters, is dependent on both particle size and composition (*14,18-19*). When the opacity data are plotted against only the solid or carbon fraction of the aerosol (fig. 9), the degree of underestimation decreases. This result is consistent with the results of other investigators (*21-23*); who concluded that opacity meters primarily respond to the carbon component in diesel aerosols.

One application for opacity meters in mines is diesel emissions monitoring of equipment to determine when engine maintenance is required for acceptable emissions control. Portable, battery-operated opacity meters, which are designed for pipe-end measurements, are available for this purpose (*24*). A second application of these instruments is validation of the use of other instruments as continuous monitors of soot mass concentrations. Figure 10 illustrates the precision that can be expected for light-scattering instruments such as the RAM-1. The RAM-1 data are compared with those from the in-line opacity meter used in the Bureau's diesel emissions test facility. To obtain this comparison the RAM-1 readings were adjusted so that the areas under the two curves are equal; the opacity data were corrected from exhaust to room (RAM) temperature. The result is excellent tracking of the two instruments. The correlation between the two instruments is actually better than illustrated because some of the discrepancies are the result of deficiencies and limitations of the data acquisition system. The fact that these instruments correlate so well simplifies the task of comparing results from the two and assures that they will complement one another in in-mine evaluations.

CRITIQUE OF DIESEL EMISSIONS AEROSOL MEASUREMENT METHODS

The main criticism concerning in-mine aerosol sampling and measurement techniques for diesel emissions is that the sampled aerosol is mixed thus creating an ambiguous analytical situation. For metal-nonmetal mines, chemical analysis can separate the diesel component but the presence of another carbonaceous aerosol in the mixture will cause interference in the analytical procedure. This is particularly true in the case of coal mine aerosol measurements. To determine relative diesel and dust aerosol fractions in this latter case requires even more cumbersome and expensive analytical techniques. Sampling techniques such as the Bosch smoke meter also suffer from the same problem when coal dust aerosol is involved. Reflectance measurements of

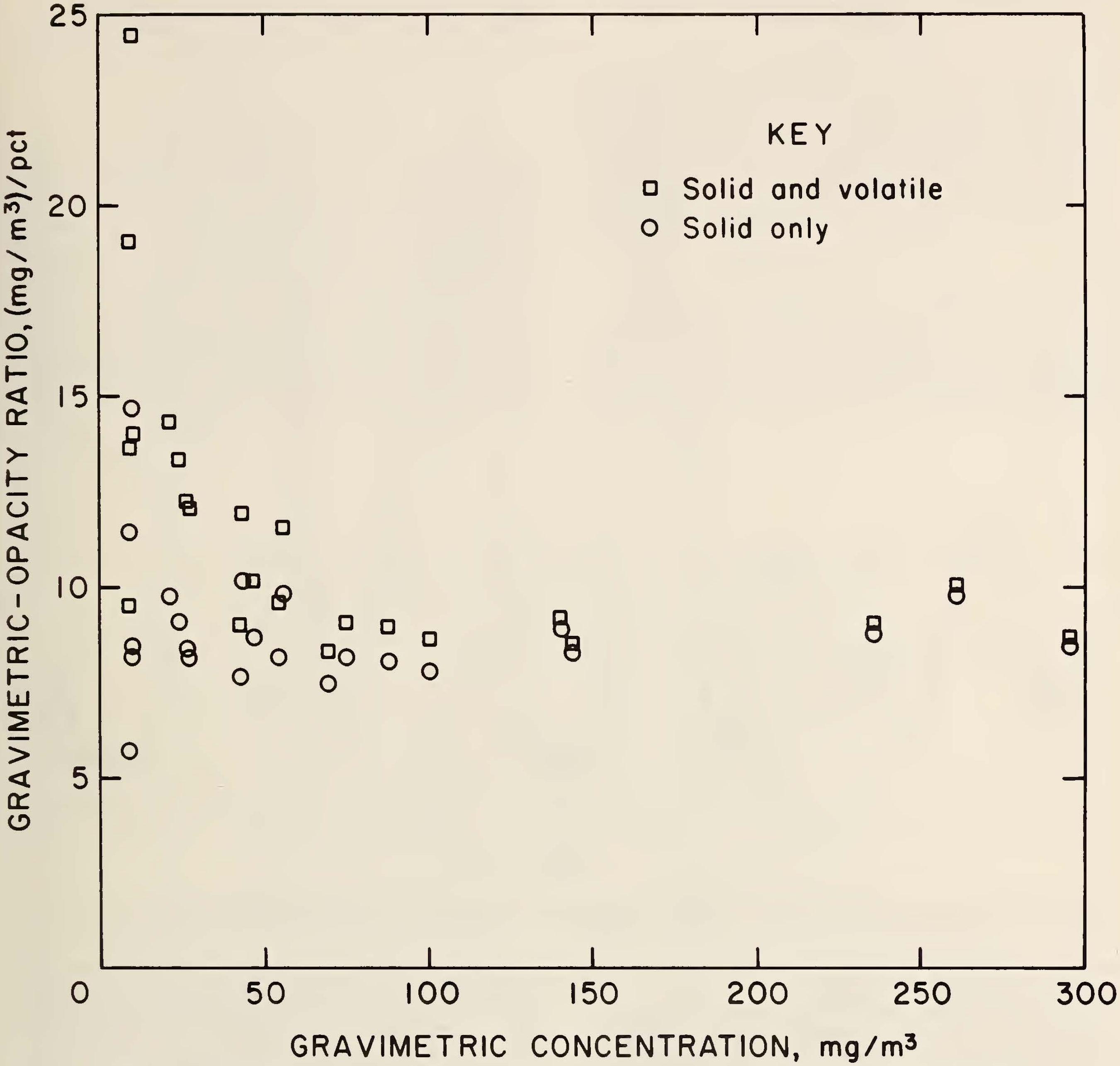

Figure 9.—Variation in opacity response as a function of gravimetrically measured aerosol concentration.

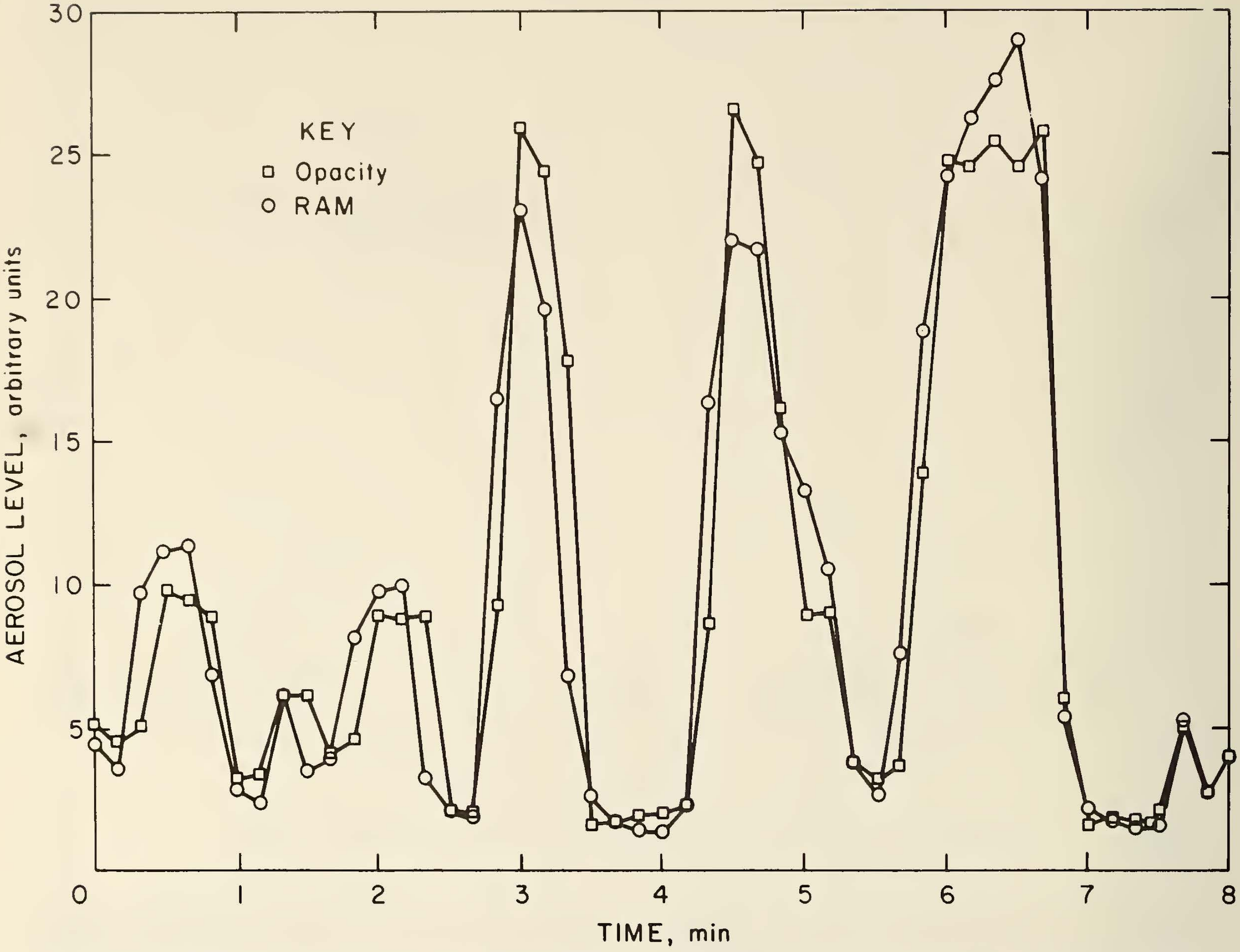

Figure 10.—Comparison of GCA RAM-1 and opacity measurement of diesel aerosol emissions during a standard test cycle.

in-mine diesel aerosol admixed with coal dust aerosol are unreliable because of interference.

The response of the optically based instruments depends on the light-scattering and absorption properties of aerosols. A serious limitation on the use of such instruments is unpredictable response caused by changes in aerosol composition or size which, in turn, affect optical properties.

For in-mine applications, these aerosol property changes can result from numerous causes. Major engine-related causes include engine type, engine condition, operating duty cycle, use of fuel additives, and exhaust emission controls. Mine-related effects on diesel aerosol properties include effects of ventilation, dilution factors, aerosol age, and interferences from other aerosols such as coal dusts.

To address these problems, use is being made of the size characteristics of the diesel and mine dust aerosol. A series of sampler modifications and new designs are now being used that employ size selective sampling techniques to separate diesel and mineral dust aerosol during sampling.

SIZE SELECTIVE MONITORS FOR DIESEL AEROSOL SAMPLING

The contribution of diesel aerosol emissions to total respirable aerosol in coal mines using diesel-powered equipment is not easily determined by chemical means. Since diesel aerosols are expected to be predominately submicrometer in size, while mechanically generated dust aerosols are generally larger than 1 μm, a solution for this problem is to physically separate these aerosol fractions on the basis of aerosol size during sampling. Under sponsorship of the Bureau and NIOSH, aerosol samplers employing such techniques are now being developed to obtain size-dependent information on respirable aerosol containing a diesel component. These can be grouped into two categories: (1) samplers that separate the mine aerosol into a series of several size intervals during sampling, yielding a differential size distribution of the aerosol, and (2) samplers that separate the sampled aerosol into two or three size intervals in an attempt to isolate the diesel and dust aerosol fractions. Samplers of the first category are used to obtain general information about aerosol size distributions and thereby establish the sampling criteria for the second category of samplers.

INERTIAL IMPACTORS

Many size selective sampling devices use inertial impaction to select for specific sizes during sampling. The theory of inertial impactors has been described by Ranz (*25*) and, more recently, by Marple (*26*) and Fuchs (*27*). An inertial impactor is a device that classifies aerosol particles by their aerodynamic diameter. This is accomplished, as shown in figure 11, by directing a jet of particle-laden air at an impaction or collection plate. Particles with sufficient inertia will impact on the plate while smaller, lower inertia particles will not impact but remain suspended in the airstream. The size of the aerosol at which this inertial selection occurs is termed the cutoff size of the impactor.

DIFFERENTIAL SIZE SELECTIVE SAMPLING TECHNIQUES

Differential size selective sampling is achieved by cascading several of the impaction stages so that they act on the sample air sequentially. By designing each successive stage with a smaller cutoff size the net effect is to divide the sampled aerosols into contiguous size interval samples. Gravimetric analysis of substrates placed on the impaction plates will yield a mass weighted size distribution for the sampled aerosol.

Marple Personal Sampler

A differential size selective sampling technique that has found use for in-mine measurement of both diesel and mineral dust aerosol is the Marple personal impactor (MPS) manufactured by Anderson/Sierra as the series 290 sampler. This is a compact, radial-slot cascade impactor designed to

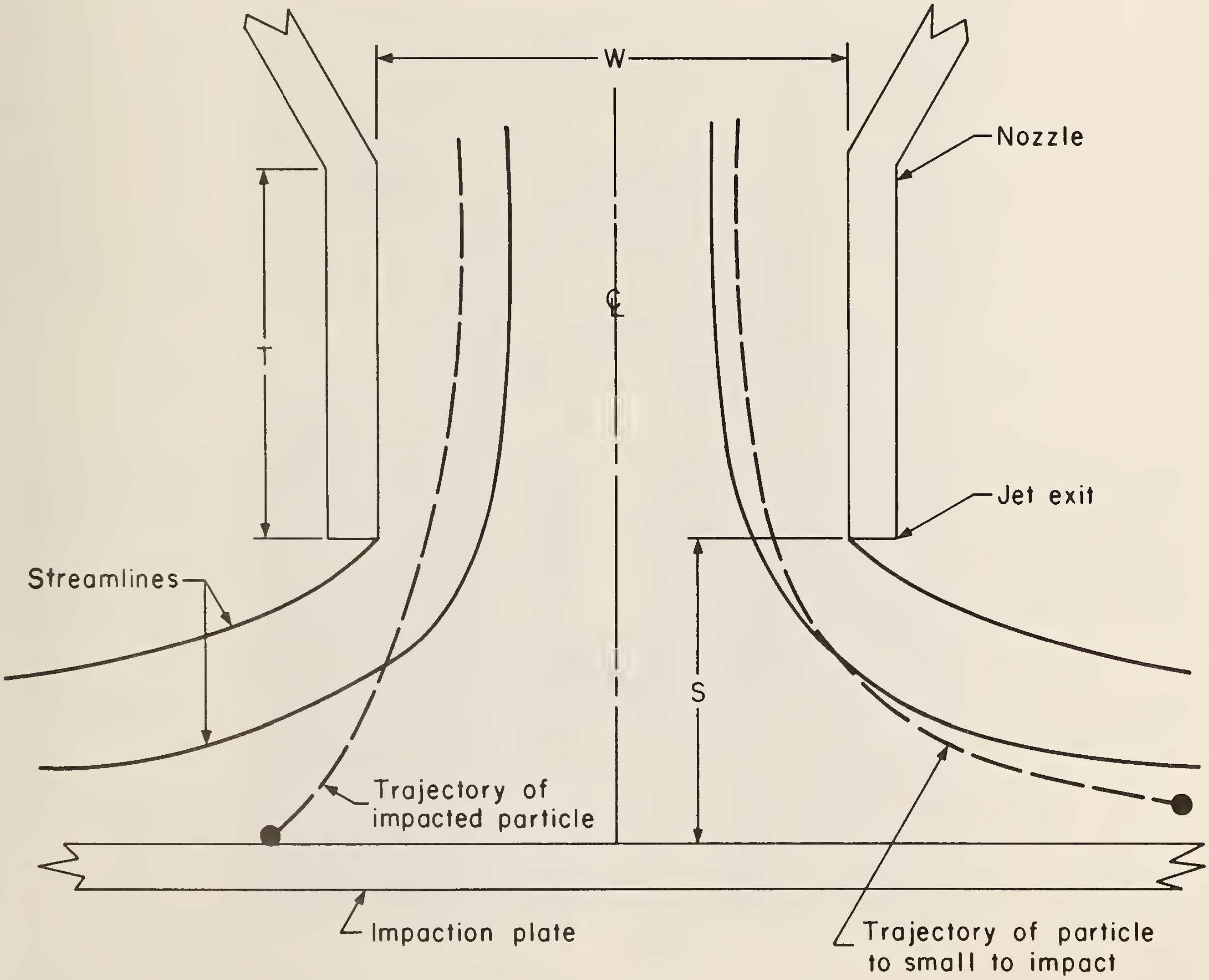

Figure 11.—Streamlines and particle trajectories for a typical impactor.

be worn as a personal sampler. The impactor, pictured in figure 12, can be used in several configurations with up to eight impactor stages plus an afterfilter. Nominal size separations for these stages are 21, 15, 10, 6.0, 3.5, 2.0, 0.9, and 0.5 µm. The impactor operates with a flow rate of 2 L/min and uses the same sample pump as the personal cassette sampler.

The MPS was originally designed for NIOSH as a wood-dust sampler by Rubow (*28*). More recently, it has been used in surveys of diesel-equipped mines and by the Bureau and NIOSH as a device for size characterization of diesel and dust aerosol (*17*). These surveys compared the operation of the cascade impactor with that of the standard cassette sampler and a simplified dichotomous sampler that uses a single impaction stage. Figure 13 gives a typical size distribution measured during the survey using the MPS. This distribution was obtained from an average of several full shift samples collected in a haulage road of a diesel-equipped coal mine. It shows a distinct coarse particle mode and a smaller submicrometer mode. These can be used to estimate average levels of diesel and mineral dust aerosol during a working shift.

Micro-Orifice, Uniform-Deposit Impactor

The micro-orifice, uniform-deposit impactor (MOUDI) holds promise for use in measuring the size distribution of mine aerosol over the size range in which diesel aerosol is expected to predominate (*29*). The basic sampler is an eight-stage cascade impactor designed for a flow rate of 30 L/min. A picture of the device is shown in figure 14. Each stage of the impactor consists of an impaction plate for the stage above it and a nozzle plate for the stage below. When alternate stages are rotated, the impaction plates of all stages are rotated relative to the nozzle plates, creating a uniform deposit on the impaction plate. Four of the stages are of micro-orifice design with 2,000 nozzles in each stage. An electric motor and gear assembly can be used to rotate the stages to obtain the uniform deposits on the impactor substrates. Nominal size separations for the impactor are 18.7, 10.0, 4.9, 2.6, 1.0, 0.60, 0.23, and 0.10 µm.

The MOUDI has been used during in-mine field sampling experiments (*30*) to evaluate its ability to separate diesel aerosol from dust aerosol on the basis of their size distribution. In addition to the MOUDI, a two-stage

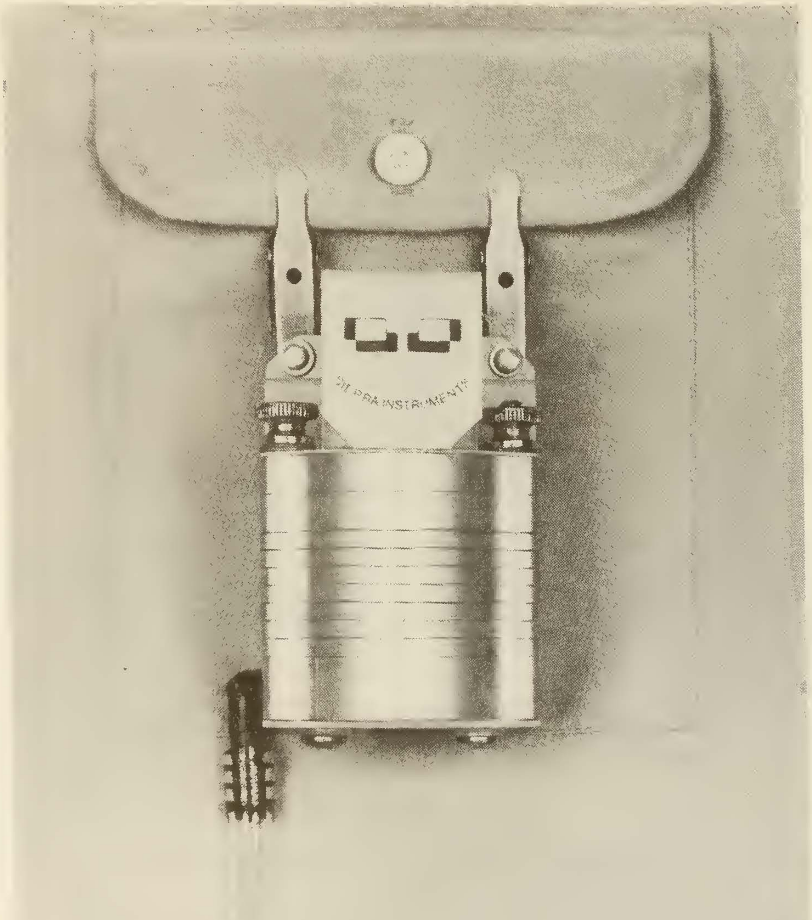

Figure 12.—Marple personal sampler.

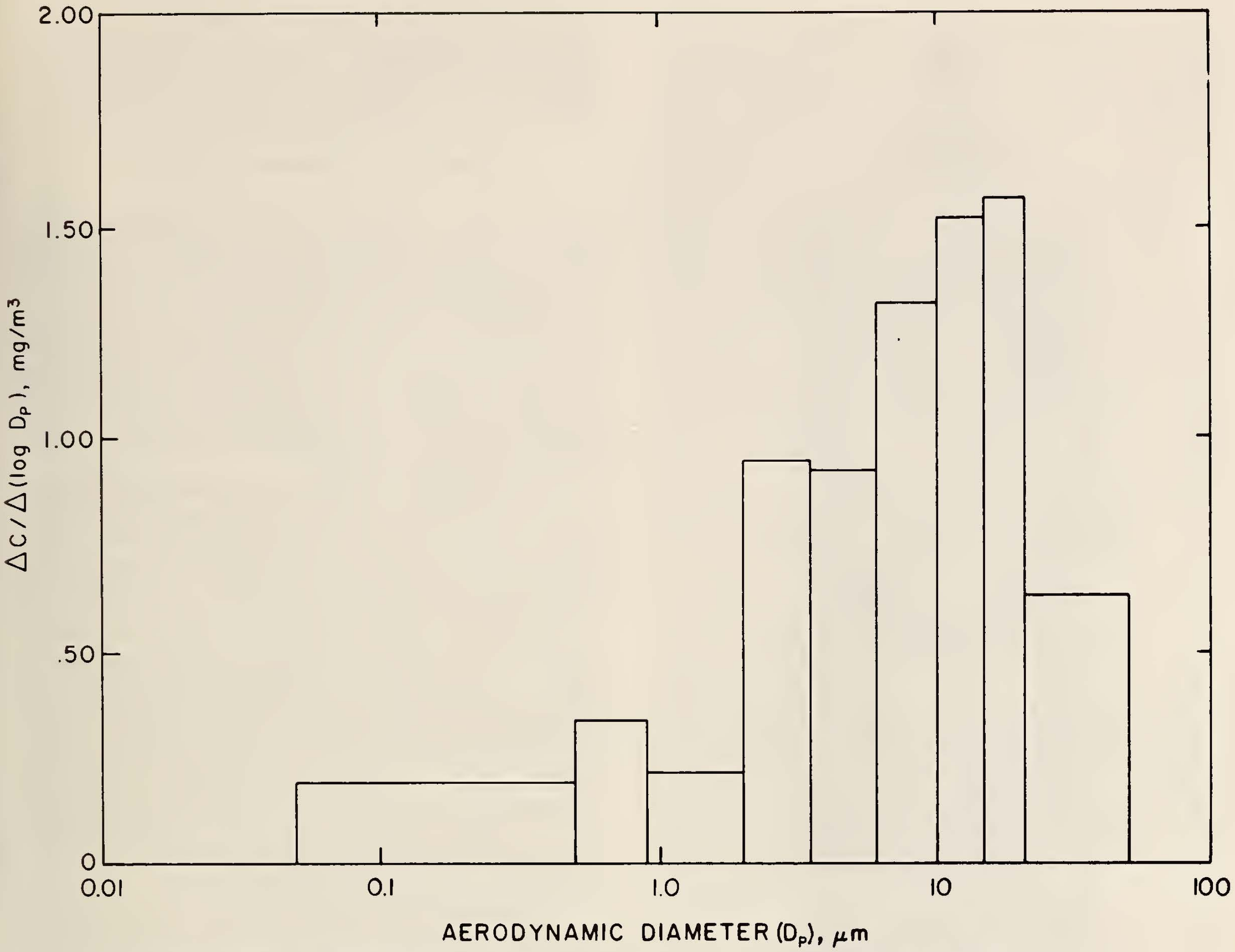

Figure 13.—Mass size distribution collected in a return airway with a Marple personal sampler.

respirable impactor, with the second size separation at 0.6 μm, was also used to provide samples of submicrometer and supermicrometer aerosol for elemental analysis. The field evaluation was conducted in three underground mines; in one mine, which used only electric-powered mining equipment, and in two others that used diesel-powered mining equipment. For each mine visited, sampling was conducted in secondary return airways near mine conveyor systems, in primary ventilation returns, and in primary intakes.

Mass size distributions of aerosol measured in the dieselized mines using the MOUDI and exemplified in figure 4 show two distinct maximums; one submicrometer and the other greater than a micrometer in size. To provide a measure of the distribution of diesel aerosol between these two size ranges, the samples collected with the respirable impactor were analyzed using CMB model source apportionment analysis. Trace element concentrations used in this analysis were obtained using instrumental neutron activation. Results of these analyses, given in table 1 for the two diesel mines, confirm that diesel emission aerosols in the dieselized mines studied are predominantly submicrometer in size. The diesel associated submicrometer aerosol accounted for approximately 40 to 60 pct of the respirable aerosol mass concentration. For respirable aerosol concentrations less than 2 mg/m^3, 10 pct or less of the submicrometer aerosol mass was dust associated. In contrast, aerosol size measurements in the all-electric equipment coal mine, typified by figure 5, exhibit no submicrometer maximums and less than 10 pct of the measured respirable aerosol mass was in the submicrometer size range. Based on the success of the MOUDI in separating the two aerosol fractions, a simpler, two-stage sampler with size separation at 0.8 μm can be recommended for sampling diesel and dust aerosol in mines.

The MOUDI, with a weight of approximately 10 lb and sample pump requirements of 150 H_2O at 30 L/min, is not suitable for routine in-mine monitoring. Its use has been as a research tool for characterization of diesel aerosol.

Table 1.—Average source apportionment analysis results for two coal mines, percent

Source	Fine	Coarse
	MINE A	
Coal	7 ± 8	87 ± 7
Rock dust	.4 ± .2	13 ± 7
Diesel fuel	92 ± 8	< 8
	MINE B	
Coal	25 ± 4	92 ± 5
Rock dust	.2 ± .1	8 ± 2
Diesel fuel	75 ± 3	< 6

Figure 14.—Eight-stage micro-orifice, uniform deposit impactor.

However, the micro-orifice impactor design has a low-pressure drop for stages with size cut points in the 0.8- to 1.0-μm range. As a result, it is feasible to design a single-stage dichotomous sampling unit that will operate at 2 to 4 L/min using sampling pumps approved for in-mine use.

Dichotomous Sampling Techniques

A dichotomous sampler is an impactor with one impaction stage and an afterfilter. All aerosols with diameters greater than the cutoff size of the single stage are collected on an impaction substrate and all aerosol smaller than the cutoff size are collected by the afterfilter. Such a two-stage impactor with a cut point of approximately 1 μm aerodynamic diameter has been developed for use in place of the cassette filter unit in a respirable coal mine dust sampling unit (*26, 31*). This device is intended to separate submicrometer and supermicrometer respirable dust aerosol fractions during sampling.

Figure 15 gives a schematic representation of the complete impactor with its cyclone preseparator. Sample air containing aerosol first passes through a Dorr-Oliver 10-mm nylon cyclone at a flow rate of 2 L/min to separate the respirable from nonrespirable aerosol. After leaving the cyclone, the respirable aerosol passes through an orifice and is then deflected by a foil impaction substrate. Most of the respirable aerosol greater than 1.0 μm aerodynamic diameter impacts on the preweighed, greased foil substrate. Most of the submicrometer aerosol passes through the holes in the substrate and deposits on a polyvinylchloride (PVC) final filter. The MRE equivalent total respirable mass can be determined from the sum of the weight change of the foil substrate and final filter using the 1.38 accommodation factor. The submicrometer mass, and presumably the diesel fraction of the respirable aerosol, can be determined from the weight change of the afterfilter.

Estimates of submicrometer aerosol concentration have been made (*17*) using sample mass data collected with the dichotomous sampler in several diesel-equipped coal mines. These were compared to similar estimates made from 53 paired Marple personal impactor samples. Results, given in figure 16, show personal impactor derived submicrometer aerosol concentrations plotted against concentrations obtained using dichotomous impactor measurements. A regression analysis of these data shows that the personal impactor concentrations equal 1.0 times dichotomous sampler results + 0.02 mg/m^3. The correlation coefficient was 0.95 and the standard deviation from the regression line was 4 pct. These results indicate that the dichotomous impactor can perform at least as well as the MPS in sampling submicrometer aerosol.

The MOUDI experiment verified that the submicrometer aerosol mass determined with a dichotomous sampler in diesel coal mines can provide an estimate of the diesel aerosol concentration accurate to within approximately 20 pct. As such, this sampler can be used within its stated error limits to identify and quantify the contribution to mine aerosol from diesel equipment.

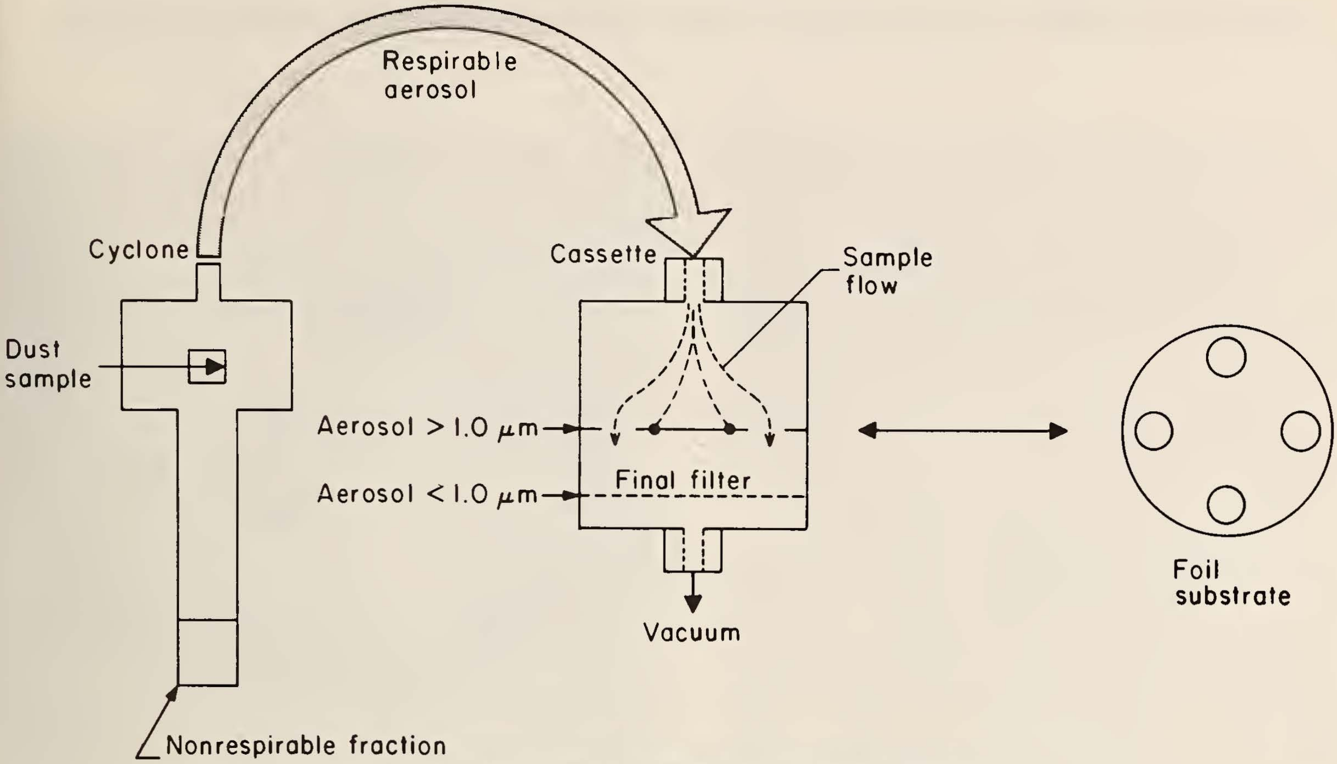

Figure 15.—Dichotomous sampler with cyclone preseparator.

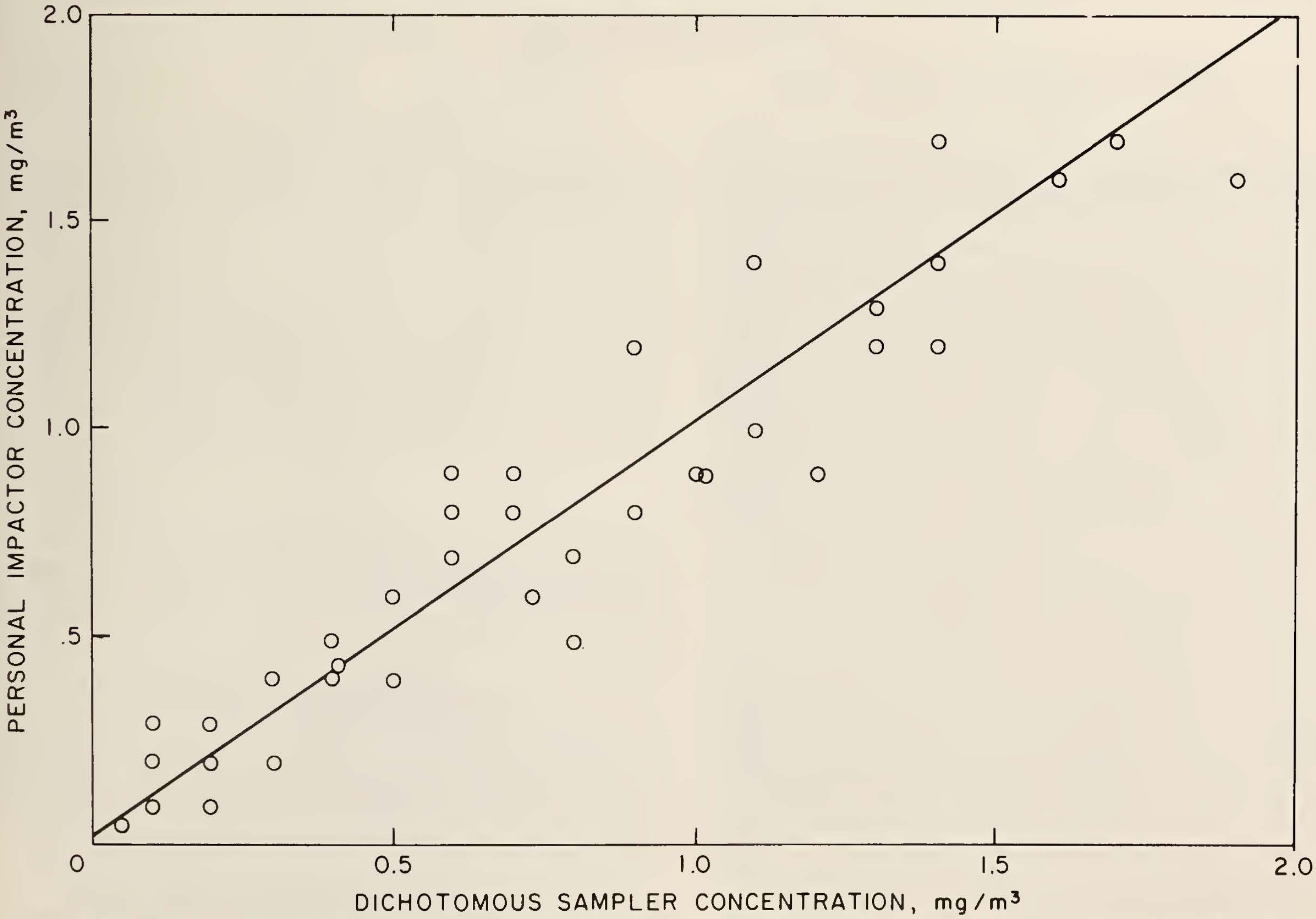

Figure 16.—Comparison of submicrometer aerosol mass concentrations measured with the dichotomous sampler to that measured using the Marple personal sampler.

PROPOSED MONITORS FOR REAL-TIME MEASUREMENTS OF DIESEL AEROSOL

The following sections describe two prospective instruments for real-time measurement of both laboratory-generated and in-mine diesel aerosol. Each of these instruments is proposed for use as a continuous aerosol detector in place of the afterfilter in a dichotomous sampling train similar to that discussed in the previous section. Use of the preliminary impaction stage enhances the response of the instrument to diesel aerosol by removing the majority of mineral dust aerosol from the sample. The instruments thus configured will be particularly useful for real-time mass concentration measurement of diesel exhaust aerosol in laboratory tests of engines operated in transient modes; especially those involving fast transients intended to simulate the duty cycles of load-haul-dump equipment as described by Alcock (*32*) and other Bureau work.[7]

In addition to laboratory needs, real-time diesel aerosol mass concentration instruments would also be useful in mines for the following: (1) identify and prioritize problem areas such as changes in control equipment efficiency, (2) quickly assess the benefits of diesel aerosol control changes to determine cost effectiveness, (3) evaluate the diesel aerosol control effectiveness of engine maintenance programs, and (4) determine relative importance of diesel aerosol and mineral dust sources so that resources can be directed at the most significant problems.

CONDENSATION NUCLEI COUNTER

A method that is specific for detection of submicrometer aerosol and hence diesel emissions is the condensation nuclei counter (CNC). This device, described by Aitken in 1888 (*33*), operates by condensing water or other vapor on nuclei particles. These aerosols grow to a uniform size and are then detected using an optical particle detector operated as either a single particle detector or as a forward scattering nephelometer. The instrument output is the integral of aerosol number over its range of sensitivity. This range is usually 0.003 to 0.5 µm, just the range where most of the diesel emissions contribution is made to in-mine respirable aerosol. Figure 17 shows a schematic of a TSI model 3204 CNC. This device uses alcohol vapor to increase the sample aerosol size and employs both single particle and nephelometric detection modes for measurement depending on the number concentrations of the aerosol. The resultant data are expressed in number per cubic centimeter.

Although this measurement is accurate for number, the correlation with aerosol mass is highly dependent on the operating mode of the diesel source. This is because the size distribution changes continually with the operating mode; e.g., an equivalent nuclei mode mass can be achieved with much fewer accumulation mode aerosols. For coal mine aerosol not dominated by an immediate diesel source, this may not be a serious drawback because measurements, such as those reported in figure 4, indicate a relatively stable submicrometer aerosol. This stable relationship between number and mass permits conversion of aerosol number measurement to mass concentration, though it must still be measured in each case where the CNC is used.

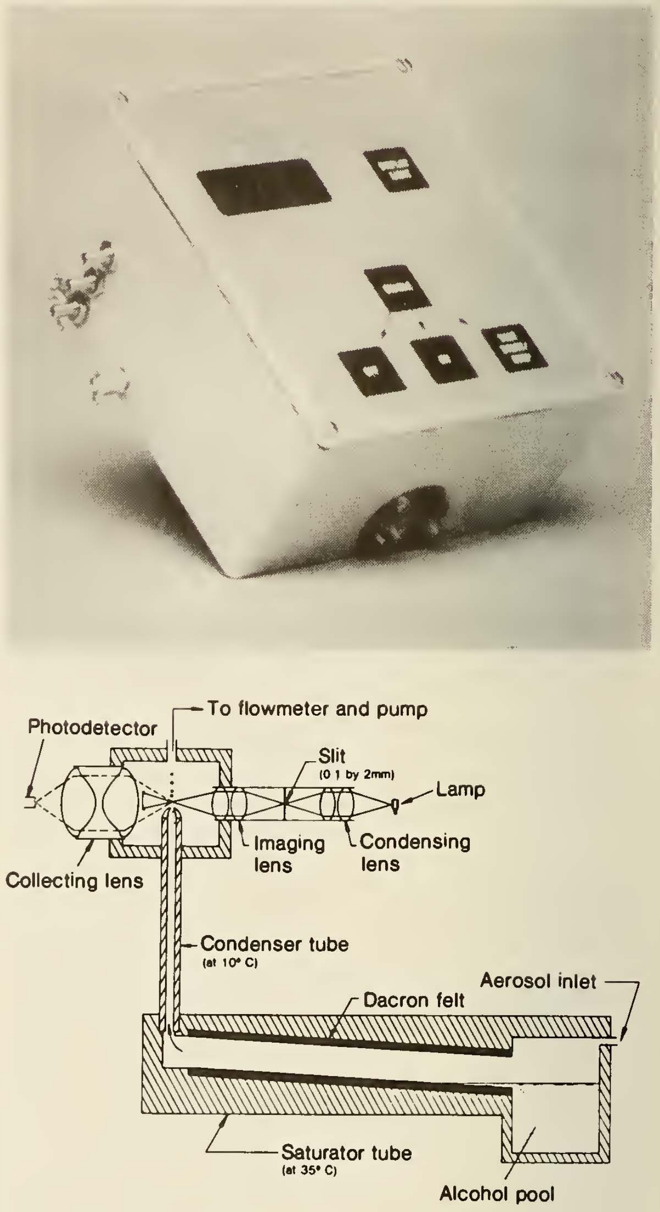

Figure 17.—TSI model 3204 condensation nucleus counter (top) and schematic (bottom).

TAPERED ELEMENT MASS MONITOR

The tapered element oscillating microbalance (TEOM) technique was developed to measure the mass concentration of various types of airborne respirable dust. This technique uses the inertial behavior of a vibrating tapered element to directly measure the mass of a sampled dust, thus avoiding measurement errors associated with other particle characteristics. Other TEOM dust monitors have been used to measure diesel equipment exhaust emissions (*34-35*), atmospheric aerosols (*36*), and stack emissions (*37*). The

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[7] Contract J0100010, "Study of Duty Cycles of Diesel Vehicles Used in Mines."

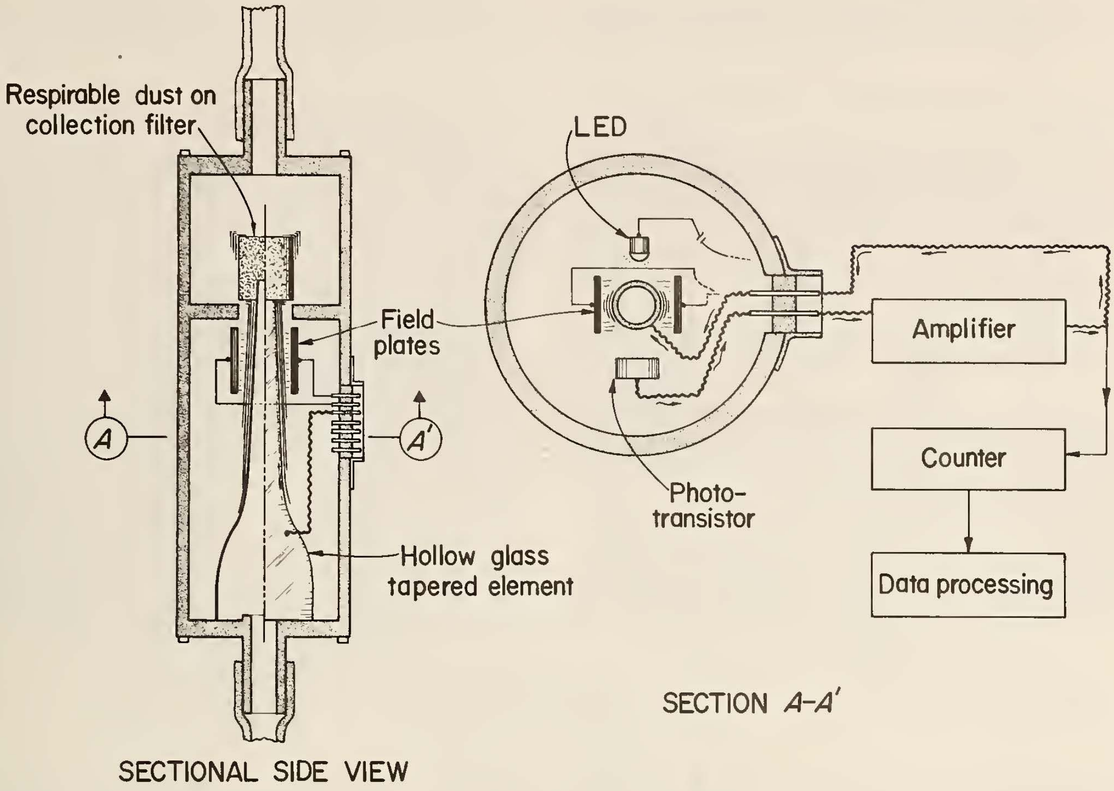

Figure 18—TEOM sample analysis.

Bureau and the NIOSH cosponsored the development of a prototype TEOM dust monitor for measuring respirable coal mine dust mass concentrations (*38*). The original objective was to develop a personal sampler that used the tapered element oscillating microbalance measurement technique.

The active element of the system, shown in figure 18 mounted in a sampling canister, is a specially tapered hollow tube constructed of elastic, glasslike material. The wide end of the tube is firmly mounted on an appropriate base plate, while the narrow end supports a replaceable filter and is permitted to oscillate. As the filter collects dust, the mass increases thereby decreasing the frequency of oscillation.

The frequency of oscillation is detected by using a light-emitting diode (LED)-phototransistor pair aligned perpendicular to the plane of oscillation of the tapered element as depicted in figure 18. The output signal of the phototransistor is modulated by the light-blocking effect of the oscillating element positioned between the phototransistor and the LED. This signal is amplified.

Part of the amplified signal is applied to a conductive coating on the outside of the tapered element. In the presence of constant electric field plates, this signal provides sufficient force to keep the tapered element in oscillation. In other words, part of the amplified signal from the LED-phototransistor pair is used in an electrical feedback loop to overcome any amplitude damping of the tapered element oscillation.

In use as a submicrometer aerosol sampler, a canister containing the sensing cone and filter is connected to a 10-mm Dorr-Oliver nylon cyclone and single-stage impactor. By using a typical personal sampling pump operating at 2 L/min, air can be drawn through the cyclone. The cyclone removes large particles, passing respirable dust to the impactor and finally the filter mounted atop the tapered element. The filtered air passes through the tapered element to the sampling pump. During sample collection the canister is used like any filter that might be used in gravimetric personal samplers.

A time-resolved measurement of diesel aerosol emissions collected, using the TEOM alone, during a heavy-duty test cycle is given in figure 19. Here, the transient emissions from the engine are clearly evident with a time resolution of about 1 min. In laboratory tests by the Bureau, the TEOM had a mass resolution of 1.6 μg. Its response to a large sudden change in relative humidity is a change of less than 0.02 μg/min in its zero reading. Orientation of the device during readout does not appear to affect readings. Other than the sensitivity to relative humidity, the TEOM seems suited to use as a diesel aerosol mass detector.

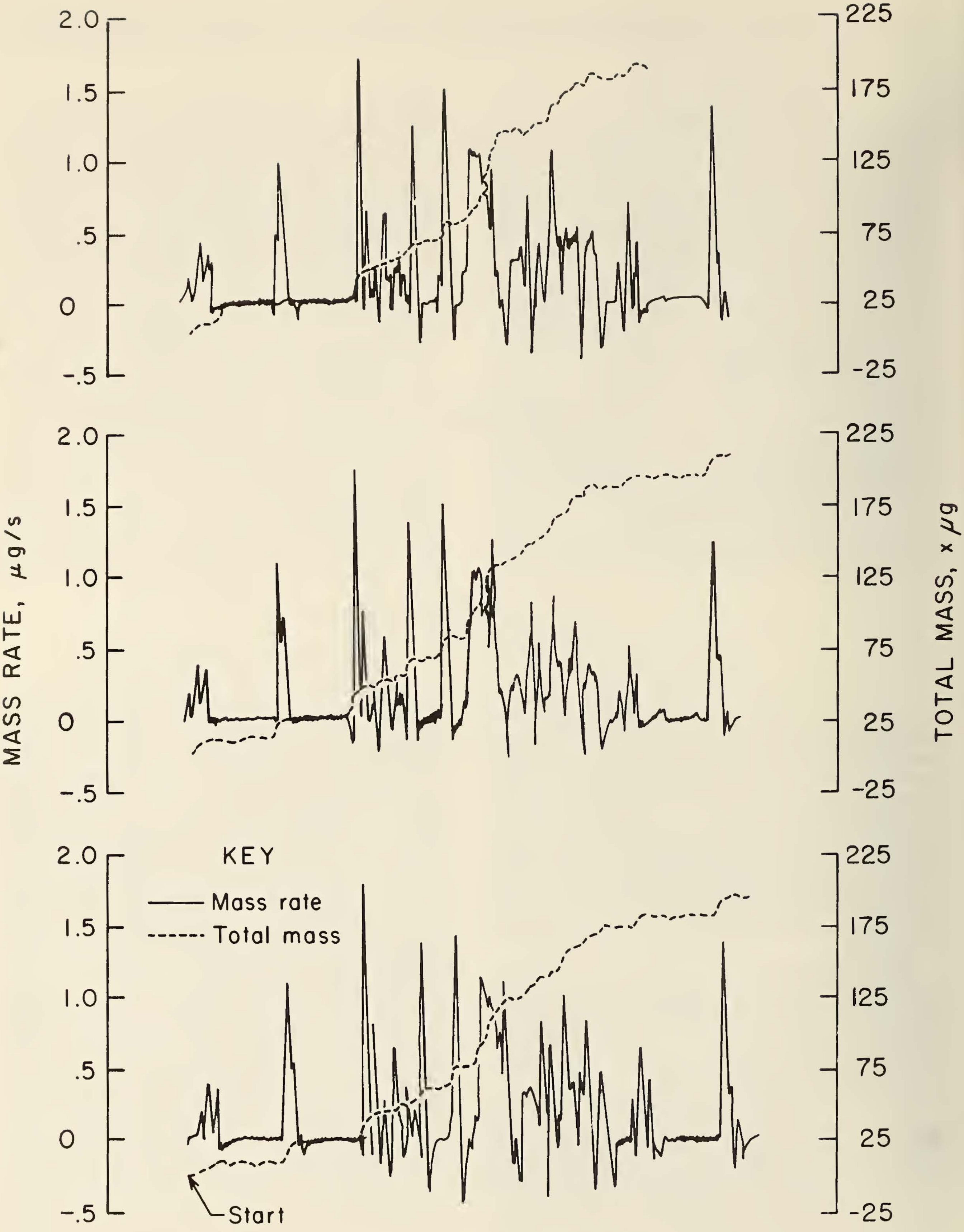

Figure 19—Triplicate hot-start particulate emission rate over the U.S. Federal heavy duty transient cycle.

SUMMARY OF MINE AEROSOL MEASUREMENT TECHNIQUES

Accurate measurement of diesel aerosol emissions in a mine environment depends to a large extent on the manner in which the sampling or measurement device exploits the physical and chemical characteristics of the aerosol. Diesel aerosol is primarily carbonaceous and predominantly submicrometer in size as opposed to the mineral dust aerosol fraction which is predominantly greater than 1 µm. The trace elemental and chemical composition of diesel aerosol has been found to be sufficiently different from most mineral dust aerosol so that special analytical techniques can be used to resolve diesel and mineral dust components of a collected aerosol sample. This is even true for mineral dust aerosols like coal, which are also primarily carbonaceous.

A review of the aerosol sampling techniques currently used in mines for compliance monitoring reveal that without modification they are, at best, marginally useful for diesel aerosol measurement. Because all of these techniques were designed to sample respirable dust, in diesel-equipped mines they provide mixed aerosol samples for subsequent analysis. Analyses of these samples for the diesel fraction require special analytical techniques that are of a research nature and hence unavailable to most mine operators.

The Bureau and other agencies such as NIOSH are currently sponsoring development of aerosol samplers designed to selectively sample the diesel aerosol component of mine dust aerosol. For the most part, these samplers employ physical size selective sampling using inertial impaction to achieve this end. The goal of these development studies is to produce and validate a simplified sampler for mine owners that will provide separate measurement of diesel and mineral dust aerosol mass concentrations in the mine environment.

As a collateral development, the Bureau is also evaluating designs for a real-time diesel aerosol monitor for in-mine use. All of the proposed instruments are designed to accommodate a size-selective sample inlet that will eliminate the mineral dust fraction of the aerosol sample before it is introduced into the detector mechanism. This separate development is admittedly for research purposes but could be adapted for compliance monitoring should the need ever arise in the future.

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