

26 Mine Aerosol Measurement

BRUCE K. CANTRELL and JON C. VOLKWEIN

National Institute for Occupational Safety and Health, Pittsburgh Research Laboratory, Pittsburgh, PA

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 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.

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, CO₂, NO, NO₂, SO₂, 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

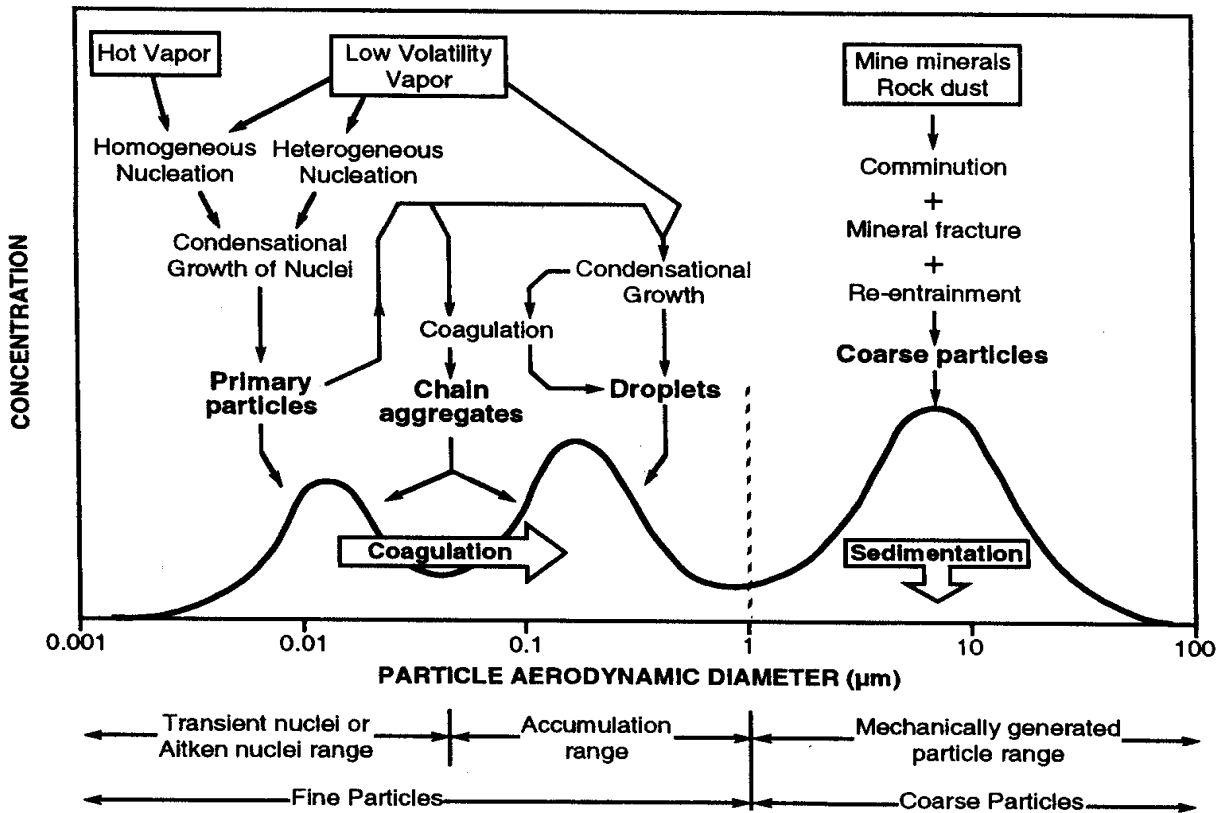


Fig. 26-2. Size distribution summarizing the general physical characteristics of mine aerosol. (From Cantrell et al., 1987.)

secondary aerosols or chain aggregates, formed by coagulation of primary aerosols. The next size range, from 0.08 to approximately $1.0\mu\text{m}$, 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, $1.0\mu\text{m}$ to approximately $40\mu\text{m}$, 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 $1.0\mu\text{m}$. 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

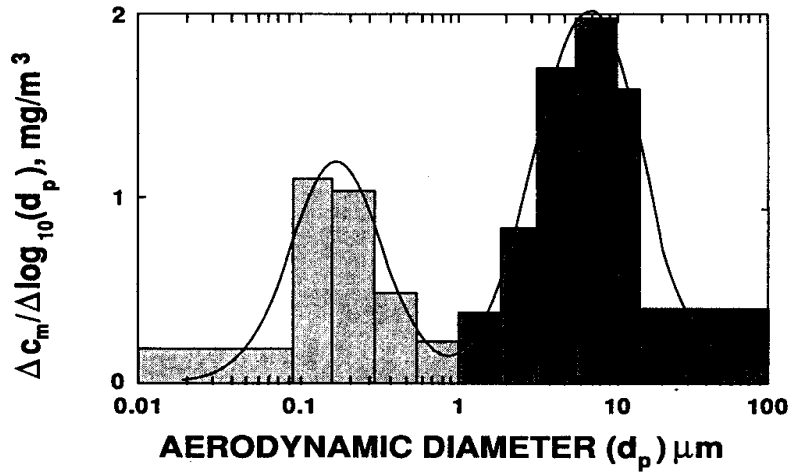


Fig. 26-3. Mass size distribution of mine aerosol in diesel-equipped mine. (From Cantrell and Rubow, 1990.)

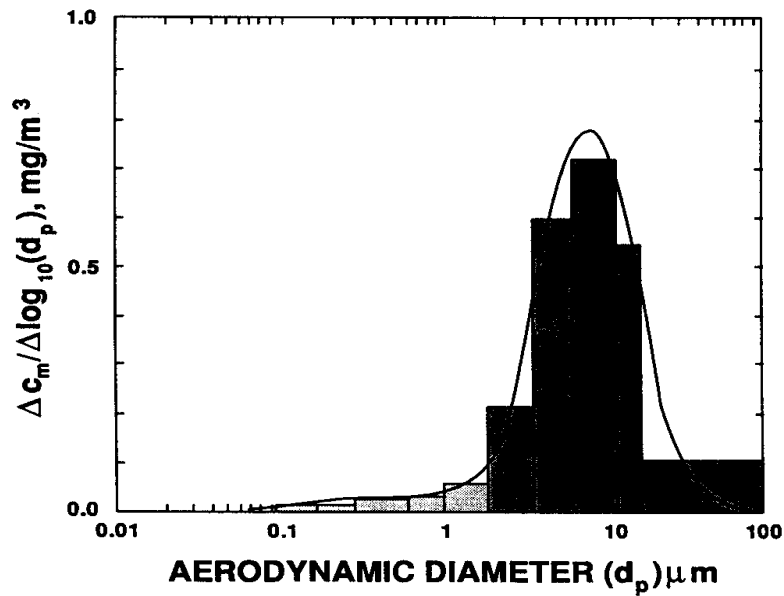


Fig. 26-4. Mass size distribution of mine aerosol in an all-electric-equipped mine. (From Cantrell and Rubow, 1990.)

hauling 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

$$PEL_{\text{quartz}} = \frac{10 \text{ mg/m}^3}{\text{percent respirable quartz} + 2} \quad (26-1)$$

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/m³ 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/m³ 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

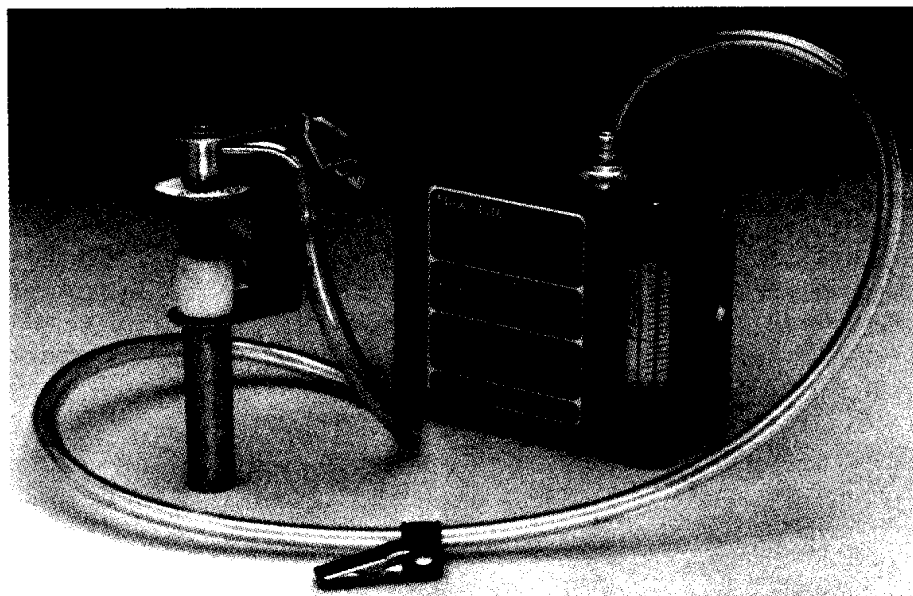


Fig. 26-5. Personal Respirable Dust Monitor. (Courtesy of MSA Co.)

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

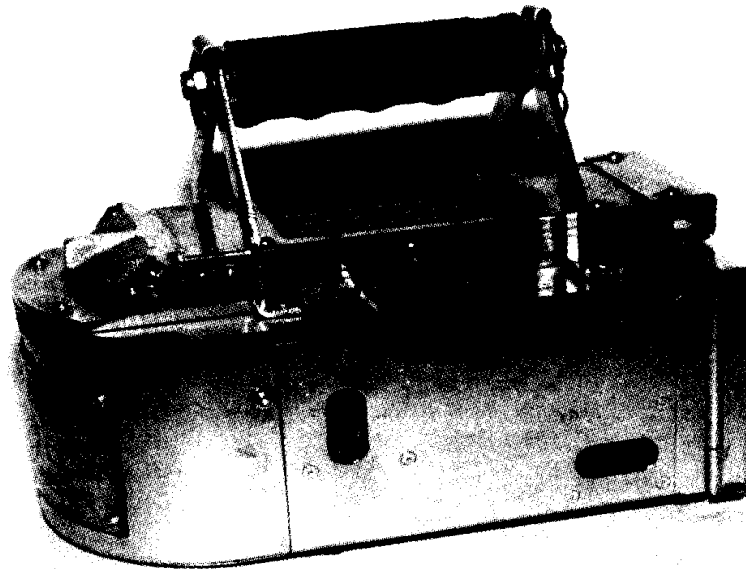


Fig. 26-6. Casella, Model 113a, MRE Respirable Dust Monitor. (From Cantrell et al., 1987.)

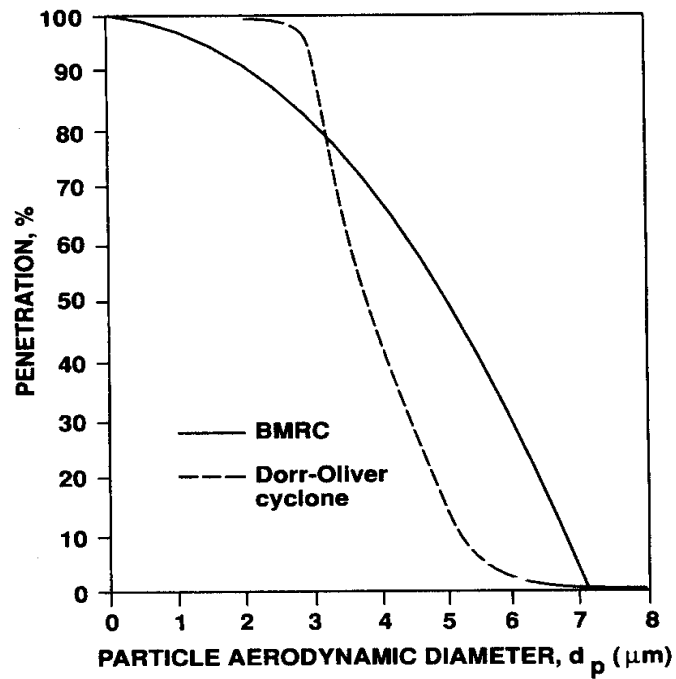


Fig. 26-7. Respirable aerosol sampling criteria; BMRC, Dorr-Oliver Cyclone. (From Caplan et al., 1977a,b; Lippman, 1989.)

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 $50\mu\text{g}/\text{m}^3$ (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 $400\mu\text{g}/\text{m}^3$ based on an 8 hour sample and, after the year 2005, a final PEL of $160\mu\text{g}/\text{m}^3$.

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- $1.0\mu\text{m}$ 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 $0.7 \pm 0.3\text{ mg}/\text{m}^3$.

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 10mm 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 $3.33 \times 10^{-5} \text{ m}^3/\text{s}$ [2L/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.