26 Mine Aerosol Measurement

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INTRODUCTION

Exposure to mineral aerosol is an occupational health hazard in mining and mineral processing industries because of the risk of developing pneumoconiosis. Agricola (1556) described this hazard for metal mining in Carpathia. He described shortness of breath and consumption, conditions that are now associated with asthma and emphysema. By the end of the nineteenth century, several respiratory diseases were known to affect miners, including silicosis and coal workers' pneumoconiosis (Fletcher, 1948; Seaton et al., 1981). For example, silicosis, not tuberculosis, was clearly recognized as the hazard in the Vermont granite quarries and stone-cutting sheds (McFarland, 1927). The Gauly Bridge Tunnel disaster in the mid-1930s caused the deaths of an estimated 700 workers by acute silicosis and focused the nation's attention on this disease (Cherniack, 1986). By the mid-twentieth century, it was clear that risk of simple pneumoconiosis is associated with a miner's cumulative exposure to mine aerosol in the respirable size range and that prevention lies in reducing that exposure through regulation (Seaton, 1986).

In the United States, regulation of mine worker exposure to airborne mine dust is the responsibility of the Mine Safety and Health Administration (MSHA) in the U.S. Department of Labor. The key legislation relating to improved mine worker health was the Federal Coal Mine Health and Safety Act, enacted in 1969 (U.S. Congress, 1969) and subsequently amended as the Federal Mine Safety and Health Act of 1977 (U.S. Congress, 1977). MSHA receives technical assistance from the National Institute for Occupational Safety and Health (NIOSH). NIOSH also provides recommended exposure limits (RELs) for contaminants to MSHA. MSHA's regulation of mines includes the establishment of a dust standard administratively based on the these RELs. Some mine operators must submit a dust control plan designed to meet the dust standard. Periodic mine inspections determine if mines are complying with both the dust standard and the dust control plans (MSHA, 1991).

The most common dust measurements are those for respirable dust (according to the definition given in Fig. 26–7), that is, the fraction of aerosol particles able to reach the gas exchange region of the lungs. The other health-related size fractions (inhalable and thoracic—see Fig. 25–1, and "total" dust) are also occasionally measured. A "total" dust measurement is defined by the common practice of the last 30 years or so, using 25 mm or 37 mm plastic cassettes (e.g., from ***PAL***, ***MIL***, ***SKC****). The types of mines have been categorized

* See Appendix I for full manufacturer addresses referenced to the italicized three-letter codes.

Aerosol Measurement: Principles, Techniques, and Applications, Second Edition, Edited by Paul A. Baron and Klaus Willeke.
ISBN 0-471-35636-0

for regulatory purposes as either coal mines or other types of mines (indicated as metal and nonmetal mines).

This chapter summarizes aerosol measurement technology currently used in the U.S. mining industry as it relates to regulation, research, and personal exposure monitoring.

MINE AEROSOL SOURCES

The choice of measurement techniques and the performance of various aerosol monitors may be affected by the type of aerosol to be sampled. Mine aerosols typically originate from comminution, re-entrainment, and combustion sources.

Comminution

Mechanical crushing of the mined material by drill bits, crushers, and mining machine picks generate significant concentrations of respirable aerosol mass in the mine. In metal and nonmetal mines, a typical mining process begins with the cutting or drilling and blasting of the ore from the parent rock. The ore is then scooped or gathered and loaded into trucks or onto conveyers for transport to the surface. In some cases the ore is crushed underground to facilitate transportation. The aerosol composition generated from these activities is generally similar to the host ore; however, some selective fractionation of the composition may occur based on the cleavage and strength patterns of the host ore. After the ore is removed, underground construction activities then begin to support the roof, direct ventilation air, and extend the mine's infrastructure.

Continuous mining methods are the most prevalent underground coal extraction processes, accounting for most of the underground coal mined (Organiscak, 1989). In continuous mining, a mining machine, pictured in Figure 26–1, cuts coal from the face and loads it directly into shuttle cars. The shuttle cars transport the coal from the face area to the material transfer system, usually a crusher that loads onto a conveyor belt.

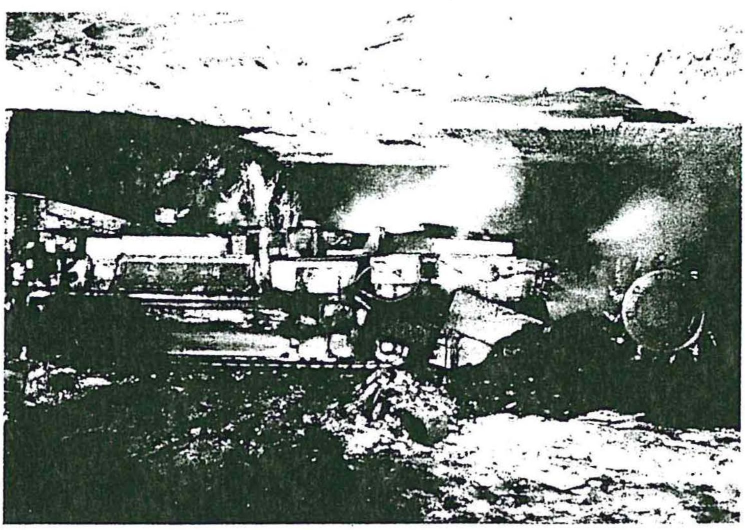

Fig. 26–1. Continuous miner. (From U.S. Bureau of Mines.)

Re-entrainment

Aerosols that result from comminution may settle on roadways or in return air entries and be subject to re-entrainment through the activities of mobile equipment such as shuttle cars, ventilation, or in-mine construction activities (Jankowski and Hake, 1989). In coal mining, an inert limestone dust is spread on the entryway roof, floor, and ribs to prevent coal dust explosions. This limestone dust is coarse and contributes only a small fraction to the overall mine aerosol concentrations.

Combustion

Combustion by-products are the other major source of aerosols in mines. Combustion aerosol particles are smaller in size and currently can contribute significantly to the overall mass of respirable aerosols. They have higher number concentrations than the coarser comminution aerosol and a greater interaction potential with the lungs. Typical mining sources include blasting agent fumes, welding fumes, and diesel engine particles and condensates.

Concentrations of blasting agent fumes and welding aerosols in the mine environment are primarily controlled by dilution with the mine ventilation air. Monitoring the aerosol concentration of these agents must focus on the transient nature of the aerosol and short-term exposure monitoring. Due to the intermittent nature of the sources and the substantial ventilation volumes needed for mining, the overall concentrations of these aerosols are generally low with some exceptions in areas with poor ventilation.

With the exception of coal mines, diesel engines provide the primary power source for mining equipment. In addition to being exposed to dust, a miner working in an underground mine with diesel-powered equipment is exposed to a wide array of pollutants from diesel exhaust. These include CO, CO_2, NO, NO_2, SO_2, diesel exhaust aerosol, and a variety of aerosol-associated and gas-phase hydrocarbon compounds (Cantrell and Watts, 1997). To date, ventilation rates in diesel-equipped mines have been dictated by gas concentrations. In the future, new standards may dictate that diesel exhaust aerosol concentration is the factor that will control required ventilation volumes (U.S. Department of Labor, 1998; MSHA, 2001a,b).

Of the combustion aerosols in the mining environment, diesel exhaust aerosol is of particular concern because it is almost entirely respirable in size, with more than 90% of the particles, by mass, having an aerodynamic diameter less than 1.0 µm (Cantrell, 1987). This means that the aerosol can penetrate to the deepest regions of the lungs and, if retained, cause or contribute to the development of obstructive or restrictive lung disease (Watts, 1987).

PHYSICAL CHARACTERISTICS OF MINE AEROSOL

Aerosols in mines sources have particle size distributions that are determined by both the mining method and the source of the aerosol (Cantrell and Rubow, 1992a,b). A size distribution summarizing the physical characteristics of mine aerosols is shown in Figure 26–2. The shape of the aerosol size distribution is influenced by the different sources contributing to the aerosol. Figure 26–2 displays some of these sources and the physical mechanisms, such as condensation and coagulation, which transfer aerosol mass from one size to another. It should be noted that these mechanisms and the general shape of the distribution are not unique to mine aerosols.

There are three distinct aerosol size ranges identifiable by features in measured mine aerosol 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

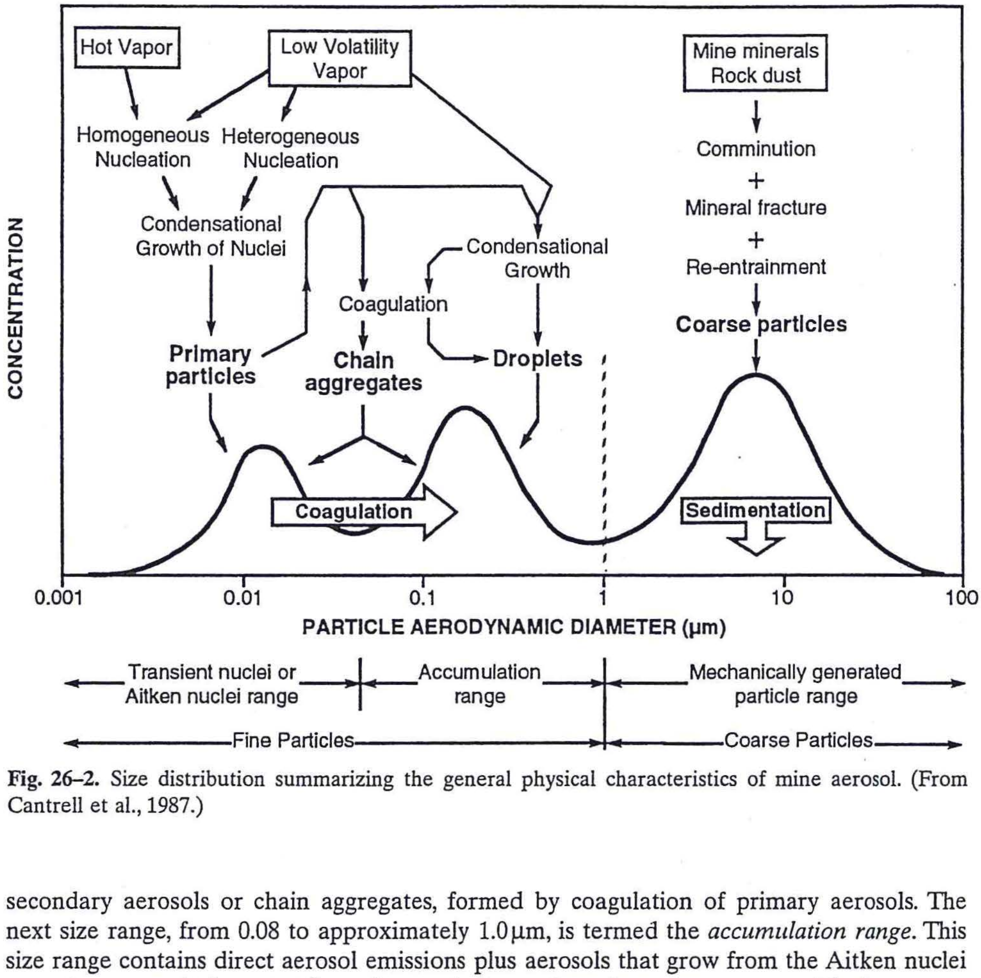

Fig. 26–2. Size distribution summarizing the general physical characteristics of mine aerosol. (From Cantrell et al., 1987.)

secondary aerosols or chain aggregates, formed by coagulation of primary aerosols. The next size range, from 0.08 to approximately 1.0 µm, is termed the *accumulation range*. This size range contains direct aerosol emissions plus aerosols that grow from the Aitken nuclei range by accumulating mass through coagulation and condensation processes. The last range, 1.0 µm to approximately 40 µm, is termed the *coarse particle range*. Aerosols within this size fraction generally result from mechanical processes such as rock fracture and bulk material handling. Mineral dust aerosol re-entrained 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 ranges are combined in a single "fine" particle range. A division is usually made between this range and the "coarse" particle range at 1.0 µm. This distinction is possible because sources of aerosol in the two ranges are usually different, and the coarse particle range contains very little mass transferred from the accumulation range by coagulation.

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 range is termed the *accumulation mode*. Figure 26–3 presents a typical size distribution of aerosol mass concentration measured in a haulage entry of a diesel-equipped coal mine (Cantrell and Rubow, 1990). 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 26–4 shows a mass size distribution measured in the

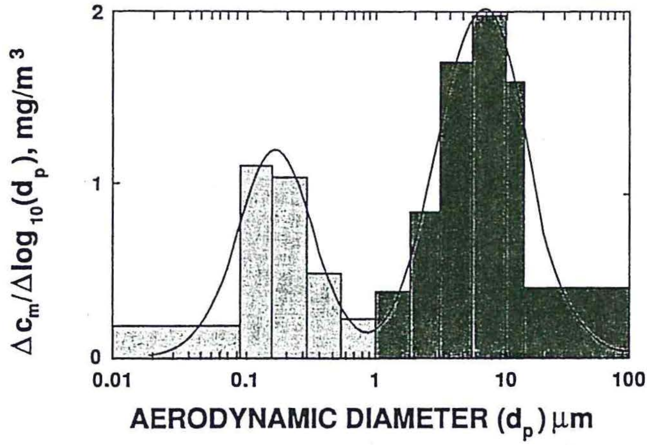

Fig. 26–3. Mass size distribution of mine aerosol in diesel-equipped mine. (From Cantrell and Rubow, 1990.)

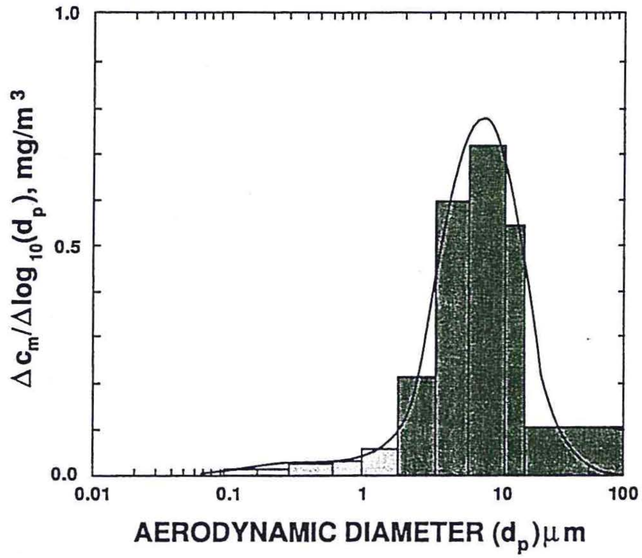

Fig. 26–4. Mass size distribution of mine aerosol in an all-electric–equipped mine. (From Cantrell and Rubow, 1990.)

haulage way of an all-electric-motor–equipped coal mine. Here the accumulation mode is much smaller than the coarse particle mode. Taken together, the figures indicate that diesel aerosols can make a strong contribution to accumulation mode aerosols in a diesel engine–equipped mine.

MEASUREMENT TECHNOLOGY

Aerosol measurement technology used by and for the mining industry can be conveniently separated into compliance measurements in support of regulation and research measurements that aid in the development of new compliance measurement techniques, determine control effectiveness, and assist in determining the fundamental properties of mine aerosols.

Compliance measurements are primarily intended for use in enforcement of regulations established by MSHA. Regulatory requirements determine the sampling strategy and instrumentation used for such measurements. Research aerosol measurements are used to evaluate engineering dust control techniques, to develop new aerosol instrumentation, to define new occupational health hazards, and to expand knowledge regarding mine aerosols. They draw on all of the technology available to the aerosol community. Consequently, compliance and research aerosol measurements are treated separately here. Also, the following discussion focuses on aerosol measurements in U.S. mines. For a discussion of measurement practices in the European Community, see Vincent (1991).

Compliance Measurements and the Regulatory Environment

Regulatory Requirements

Metal and Nonmetal. MSHA regulates practices affecting health and safety in metal and nonmetal mines and mills under the authority of the Federal Mine Safety and Health Act of 1977 (U.S. Congress, 1977). The specific regulations are found in the Code of Federal Regulations, Title 30 (MSHA, 1991). MSHA continues to use the 1973 recommended threshold limit values of the American Conference of Governmental Industrial Hygienists (ACGIH, 1973). Compliance with these regulations is determined by the collection of environmental samples by MSHA inspectors. Aerosol-related contaminants that are regulated include total dust, respirable dust, quartz, asbestos, silicates, radionuclides in air, diesel exhaust aerosol, and welding fumes (MSHA, 1990; 2001a,b).

The following example illustrates the type of sampling and analysis procedure for a respirable dust containing more than 1% quartz. A sample is collected using the personal respirable dust sampler shown in Figure 26–5. Sample air is first passed through a Dorr-Oliver nylon cyclone pre-classifier (***MSA***) at a flow rate of 1.7 L/min to remove the nonrespirable fraction of sampled dust. Respirable dust is then collected on a filter that is analyzed gravimetrically to determine mass concentration. The filter deposit is also analyzed for quartz content using X-ray diffraction (MESA, 1975). The measured mass concentration is compared with the PEL determined from the quartz content of the respirable dust by

$$\mathrm{PEL}_{\mathrm{quartz}} = \frac{10\,\mathrm{mg/m^3}}{\text{percent respirable quartz} + 2} \tag{26–1}$$

For a given exposure level, the magnitude of the toxicity is proportional to the quartz content (ACGIH, 1980). The factor 2 in the denominator of the PEL formula ensures that dust exposures will not be excessively high when the quartz content is less than 5%. When quartz levels are less than 1%, nuisance particles listed by the 1973 ACGIH standard are regulated to 10 mg/m^3 of total dust. MSHA has proposed a revision of many of the existing health regulations (MSHA, 1989a). Included in these revisions is a proposed change in the PEL for respirable quartz. The current PEL is 100 μg/m^3 of respirable quartz (MSHA, 1971).

Coal. Respirable coal mine dust measurements are made to determine compliance with MSHA-established dust standards (MSHA, 1989b). In 1970, a mandatory total respirable dust

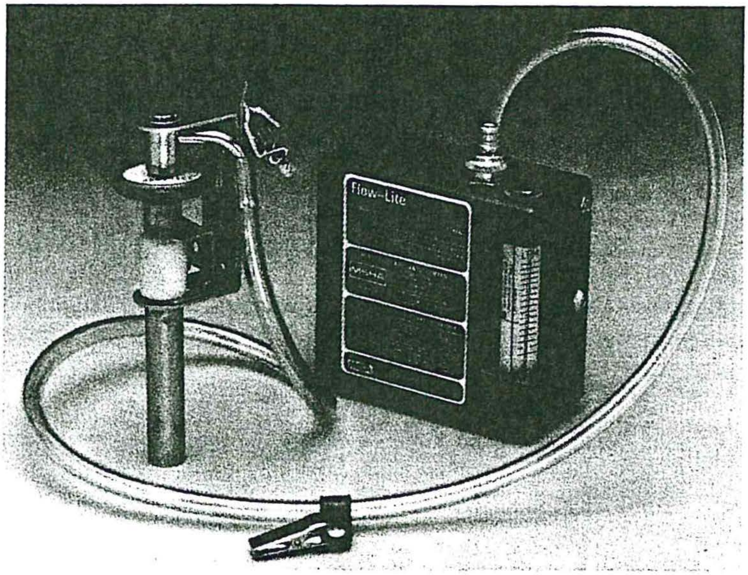

Fig. 26–5. Personal Respirable Dust Monitor. (Courtesy of MSA Co.)

standard of 3.0 mg/m^3 was established for underground coal mines in the Federal Coal Mine Health and Safety Act of 1969 (U.S. Congress, 1969). The respirable dust standard was subsequently lowered in 1972 to 2.0 mg/m^3. 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 (U.S. Congress, 1977), 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 that measured using a Mining Research Establishment (MRE) parallel plate elutriator (Casella, model 113A, United Kingdom) sampling instrument (Fig. 26–6) 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) (Lippman, 1989). The 1977 Act changed the definition of "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 personal respirable dust sampler illustrated in Figure 26–5 is also approved for measuring respirable coal mine dust (MSHA, 1989b). The sampling rate used for coal, however, is 2 L/min (Tomb and Raymond, 1970). Sample analysis for total respirable dust is gravimetric (Raymond et al., 1987). Analysis for quartz is by Fourier transform infrared spectrometry (Ainsworth et al., 1989). Measurements are converted to equivalent MRE concentrations by multiplying the measured concentrations by an accommodation factor of 1.38 (Treaftis et al., 1984). The difference between the Dorr-Oliver and BMRC sampling efficiency curves is evident from Figure 26–7 (Caplan et al., 1977a,b; Lippman, 1989). Specific regulations detailing the methods for collecting respirable dust samples are found in the Code of Federal Regulations, Title 30 (MSHA, 1991).

A mine is in noncompliance with its dust standard if the arithmetic average concentration of five consecutive respirable dust samples is in excess of the applicable standard (MSHA, 1989b). If the percent quartz is less than 5%, the standard is 2.0 mg/m^3, calculated using Eq. 27–1. In underground coal mines, samples are collected on workers with a designated occupation, usually a mining machine operator. A mine may also not be in compliance

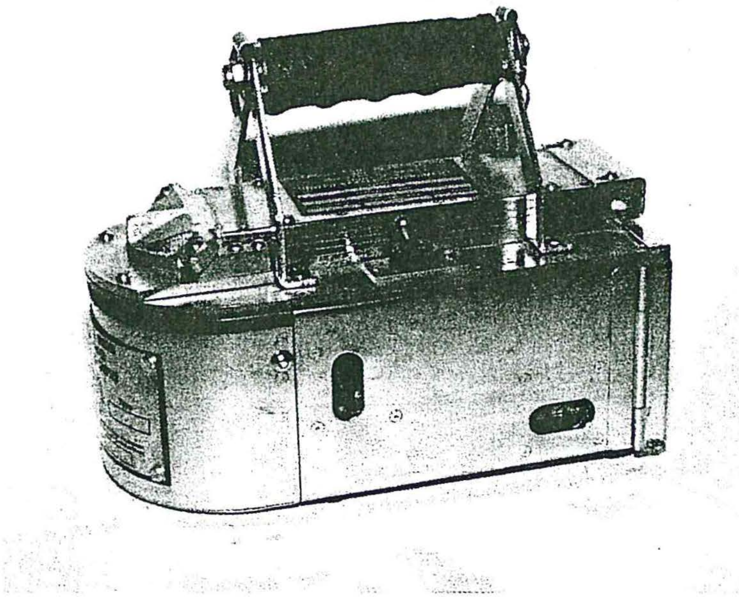

Fig. 26–6. Casella, Model 113a, MRE Respirable Dust Monitor. (From Cantrell et al., 1987.)

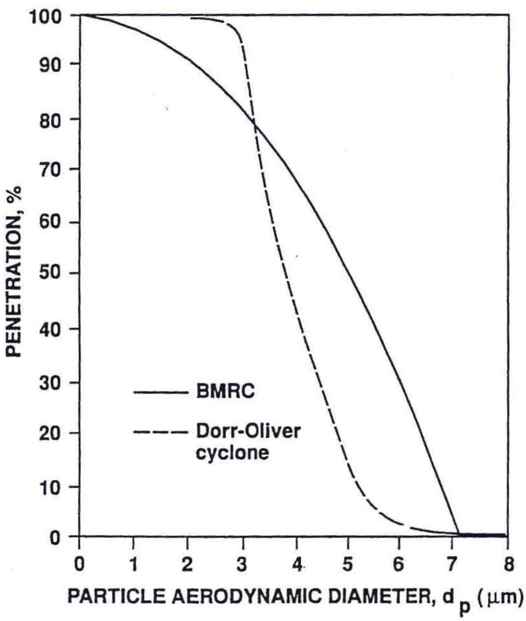

Fig. 26–7. Respirable aerosol sampling criteria; BMRC, Dorr-Oliver Cyclone. (From Caplan et al., 1977a,b; Lippman, 1989.)

with the law if the dust control plan is not being used. MSHA is required to inspect all underground coal mines four times a year, and the mine operators are required to sample bimonthly.

Diesel Exhaust Aerosol. NIOSH (1988) has recommended that "whole diesel exhaust be regarded as a 'potential occupational carcinogen,' as defined in the Cancer Policy of the Occupational Safety and Health Administration." NIOSH further stated that "though the excess risk of cancer in diesel-exhaust–exposed workers has not been quantitatively estimated, it is logical to assume that reduction in exposure to diesel exhaust in the workplace would reduce the excess risk." The International Agency for Research on Cancer (1989) has also classified diesel exhaust as "probably carcinogenic to humans." Additionally, the Mine Safety and Health Administration (MSHA, 1988) received a recommendation from an advisory committee to establish a diesel exhaust aerosol standard and to establish regulations to minimize exposure to all diesel pollutants in underground coal mines. The ACGIH has proposed a threshold limit value (TLV) for diesel exhaust particles of 50 $\mu g/m^3$ (ACGIH, 2000).

MSHA has proceeded to establish a diesel exhaust aerosol emission standard for diesel powered equipment in underground coal mines (MSHA, 2001a) and a PEL for diesel exhaust aerosol in metal and non-metal mines (MSHA, 2001b). The regulation for coal mines specifies a limit of 2.5 grams per hour for permissible heavy duty equipment. The regulation also specifies an interim aerosol emissions limit of 5.0 grams per hour and, after the year 2005, a limit of 2.5 grams per hour for non permissible heavy duty equipment. Light duty diesel powered equipment exhaust aerosol emissions are limited to 5.0 grams per hour. For metal/non-metal mines MSHA has proposed an interim total diesel aerosol carbon (TC) PEL of 400 $\mu g/m^3$ based on an 8 hour sample and, after the year 2005, a final PEL of 160 $\mu g/m^3$.

Research Aerosol Measurements

Research measurements are used to characterize the mine aerosol's mass and specific components such as quartz, trace elements, and carbon as a function of aerosol size. Recent emphasis on the potential health hazard associated with exposure to diesel exhaust aerosols has focused attention on specific techniques to measure these aerosols. The primary technique used to collect samples in coal and noncoal mines for all of these measurements is size-selective sampling using inertial impaction. In addition, several aerosol sensor techniques are being developed for continuous monitoring of respirable mine aerosols. These include both light-scattering and direct mass measurement.

Size-Selective Sampling. A size-selective sampling technique that has been useful for in-mine measurement of both diesel and mineral dust aerosol employs the Marple personal impactor (series 290, ***AND***) discussed in Chapter 10. The series 290 sampler was originally designed for NIOSH as a wood dust sampler by Rubow et al. (1987). More recently, it has been used in surveys of diesel-equipped mines by the U.S. Bureau of Mines (BOM) and NIOSH to measure the size distribution of mine aerosol (NIOSH, 1987). Estimates were made of average concentration levels of respirable diesel aerosol for the working shift using the sub-1.0 μm portion of each sample under the assumption that this accounted for most of the diesel exhaust in the mine atmosphere. The average concentration for submicrometer aerosol generated in the mining sections was $0.7 \pm 0.3\,mg/m^3$.

The micro-orifice, uniform deposit impactor (MOUDI) (model 100, ***MSP***), also discussed in Chapter 10, has also been used to measure the size distribution of mine aerosol over the size ranges in which respirable coal dust and diesel aerosols are expected to predominate (Marple et al., 1991). In addition to laboratory studies of these aerosols (Marple et al., 1986), the MOUDI has been used during field experiments in underground coal mines to evaluate its ability to separate diesel aerosol from coal dust aerosol on the basis of their size distributions (Rubow et al., 1990a). The field evaluations were conducted in underground mines that used only electric-powered haulage equipment and in other mines that used diesel-powered haulage equipment.

Typical mass size distributions of aerosols measured in the haulage entry of the diesel-equipped mines, shown in Figure 26–3, exhibit two distinct maxima: one submicrometer and the other greater than 1 µm. These measurements indicate that more than 90% of diesel exhaust aerosols in the diesel-equipped coal mines studied were submicrometer in size (Cantrell, 1987). The diesel-associated submicrometer aerosol accounted for approximately 40% to 60% of the respirable aerosol mass concentration. In contrast, aerosol size measurements in the all-electric coal mines, typified by Figure 26–4, exhibited a very small submicrometer maximum. Less than 10% of the measured respirable aerosol mass was in the submicrometer size range.

Diesel Aerosol Sampling and Analysis. Three analytical methods have been used for measurement of diesel exhaust aerosol in underground mines. These methods are (1) its mass concentration, (2) its carbon content, and (3) the combustible fraction of the sample. The first is measured using typical filter gravimetric techniques and the second by direct analysis of the organic carbon (OC) and elemental carbon (EC) content of the aerosol through thermal–optical analysis (see Chapter 11). The third is the respirable combustible dust (RCD) method that uses gravimetric techniques combined with ashing to separate mineral from combustible matter. In all cases, size-selective sampling can be used to provide a sample that contains most of the diesel-associated portions of the sampled respirable aerosol.

A personal diesel exhaust aerosol sampler based on size-selective sampling, developed for use in underground coal mines (Rubow et al., 1990b; McCartney and Cantrell, 1992), is pictured in Figure 26–8. It has three stages and employs inertial impaction for separating and collecting the diesel and mineral dust fractions of the sampled respirable aerosol. The first stage is an inertial preclassifier that separates and collects the larger, nonrespirable aerosol. The pre-classifier used in this design is a 10 mm Dorr-Oliver cyclone. Its second stage is a four-nozzle impactor with a 50% cut point of 0.8 µm aerodynamic diameter. The third stage, which is a filter, collects the remaining aerosol particles with less than 0.8 µm aerodynamic diameter. The sampler components are used with an ***MSA*** dust monitor sampling frame and operate at a sampling flow rate of $3.33 \times 10^{-5}\,m^3/s$ [2 L/min]. It is designed to be compatible with commercial personal sampling pumps.

Gravimetric Analysis. Coupled with gravimetric analysis, the personal diesel exhaust aerosol sampler can provide measurements of diesel exhaust aerosol concentrations in coal mines under worst-case sampling conditions, which are accurate to within 25%, with a confidence of 95%, for concentration levels greater than $0.3\,mg/m^3$ (Cantrell and Rubow, 1991). During field evaluation tests, the sampler was used to make numerous aerosol concentration measurements in underground coal mines that use diesel haulage equipment. Figure 26–9 summarizes respirable aerosol concentrations in these mines, determined from area samples collected in the haulage entries, on coal shuttle cars, and in the ventilation return entries (Cantrell et al., 1992). Figure 26–10 summarizes the diesel exhaust aerosol concentrations measured using the same samples.

The haulage, shuttle car, and return locations have similar distributions for the diesel exhaust aerosol portion of the respirable total. This implies that diesel exhaust aerosol concentrations are uniform regardless of where they are measured in the section. Total respirable aerosol concentration levels are different depending on where the samples are taken. The highest is in the ventilation return, and the lowest is in the haulage way. These results imply that exposure to respirable mineral dust is location and hence, is occupation dependent.

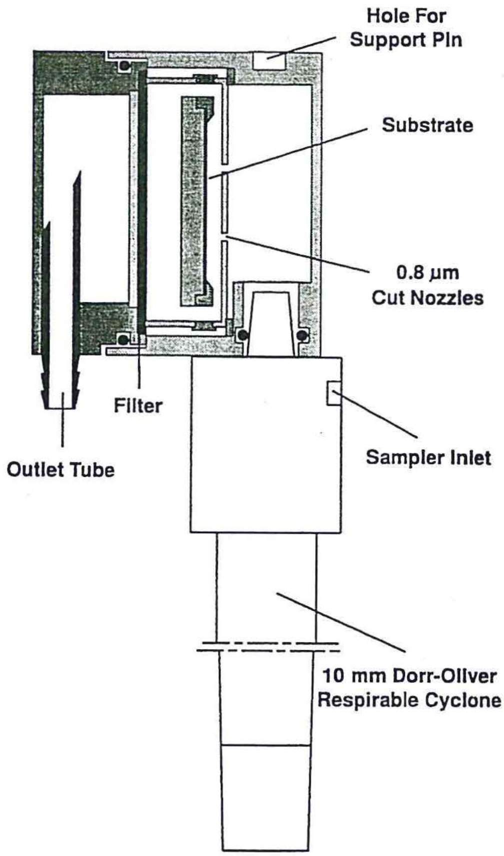

Fig. 26–8. Personal diesel exhaust aerosol sampler. (From McCartney and Cantrell, 1993.)

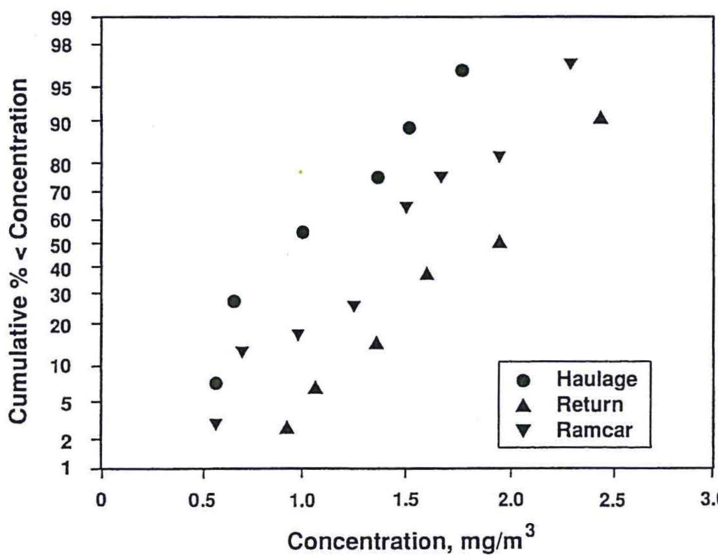

Fig. 26–9. Cumulative frequency plot of respirable aerosol concentrations in continuous mining operations using diesel-equipped haulage vehicles. (From Cantrell et al., 1991.)

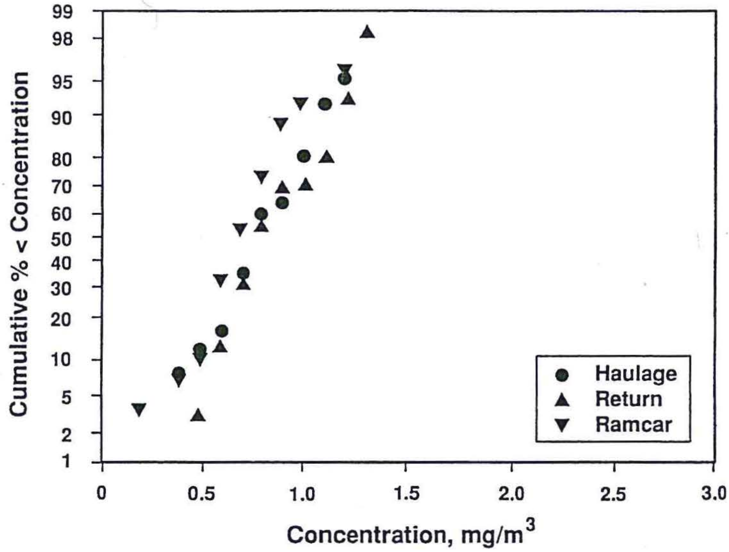

Fig. 26–10. Cumulative frequency plot of respirable diesel aerosol concentrations in continuous mining operations using diesel-equipped haulage vehicles. (From Cantrell et al., 1991.)

The median diesel exhaust aerosol concentration determined with the personal sampler at the haulage location for the three mines surveyed was 0.8 ± 0.2 mg/m^3. Diesel aerosol contributed 65% of the respirable aerosol at this location.

Direct Carbon Analysis. The use of size-selective sampling with gravimetric analysis is only intended for measuring diesel exhaust aerosol concentrations at the levels displayed in Figure 26–10 and cannot be used to support a standard below approximately 300 μg/m^3. Because control technology is currently capable of reducing diesel exhaust aerosol concentrations to levels well below 300 μg/m^3, there is a need for an analytical technique that can be used to measure diesel exhaust aerosol at this level (Ambs et al., 1991).

One approach is the thermal–optical method (Birch and Cary, 1996) published as Method 5040 by NIOSH. The method was initially described in 1996 and was recently updated (NIOSH, 1999). In the analysis, the OC and EC in a quartz fiber filter sample are determined through temperature and atmosphere control. The instrument has an optical feature that corrects for sample charring. The analytical technique on which the method is based was originally developed for atmospheric aerosols (Johnson et al., 1981; Cadel and Groblicki, 1980; Hering et al., 1990). NIOSH proposed its use for occupational monitoring of DPM. Although OC and EC are determined by the method, NIOSH researchers proposed use of EC as an exposure index because it is a selective marker of DPM in many occupational settings. In contrast, OC can originate from many nondiesel sources (e.g., drill oil mist, hydraulic oil mist, hydraulic fluids, and carbonates). The method evaluation included field studies and interlaboratory comparisons (Birch, 1998; Birch et al., 1999). Improvements in the original method and instrument design were made in collaboration with the laboratory that first offered the analysis and instrument on a commercial basis. The method can detect as little as 1 μg/m^3 of EC. Currently, there are five commercial laboratories (four in the United States and one in Canada) that perform the analysis. In underground mines, EC and total carbon (TC = EC + OC) account for about 50% and 80% respectively, of the submicrometer particulate mass, but these percentages vary depending on the engine duty cycle, fuel quality, after-treatment devices, and other factors. Thermal analysis techniques for OC and EC are also being used in several European countries.

The simplest sampling train for EC analysis, and the one used by MSHA to obtain field samples, consists of a 10 mm Dorr-Oliver cyclone followed by a 37 mm precombusted ultra-pure tissue–quartz fiber filter (PALL 2500QAT, ***GEL***) mounted in a 37 mm plastic cassette. Alternatively, the Dorr-Oliver cyclone can be followed by the 0.8 µm size-selective impactor described above. In this situation, diesel exhaust aerosol particulates, which are primarily smaller than 0.8 µm, are collected on the filter. This is advantageous because large, mechanically generated aerosols are not collected on the filter and cannot interfere with the carbon analysis.

Respirable Combustible Dust Analysis. In the RCD method, total respirable dust (TRD) is collected from sample air on a 25 or 37 mm, 0.8 µm pore size silver membrane (SM) filter after passing through a 10 mm Dorr-Oliver cyclone pre-classifier at a flow rate of 2.83×10^{-5} m^3/s [1.7 L/min]. Flow is controlled using a personal sampling pump. At this flow rate, the cyclone is a respirable dust pre-classifier with a 50% cut point of 4 µm. TRD is determined gravimetrically by weighing the SM filter before and after the sample is collected. The RCD fraction of TRD is determined gravimetrically from the amount of material removed from the SM by controlled combustion at 673 K [400°C] for 1 to 2 h. A correction is made for loss of mass from the SM due to combustion (Gangal et al., 1990; Gangal and Dainty, 1993).

Elemental and Mineral Analysis. Another method for analyzing diesel aerosol is source apportionment. This technique has been used to evaluate measurements made in underground mines using size-selective sampling (Cantrell, 1987; Rubow et al., 1990a; Cantrell and Rubow, 1990). It relates elemental, mineral, or chemical components in an aerosol sample to those same components in the sources of the aerosol. Using this relationship, the contribution of each source to the sampled aerosol can be determined. For diesel-equipped coal mines the primary sources of aerosol are coal, rock dust used as a fire retardant on the mine walls, and diesel exhaust aerosol emissions. One specific analytical technique used to apportion collected aerosol among these sources is chemical mass balance model analysis (Watson, 1984; Henry et al., 1984; Davis, 1984).

The model is expressed as

$$c_{ei} = \sum_{j=1}^{p} a_{ij} S_j \tag{26–2}$$

Here, c_{ei} is the mass concentration of the ith elemental, mineral, or chemical component of the sample in $\mu g/m^3$; a_{ij} is the fractional amount of component i in emissions from source j; S_j is the total contribution of source j to the sample; and p is the number of sources. 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 Eq. 26–2.

Real-Time Measurement

Real-time measurement of mine dust remains an objective for aerosol research. A report of the Secretary of Labor's Advisory Committee on the Elimination of Pneumoconiosis Among Coal Mine Workers listed several recommendations dealing with the need for continuous respirable dust monitors to help protect workers' health (U.S. Department of Labor, 1996). In addition, a NIOSH Criteria Document lists improved sampling devices as a research need pertinent to coal miner respiratory health and prevention of disease (NIOSH, 1995). In mining, personal exposure monitoring is preferable to area monitoring (Leidel et al., 1977). Dust concentrations have been shown to change dramatically over times of a few seconds and distances of just 0.6 m in underground coal mines (Kost and Saltsman, 1977). Therefore, to meaningfully approximate a worker's dust exposure, personal real-time monitoring is the preferred strategy.

Several approaches are being taken to address these needs. The more promising technologies include light-scattering dust monitors, a person-wearable tapered-element oscillating microbalance, and the Dust Dosimeter (Tsao et al., 1996; Lehocky and Williams, 1996; Volkwein et al., 2000). The principal goals of each of these efforts has been to develop an instrument that will give short-term or real-time measurements of worker dust exposure.

Light Scattering. Often called *photometers* or *nephelometers*, light-scattering instruments use a light source to illuminate sample aerosol and a light sensor to measure the scattered light that can be related to the mass concentration of the dust. The theory of these monitors is summarized in Chapter 15. Several of the monitors have been characterized in the laboratory for different dusts (Kuusisto, 1983; Marple and Rubow, 1981, 1984; Keeton, 1979; Rubow and Marple, 1983). The relationship of the instruments' responses to dust concentration is not simple but depends on particle size, particle composition, and instrument design and manufacturing differences. Significant changes in dust particle characteristics such as shape, size, surface properties, and density, can affect the instrument's correlation with mass concentration and require calibration of the instrument for each type of dust measured (Williams and Timko, 1984). These factors have limited the use of photometers to dust source identification and control technology evaluation. They are not useful for monitoring compliance with dust standards.

Most of the mining community's experience with real-time, photometric instruments is with the RAM-1 and MINIRAM devices (***MIE***), which were initially designed for use in the mine environment. Intrinsically safe versions of these instruments were certified by MSHA for use in the potentially explosive atmospheres of underground coal and gassy noncoal mines. They are normally operated with the Dorr-Oliver 10 mm cyclone to remove water droplets and ensure a respirable dust sample (Treaftis et al., 1984; Tomb et al., 1981). The RAM, pictured in Figure 26–11, is a real-time light-scattering aerosol monitor with a sampling pump that pulls aerosol through the sensing zone. The MINIRAM employs similar technology but typically operates in the passive sampling mode wherein size classification is based solely on light-scattering properties. An optional chamber and pump may be used to allow a cyclone classifier to physically determine the respirable fraction. McCawley and Cocalis (1986) obtained good correlations ($r^2 = 0.92$) between in-mine MINIRAM measurements and those obtained using a gravimetric sampler fitted with an intake impactor to restrict penetration of particles larger than 1.5 μm. Analysis of the collected sample was accomplished using RCD measurements. This successful comparison between diesel aerosol and the response of a photometric instrument holds promise that it might be used to monitor diesel aerosol.

Tapered Element Oscillating Microbalance. The theory of the Tapered Element Oscillating Microbalance (TEOM, ***R&P***) is summarized in Chapter 14. Despite limited application in the mining industry, this technology offers one notable advantage: direct measurement of dust mass. Because dust exposure standards are based on dust mass, this attribute of the TEOM is significant. In 1983, the BOM and NIOSH funded the development of a prototype TEOM personal dust monitor (Patashnick and Rupprecht, 1983). The prototype monitor developed is a system configured for end-of-shift measurements. It is not a real-time monitor,

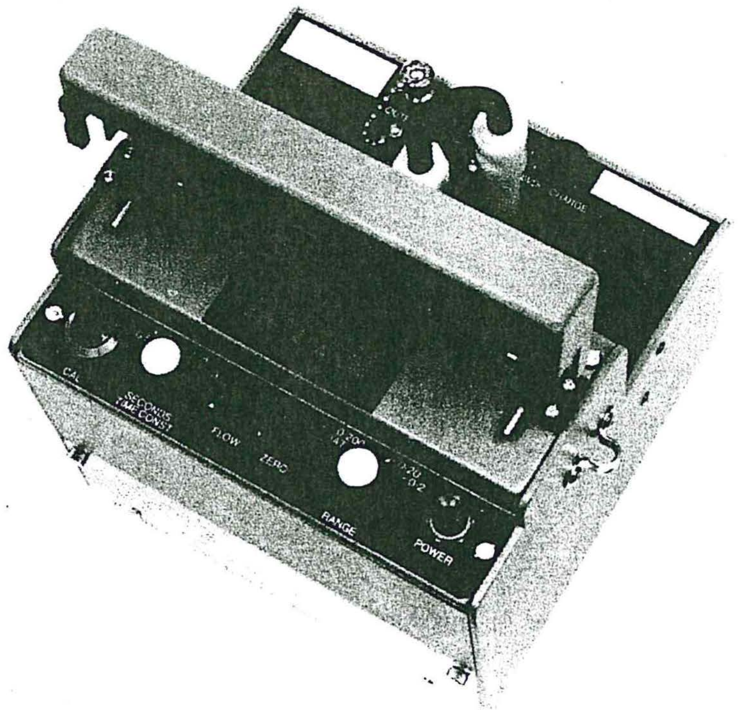

Fig. 26–11. MIE RAM-1 Real-Time Respirable Aerosol Monitor equipped with a Dorr-Oliver Cyclone Sample Inlet. (From Olson and Veith, 1987.)

but uses oscillating microbalance technology to "weigh" the collection filter before and after dust sampling.

The BOM has evaluated this prototype system in the laboratory for both end-of-shift and near-real-time applications (Williams and Vinson, 1986). The effective standard deviation of repeated measurements was 1.6 µg. Tests at controlled temperature and humidity showed less than 20 µg of drift during an 8 h shift. These early attempts to construct a person-wearable form of the TEOM required a substantial mass in the base of the element to dampen the vibrations, reducing the concept's "wearability." Recent proprietary developments by ***R&P*** have solved the need for a substantial base mass electronically, and development of a person-wearable TEOM-based personal dust sampler is nearing completion under a NIOSH contract.

Dust Dosimeter. An alternative to highly accurate mine dust measurement devices is a new instrument that is based on a dust detector tube (Volkwein et al., 2000). The Dust Dosimeter, shown in Figure 26–12, is an inexpensive device that consists of a small pump with integral pressure transducer and a disposable detector tube, much like a gas detector tube, that correlates pressure drop across the filter with mass accumulation. It has recently been tested and shown to provide qualitative mid-shift and end-of-shift determinations of cumulative dust exposure. Figure 26–13 shows the laboratory responses for a variety of coal types. The Dust Dosimeter is an example of a new type of tool to help improve workers' health by enabling frequent and timely knowledge of current dust levels. Field testing of the device has shown that it gives a higher response to diesel particulate than to coal dust.

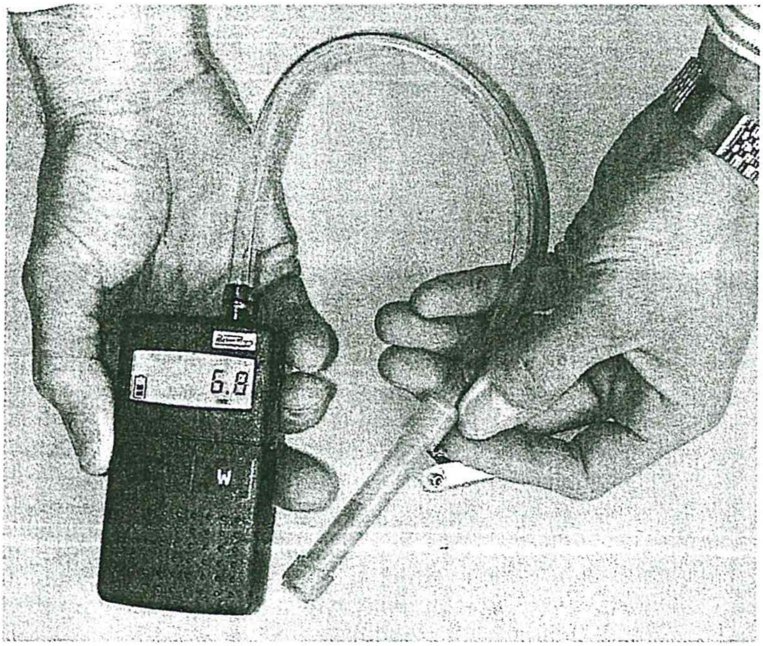

Fig. 26–12. Dust Dosimeter. (From NIOSH, 2000.)

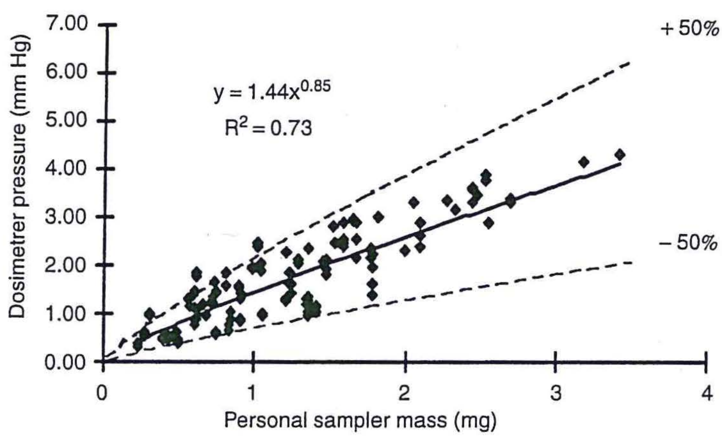

Fig. 26–13. Differential pressure response of Dust Dosimeter to six different laboratory coal dusts. (From Volkwein et al., 2000.)

REFERENCES

ACGIH. 1973. *TLVs—Threshold Limit Values for Chemical Substances in Workroom Air.* Cincinnati, OH: ACGIH.

ACGIH. 1980. *Documentation of the Threshold Limit Values*, 4th ed. Cincinnati, OH: ACGIH, pp. 364–365.

ACGIH. 2000. *TLVs—Threshold Limit Values for Chemical Substances and Physical Agents. Notice of Intended Changes for 2000.* Cincinnati, OH: ACGIH, p. 73.

Agricola, G. 1556. *De re Metallica*. Translated by M. C. Hoover and L. H. Hoover. New York: Dover Publications.

Ainsworth, S. M., P. S. Parobeck, and T. F. Tomb. 1989. *Determining the Quartz Content of Respirable Dust by FTIR*. MSHA IR 169, Arlington, VA.

Ambs, J. L., B. K. Cantrell, and A. D. Klein. 1991. Evaluation of a disposable diesel exhaust filter. *Am. Fil. Soc.* 4:287–291.

Birch, M. E. 1998. Analysis of carbonaceous aerosols: Inter-laboratory comparison. *Analyst* 123:851–857.

Birch, M. E. and R. A. Carey. 1996. Elemental carbon-based method for occupational monitoring of particulate diesel exhaust: Methodology and exposure issues. *Analyst* 121:1183–1190.

Birch, M. E., D. Dahmann, and H. Hennig-Fricke. 1999. Comparison for two carbon analysis methods for monitoring diesel particulate levels in mines. *J. Environ. Monitor.* 1:541–544.

Cadle, S. H. and J. Groblicki. 1980. *An Evaluation of Methods for Determination of Organic and Elemental Carbon in Particulate Samples*. General Motors Report GMR-3452, ENV #86. Detroit: General Motors.

Cantrell, B. K. 1987. *Source Apportionment Analysis Applied to Mine Dust Aerosols: Coal Dust and Diesel Emissions Aerosol Measurement*. Proceedings of the 3rd Mine Ventilation Symposium. Society for Mining, Metallurgy, and Exploration, Inc., Littleton, CO: Society for Mining Metallurgy and Exploration, pp. 495–501.

Cantrell, B. K. and K. L. Rubow. 1990. *Mineral Dust and Diesel Exhaust Aerosol Measurements in Underground Metal and Nonmetal Mines*. Proceedings of the VIIth International Pneumoconioses Conference. NIOSH Pub. No. 90-108, Cincinnati, NIOSH, pp. 651–655.

Cantrell, B. K. and K. L. Rubow. 1991. Development of personal diesel aerosol sampler design and performance criteria. *Mining Eng.* February:232–236.

Cantrell, B. K., K. L. Rubow, W. F. Watts, Jr., and D. E. Carlson. 1991. Pollutant levels in underground coal mines using diesel equipment. In *Proceedings of the SMME Annual Meeting and Exhibit*, Denver, CO, Feb. 25–28, 1991. Society for Mining Metallurgy and Exploration (SME), Littleton, CO, Preprint No. 91-35, p. 8.

Cantrell, B. K. and K. L. Rubow. 1992a. *Measurement of Diesel Exhaust Aerosol in Underground Coal Mines*. U.S. Bureau of Mines IC 9324, Washington, DC: Bureau of Mines, pp. 11–17.

Cantrell, B. K. and K. L. Rubow. 1992b. *Diesel Exhaust Aerosol Measurement in Underground Metal and Nonmetal Mines*. U.S. Bureau of Mines IC 9324, pp. 18–23.

Cantrell, B. K., K. L. Rubow, W. F. Watts, Jr., and D. E. Carlson. 1992. *Pollutant Levels in Underground Coal Mines Using Diesel Equipment*. Transactions of the Society for Mining, Metallurgy, and Exploration, Inc., v. 290, Littleton, CO: Society for Mining, Metallurgy and Exploration, pp. 1901–1907.

Cantrell, B. K. and W. F. Watts Jr. 1997. Diesel exhaust aerosol, review of occupational exposure. 2nd International Conference of the Health of Miners, November 11–13, 1995, Pittsburgh, PA. *Appl. Occup. Environ. Hyg.* 12:1019–1027.

Caplan, K. J., L. J. Doemeny, and S. D. Sorenson. 1977a. Performance characteristics of the 10-mm respirable mass sampler: Part I—Monodisperse studies. *Am. Ind. Hyg. Assoc. J.* 38:83–95.

Caplan, K. J., L. J. Doemeny, and S. D. Sorenson. 1977b. Performance characteristics of the 10-mm respirable mass sampler: Part II—Coal dust studies. *Am. Ind. Hyg. Assoc. J.* 38:162–173.

Cherniack, M. 1986. *The Hawk's Nest Incident, America's Worst Industrial Disaster*. New Haven: Yale University Press.

Davis, B. L. 1984. X-ray diffraction analysis and source apportionment of Denver aerosol. *Atmos. Environ.* 18:2197–2208.

Fletcher, C. M. 1948. Pneumoconiosis of coal-miners. *BMJ* 1:1015–1065.

Gangal, M. K. and E. D. Dainty. 1993. *Ambient Measurement of Diesel Particulate Matter and Respirable Combustible Dust in Canadian Mines*. Proceedings of the 6th U.S. Mine Ventilation Symposium, R. Bhaskar, ed. Littleton, CO: Society for Mining, Metallurgy, and Exploration, Inc., pp. 83–89.

Gangal, M., J. Ebersole, J. Vallieres, and D. Dainty. 1990. *Laboratory Study of Current (1990/91) SOOT/RCD Sampling Methodology for the Mine Environment*. Mining Research Laboratory, Canada Centre for Mineral and Energy Technology (CANMET). Ottawa, Canada.

Henry, R. C., C. W. Lewis, P. K. Hopke, and H. J. Williamson. 1984. Review of receptor model fundamentals. *Atmos. Environ.* 18:1507–1515.

Hering, S. V., et al. 1990. Comparison of sampling methods for carbonaceous aerosols in ambient air. *Aerosol Sci. Technol.* 12:200–213.

International Agency for Research on Cancer. 1989. *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans—Diesel and Gasoline Engine Exhausts and Some Nitroarenes.* IARC, Lyon, France, 46:458.

Jankowski, R. A. and J. Hake. 1989. *Dust Sources and Controls for High Production Longwall Faces.* Proceedings of Longwall USA, Pittsburgh, PA.

Johnson, R. L., J. J. Shaw, R. A. Cary, and J. J. Huntzicker. 1981. An automated thermal-optical method for the analysis of carbonaceous aerosol. In *Atmospheric Aerosol: Source/Air Quality Relationships*, eds. W. S. Macias and P. K. Hopke. Washington, DC: ACS Symposium Series, No. 167, pp. 223–233.

Keeton, S. C. 1979. *Carbon Particulate Measurements in a Diesel Engine.* Albuquerque: Sandia Laboratories, Publication SAND 79-8210.

Kost, J. A. and R. D. Saltsman. 1977. *Evaluation of the Respirable Dust Area Sampling Concept as Related to the Continuous Miner Operator.* Bituminous Coal Research, Inc., Report L-792, January. Monroeville, PA: Bituminous Coal Research, Inc.

Kuusisto, P. 1983. Evaluation of the direct reading instruments for the measurement of aerosols. *Am. Ind. Hyg. Assoc. J.* 44:863–874.

Lehocky, A. H. and P. L. Williams. 1996. Comparison of respirable samplers to direct-reading real-time aerosol monitors for measuring coal dust. *AIHAJ* 57:1013–1018.

Leidel, N. A., K. A. Busch, and J. R. Lynch. 1977. The inadequacy of general (area) monitoring for measuring employee exposures. Technical Appendix C, *Occupational Exposure Sampling Strategy Manual*, NIOSH, NTIS #PB 77-274752. Washington, DC: Government Printing Office.

Lippman, M. 1989. Size-selective health hazard sampling. In *Air Sampling Instruments*, 7th Ed., S. V. Hering. Cincinnati: ACGIH, pp. 163–198.

Marple, V. A., D. B. Kittleson, K. L. Rubow, and C. Fang. 1986. *Methods for the Selective Sampling of Diesel Particulates in Mine Dust Aerosol.* U.S. Bureau of Mines OFR 44-87, NTIS PB 88-130810. Washington, DC: U.S. Bureau of Mines.

Marple, V. A. and K. L. Rubow. 1981. *Instruments and Techniques for Dynamic Particle Size Measurement of Coal Dust.* U.S. Bureau of Mines OFR 173-83; NTIS PB 83-262360. Washington, DC: U.S. Bureau of Mines.

Marple, V. A. and K. L. Rubow. 1984. *Respirable Dust Measurement.* U.S. Bureau of Mines OFR 92-85, NTIS PB 85-245843. Washington, DC: U.S. Bureau of Mines.

Marple, V. A., K. L. Rubow, and S. M. Behm. 1991. A micro-orifice uniform deposit impactor (MOUDI): Description, calibration, and use. *Aerosol Sci. Technol.* 14:434–446.

McCartney, T. C. and B. K. Cantrell. 1992. *A Cost-Effective Personal Diesel Exhaust Aerosol Sampler.* U.S. Bureau of Mines IC 9324, pp. 24–30. Washington, DC: U.S. Bureau of Mines.

McCawley, M. and J. Cocalis. 1986. *Diesel Particulate Measurement Techniques for Use with Ventilation Control Strategies in Underground Coal Mines.* Cincinnati, OH: ACGIH, Vol 14, pp. 271–281.

McFarland, W. 1927. Silicosis and tuburculosis as seen in the granite workers in Barre. *Br. J. Ind. Hyg.* 9:315–330.

MESA. 1975. *The Determination of Free Silica in Airborne Dust Collected on Membrane Filters.* U.S. Dept. of the Interior, Mining Enforcement and Safety Administration, IR No. 1021. Arlington, VA: Mine Safety and Health Administration.

MSHA. 1971. Code of Federal Regulations (CFR), Title 30—Mineral Resources, Chapter 1. Mine Safety and Health Administration, Department of Labor, Revision of 10 March 1971.

MSHA. 1988. *Report of the Mine Safety and Health Administration Advisory Committee on Standards and Regulations for Diesel-Powered Equipment in Underground Coal Mines.* Report to the Secretary of Labor, July 1988. Arlington, VA: MSHA.

MSHA. 1989a. Air quality, chemical substances, and respiratory protection standards; proposed rule. *Federal Register* 54(166):35760–35785.

MSHA. 1989b. Coal mine health inspection procedures. In *MSHA Handbook Series, Handbook No. 89-V-1*. Arlington, VA: MSHA.

MSHA. 1990. Metal and nonmetal mine health inspection procedures. *MSHA Handbook Series, Handbook No. PH 90-IV-4*. Arlington, VA: MSHA.

MSHA. 1991. Code of Federal Regulations (CFR), Title 30—Mineral Resources, Chapter 1. Mine Safety and Health Administration, Department of Labor, Revision of 1 July 1999, pp. 3–705.

MSHA. 1996. 30 CFR Parts 7, Exhaust Gas Monitoring, and Safety Requirements for the Use of Diesel-Powered Equipment in Underground Coal Mines; Final Rule. *Federal Register*, October 25, 1996, pp. 55411–55534. Washington, DC: U.S. Department of Labor, Mine Safety and Health Administration.

MSHA. 1998. 30 CFR Part 57, Diesel Particulate Matter Exposure of Underground Metal and Nonmetal Miners; Proposed Rule. *Federal Register*, October 29, 1998, pp. 58104–58270. Washington, DC: U.S. Department of Labor, Mine Safety and Health Administration.

MSHA. 2001a. Diesel Particulate Matter Exposure of Underground Coal Miners. *Federal Register* 66(13):5526–5706.

MSHA. 2001b. Diesel Particulate Matter Exposure of Underground Metal and Nonmetal Miners. *Federal Register* 66(13):5706–5910.

NIOSH. 1987. Diesel Particulate Measurement Techniques Applied to Ventilation Control Strategies in Underground Coal Mines. *BuMines contract No. JO 145006*. For information contact Mr. M. McCawley NIOSH, Morgantown, WV.

NIOSH. 1988. Carcinogenic effects of expsosure to diesel exhaust. *Current Intelligence Bulletin 50*, NIOSH Publ. 88-116. Cincinnati, OH: NIOSH.

NIOSH. 1995. Criteria for a recommended standard—Occupational exposure to respirable coal mine dust. Washington, DC: National Institute for Occupational Safety and Health, DHHS(NIOSH) Publication No. 95-107.

NIOSH. 1999. Elemental carbon (diesel exhaust). Method 5040. *NIOSH Manual of Analytical Methods* (NMAM), 5th Edition, January 1, 1999. Cincinnati, OH: NIOSH.

Olson, K. S. and D. L. Veith. 1987. Fugitive dust control for haulage roads and tailing basins. *BuMines RI 9069*, Washington, DC: U.S. Bureau of Mines.

Organiscak, J. A. 1989. *Respirable Dust Generation, Comparison of Continuous and Conventional Mining Methods when Excavating Rock*. RI 9233. Washington, DC: U.S. Bureau of Mines.

Patashnick, H. and G. Rupprecht. 1983. *Personal Dust Exposure Monitor Based on the Tapered Element Oscillating Microbalance*. U.S. Bureau of Mines OFR 56-84; NTIS PB 84-173749. Washington, DC: U.S. Bureau of Mines.

Raymond, L., T. F. Tomb, and P. S. Parobeck. 1987. *Respirable Coal Mine Dust Sample Processing*. Washington, DC: Mine Safety and Health Administration, IR 1156.

Rubow, K. L., B. K. Cantrell, and V. A. Marple. 1990a. *Measurement of Coal Dust and Diesel Exhaust Aerosols in Underground Mines*. Proceedings of the VIIth International Pneumoconioses Conference, NIOSH Publ. No. 90-108. Cincinnati: NIOSH, pp. 645–650.

Rubow, K. L. and V. A. Marple. 1983. An instrument evaluation chamber: Calibration of commercial photometers. In *Aerosols in the Mining and Industrial Work Environment*, V. A. Marple and B. Y. H. Liu, eds. Ann Arbor, MI: Ann Arbor Science Publishers, Inc., III:777–798.

Rubow, K. L., V. A. Marple, J. Olin, and M. A. McCawley. 1987. A personal cascade impactor: Design, evaluation and calibration. *Am. Ind. Hyg. Assoc. J.* 48:532–538.

Rubow, K. L., V. A. Marple, Y. Tao, and D. Liu. 1990b. *Design and Evaluation of a Personal Diesel Aerosol Sampler for Underground Coal Mines*. Preprint No. 90-132. Littleton, CO: Society for Mining, Metallurgy, and Exploration, Inc.

Seaton, A. 1986. Respiratory disease in miners. *Proc. Ann. Am. Conf. Gov. Ind. Hyg.* 14:21–25.

Seaton, A., J. A. Dick, J. Dodgson, and M. Jacobsen. 1981. Quartz and pneumoconiosis in coal miners. *Lancet* 1:1272.

Tomb, T. F. and L. D. Raymond. 1970. *Evaluation of the Penetration Characteristics of a Horizontal Plate Elutriator and of a 10-mm Nylon Cyclone Elutriator*. U.S. Bureau of Mines, RI 7367. Washington, DC: U.S. Bureau of Mines.

Tomb, T. F., H. N. Treaftis, and A. J. Gero. 1981. Instantaneous dust exposure monitors. *Environ. Int.* 5:85–96.

Treaftis, H. N., A. J. Gero, P. M. Kacsmar, and T. F. Tomb. 1984. Comparison of mass concentrations determined with personal respirable coal mine dust samplers operating at 1.2 liters per minute and the Casella 113a gravimetric sampler (MRE). *Am. Ind. Hyg. Assoc. J.* 45:826–832.

Tsao. C. J., T. S. Shih, and J. D. Lin. 1996. Laboratory testing of three direct reading dust monitors. *AIHA J.* 57:577–563.

U.S. Congress. 1969. Federal Coal Mine Heath and Safety Act of 1969, 30 U.S.C. Stat. 801.

U.S. Congress. 1977. Federal Mine Safety and Health Act of 1977, Public Law No. 95-164, 91 Stat. 1290 (1977), Codified at 30 U.S.C. Stat. 801.

U.S. Department of Labor. 1996. *Report of the Secretary of Labor's Advisory Committee on the Elimination of Pneumoconiosis Among Coal Mine Workers*; recommendation 8 and 17. Washington, DC: U.S. Department of Labor.

Vincent, J. H. 1991. Joint Investigations of New Generations of Sampler for Airborne Dust in Mines. Synthesis Report on a joint project carried out by six laboratories in five European member states on behalf of the Commission of European Communities during 1985–1988. *Report No. EUR 13414EN.* Luxembourg: Commission of European Communities.

Volkwein, J. C., A. L. Schoeneman, and S. J. Page. 2000. Laboratory evaluation of a pressure differential-based respirable dust detector tube. *Appl. Occup. Environ. Hyg.* 15:158–164.

Watson, J. G. 1984. Overview of receptor model principles. *JAPCA* 34(6):619–623.

Watts, W. F., Jr. 1987. Industrial Hygiene Issues Arising from the Use of Diesel Equipment in Underground Mines. *BuMines IC 9141*. Washington, DC: U.S. Bureau of Mines. pp. 4–8.

Williams, K. and R. J. Timko. 1984. *Performance Evaluation of a Real-Time Aerosol Monitor.* Washington, DC: U.S. Bureau of Mines, IC 8968.

Williams, K. L. and R. P. Vinson. 1986. *Evaluation of the TEOM Dust Monitor.* Washington, DC: U.S. Bureau of Mines, IC 9119.

AEROSOL MEASUREMENT

Principles, Techniques, and Applications

SECOND EDITION

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New York • Chichester • Weinheim • Brisbane • Singapore • Toronto

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Published simultaneously in Canada.

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Library of Congress Cataloging-in-Publication Data:

Aerosol measurement : principles, techniques, and applications / [edited] by Paul A. Baron and Klaus Willeke.—2nd ed.

p. cm.
Includes index.
ISBN 0-471-35636-0 (cloth)
1. Aerosols—Measurement. 2. Air—Pollution—Measurement. I. Baron, Paul A., 1944–
II. Willeke, Klaus.
TD884.5 .A33 2001
628.5'3'0287–dc21 2001017845

Printed in the United States of America.

10 9 8 7 6 5 4 3 2 1