American Industrial Hygiene Association Journal

ISSN: 0002-8894 (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/aiha20

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Am. Ind. Hyg. Assoc. J. 48(2):122-126 (1987)

Particle Size Distributions in Underground Coal Mines*

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This paper reports the results of a sampling program undertaken by NIOSH to determine the particle size distributions in underground coal mines. The program made use of newly developed cascade impactors capable of being operated with personal sampling pumps. Particle size distribution samples were collected at selected areas in 10 continuous mining sections in three states. Results plotted as mass frequency distributions indicate that a bimodal distribution may exist in areas away from the operations of the continuous miner. A primary size mode of about 17 μm and a secondary size mode of about 5 μm were measured consistently throughout the 10 mines studied.

Scope

This paper reports the results of a sampling program undertaken by NIOSH to determine the aerodynamic particle size distributions in underground coal mines. Data reported represent particle size distributions collected at 10 underground coal mines working in seven different coal seams. Samples were collected with newly developed cascade impactors capable of being operated with a personal sampling pump. This arrangement overcame previous difficulties in finding a portable suction source that was "intrinsically safe."

Background

The Federal Coal Mine Health and Safety Act of 1969 placed limits on the permissible concentration of airborne "respirable" coal mine dust. This respirable fraction can be defined as the percentage of inhaled particles deposited in the nonciliated region of the respiratory tract.(1) The concentration of respirable particles has been measured predominantly with the cyclone sampler. Nonspecific obstructive lung disease, however, may be primarily responsible for most of the respiratory ills of coal miners.(2) Past reports show that coal miners have a higher prevalence of chronic bronchitis than workers in non mining trades.(2-4) The most frequent respiratory complaints are chronic bronchitis and shortness of breath — the typical symptoms of "miners' asthmas".(5)

In light of these upper respiratory tract diseases, knowledge of the particle size distribution is necessary for determining pulmonary deposition as well as the total regional deposition of dust in the lungs. A direct measure of aerodynamic diameter is most appropriate since deposition by impaction and sedimentation, which accounts for most of the mass deposition in the head and lungs, is related directly to the aerodynamic diameter of the particle. Until recently, however, determining the risk of upper airway diseases in coal miners has been limited by the difficulty of sizing the aerosol "aerodynamically," since regional lung deposition is size dependent,

Introduction

Measuring particle size distributions in underground coal mines is not new; however, recent advances in instrumenta-

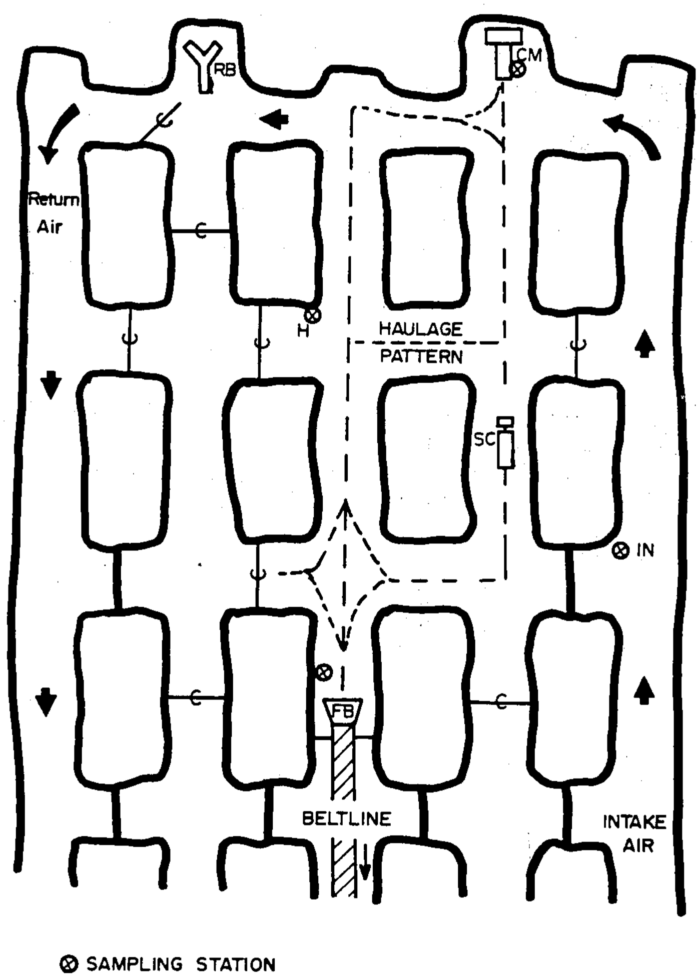

Figure 1 — Typical mining section.

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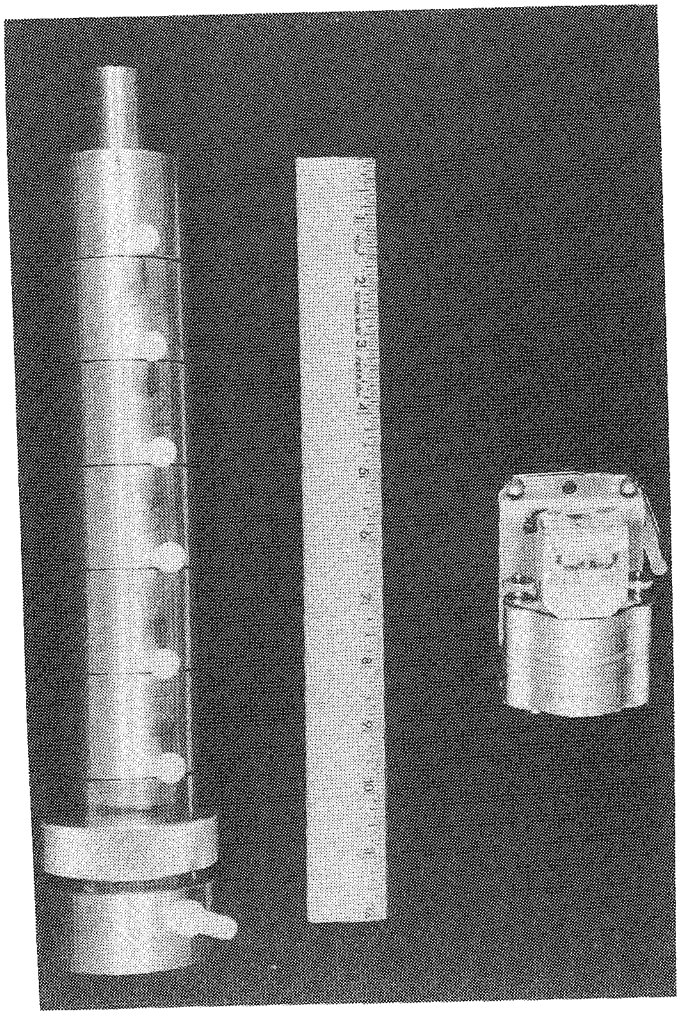

Figure 2 — Sierra Instruments Model 260 and Model 264 Cascade Impactors.

tion now enable the direct measurement of "aerodynamic" particle size distributions that are precise and representative of dusts to which coal miners actually are exposed.

Other studies have reported particle size distribution measurements with the use of various sizing instruments such as Coulter counters, electron microscopes and sedimentation cells. One report states that coal particles may be agglomerated or deagglomerated because of the analytical preparation of the particles for sizing, thus biasing the resulting size distribution.[6]

This paper reports the particle size distributions measured by cascade impactors. Cascade impactors are inertial separation devices that classify particles by their aerodynamic size by impinging a jet of particle-laden air upon an impaction plate.[7] Furthermore, cascade impactors eliminate the problems encountered in transferring particles from a filter for subsequent sizing since analysis is performed using the collection substrates. The substrates are weighed and the results are reported as the fraction of mass-per-size interval. (The mass median aerodynamic diameter is obtained directly from this measurement.)

Protocol

Particle size distributions were measured in coal mines participating in two NIOSH epidemiological studies. Three to five sampling days were spent on a continuous mining section at each of the 10 mines participating in the project. In order to characterize the particle size distributions of dust generated during mining operations, samples were collected at selected areas throughout the mining section. The areas selected for size distribution measurements were the continuous miner operator's (CM) and shuttle car operator's (SC) breathing zones, various haulage roads (H), transfer points such as belt feeders (FB), and intake airstreams (I) (Figure 1). All samples collected on continuous miners' and shuttle cars, were located within 36 in. of the operator's breathing zone, as prescribed in the dust sampling regulation 30 CFR Part 70. Haulage road samples were placed in an area approximately halfway between the face and the transfer point. Samplers located at the transfer point were placed near the feeder/breaker or trackline, depending on which haulage method the mine employed. Intake air to the section was sampled to determine the amounts and sizes of dusts coming onto the section. These samplers usually were placed upstream in the ventilation pattern, far from any mining activities. Sampling times ranged usually from 180 to 300 min per shift. A package of five or six impactors and one or two total dust samplers was placed at each sampling area. The total dust samplers were used only for comparison with the total mass collected by the impactors.

Sampling Methods

The Sierra Instruments (now Andersen Inc.) Model 260 and Model 294 cascade impactors were used to measure the particle mass *vs.* aerodynamic diameter (Figure 2). Since the impactors' equivalent cut diameters are dependent on the sampling flow rate, it was necessary to select a sampling

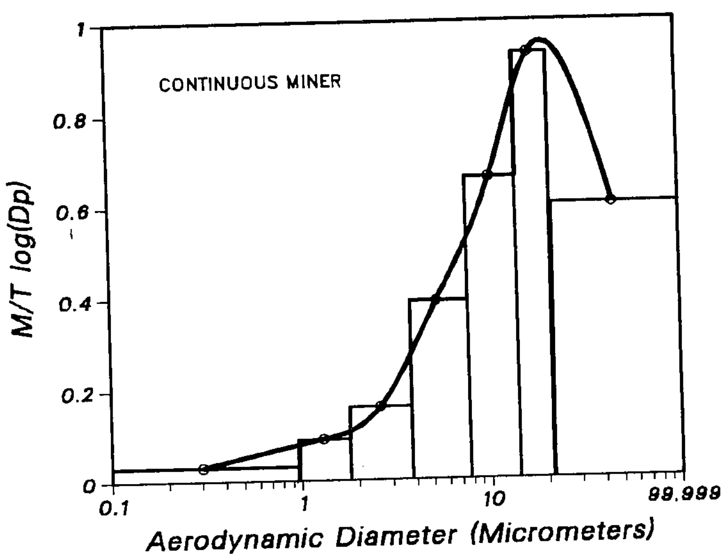

Figure 3 — Relative mass frequency distribution. A spline procedure was used to show the trend in the histogram data.

pump that would maintain a 2 Lpm constant airflow regardless of pressure drop and battery voltage drain. The "Du Pont P-2500" air sampling pump was selected because of its electronically controlled constant-flow features.

The Model 260 impactor is a six-stage, single jet impactor, and the Model 294 is a smaller four-stage, multi-jet impactor developed for personal sampling. These particular impactors were selected because they could be operated with personal sampling pumps and were small enough to be placed directly on the mining machinery. At a flow rate of 2 Lpm the Model 260 impactor provides seven cut-points ranging from approximately 20 μm to less than 0.5 μm. The Model 294 has five cut-points from approximately 20 μm to less than 3.5 μm. Because of the limited number of cut-points associated with the Model 294 impactor, all data collected with this impactor were used only to compare to the Model 260. (Note: Additional stages now can be added to the Model 294 to increase to eight the number of cut-points between 20 μm and 0.5 μm.)

The impaction substrates used in the Model 260 and 294 were 18 mm glass and 34 mm stainless steel slides, respectively. Each substrate was coated with a thin uniform layer of Apeizon-H grease to serve as the collection surface for dust particles and also to prevent particle bounce. The application of the grease to the substrates was critical for collecting valid samples. Only the areas where the dust particles could impact were greased since grease which came in contact with the impactor plate could have been lost, resulting in erroneous gravimetric weighings.

To assure uniform application with no overlap of the grease, one tube of Apeizon-H grease (25 g) was dissolved in 1 L of technical grade toluene. An air brush was used to spray the solution through a template onto each substrate. This template consisted of the first two impactor stages, with a substrate placed between them in its normal position (only the first two stages are needed for this process); then, with the air brush held approximately 10 cm above the template,

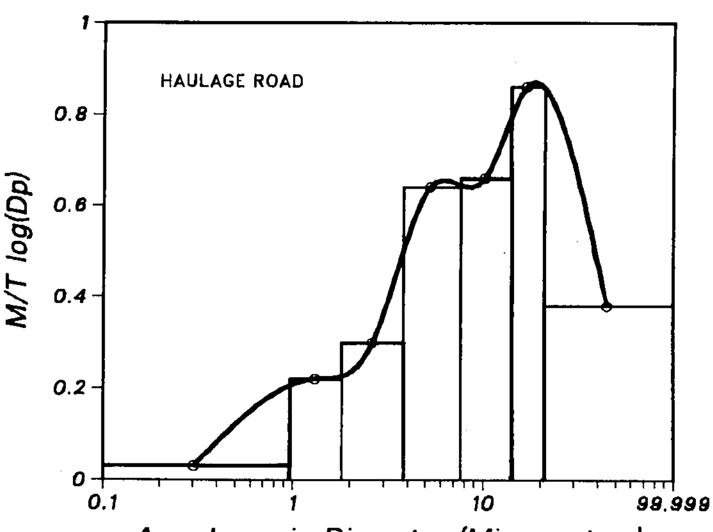

Figure 4 — Relative mass frequency distribution. A spline procedure was used to show the trend in the histogram data.

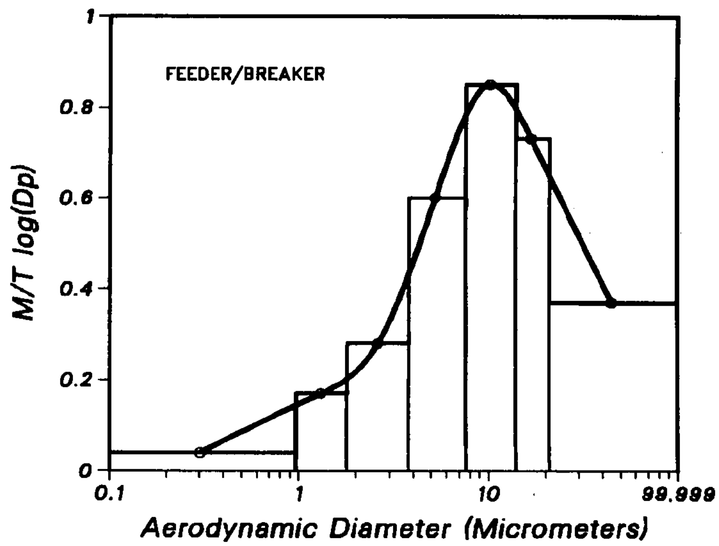

Figure 5 — Relative mass frequency distribution. A spline procedure was used to show the trend in the histogram data.

the grease solution was sprayed at a pressure of 30 psi into the template. Only a few seconds of spraying were needed to coat the substrate sufficiently. Once the substrates were sprayed, they were allowed to equilibrate for 24 hr. This was found to be sufficient time for the toluene to off-gas and the substrate weight to become stable. Each substrate then was pre-weighed (and post-weighed after sampling) in a controlled environment (20°C, 50% RH) on a Cahn Model 27 Electro-balance to a precision of 0.01 mg.

Results

The first step in analyzing the field data was to eliminate all underloaded or overloaded impactor samples. One problem with impactor sampling is the judgment of optimum sampling time. Sampling too long can cause certain stages to become "overloaded," which results in re-entrainment of some dusts and the consequent overestimation of the mass in the smaller particle sizes.[8] Too short a sampling period may result in "underloading" of some stages, with too little mass on certain collection substrates to obtain precise weighing.

As a conservative measure, all overloaded impactor samples (greater than 2.0 mg per stage) were discarded; additionally, all samples which had less than 0.5 mg of total collected mass were eliminated. The remaining particle size distributions were averaged for each area, yielding a single overall distribution. These distributions then were plotted as continuous mass frequency distributions.[9] When this method is used to represent data graphically, it is necessary to select a reasonable upper cut-off diameter for the first impactor stage and a lower cut-off diameter for the last impactor stage. When the mean derived from the mass frequency distribution, using an upper limit of 100 μm and a lower limit of 0.01 μm, was compared with the mean from a standard log probability plot[10] for a test dust with a known single mode distribution, the means were nearly identical. There-

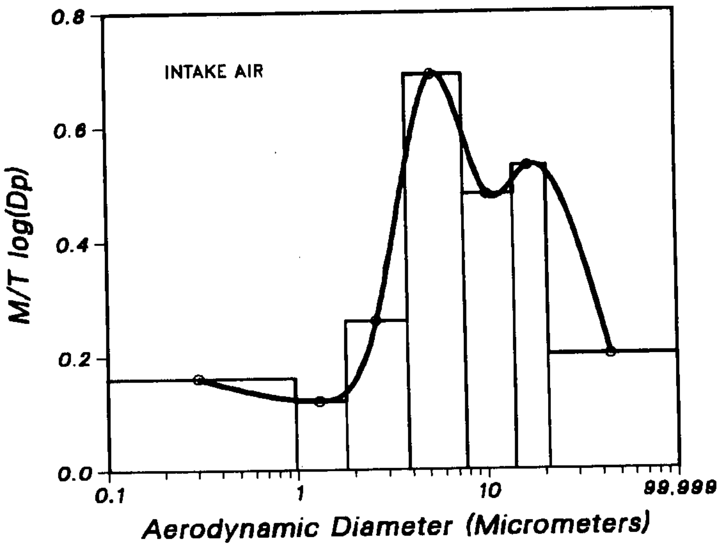

Figure 6 — Relative mass frequency distribution. A spline procedure was used to show the trend in the histogram data.

fore, the upper limit and lower limit were considered reasonable.

The mass frequency distributions for each of the studied sampling areas are presented in Figures 3-6. The ordinate for these curves has been normalized by the total amount of dust collected by the impactor. Therefore, the area under the curve is proportional to the fractional mass in that size range. The integrated area from zero to infinity is unity.

Figure 7 is an overlay of all the area size distributions. The graph shows that the size distribution for all the areas, except the feeder/breaker, shares a primary size mode of about 17 to 20 μm. It is possible that the feeder/breaker also might share this mode if additional cut points were added in this range; however, the available data indicates presently a single size mode with a mean of about 8 to 10 μm. Also, all areas except for the continuous miner and the feeder/breaker show a secondary size mode of about 5 to 8 μm.

Discussion

Figure 7 appears to indicate that there is a bimodal character to the dust in coal mines. This character was maintained throughout the 10 mines studied. It is theorized that the primary source of the larger mode (17-20 μm) may come from the operation of the continuous miner. Only the continuous miner and feeder/breaker show no bimodality. The single, larger-sized mode of the continuous miner can be overlaid on all other size distributions and shows little difference. If the continuous miner is the source of the larger mode seen in the other locations, then dust obviously is being convected from this area. The airflow patterns in the mine have been designed to carry air directly away from the continuous miner and the face into the return airways. The other areas of the mine must be considered upstream in the airflow. Therefore, some portion of the air may be partially short-circuited, and dust from the face may be allowed to disperse to other portions of the working section. This theory is supported by the trend in the distributions. The farther upstream the sampling area was located from the face, the smaller was the contribution of the larger-sized mode.

Another point of interest is the source of the smaller-sized mode noted in areas away from the face. This "secondary" dust may be the result of resuspending or settling of dust. Partially settled dust should be smaller than the dust close to a "primary" source of generation. In certain areas of the mine this "secondary" dust contributes as much to the mass as does the larger "primary" mode; that is, the two modes appear to have nearly equal areas under them. The main effort at controlling dust has been directed at this "primary" source, which required ventilating the face. According to the data we have presented in this study, miners working in areas other than the face may receive a large amount of their dust exposure from the "secondary" dust.

Many past estimations of the particle size distribution of coal mine dust may be in error since very few of the measurements were made with aerodynamic sizing devices. These techniques required estimation of the aerodynamic shape factor and density of the material. Also, since there appear to be two (or possibly more) modes for any given area in a coal mine, results interpreted from the standard log-probability plots may be in error.

Since defining the parameters of a multi-modal distribution with a log-probability plot is virtually impossible, the mass frequency method is better suited for uncovering hidden size modes. Thus, the overall dust size distributions should be characterized first by the mass frequency method before use of a log-probability plot is attempted.

Knowing the particle size distributions in underground coal is important for developing control techniques that reduce the miners' dust exposures. For example, wetting down haulage roads may eliminate the miners' exposures to the "secondary" resuspended dusts. In addition, the size distribution information is essential in determining the accuracy

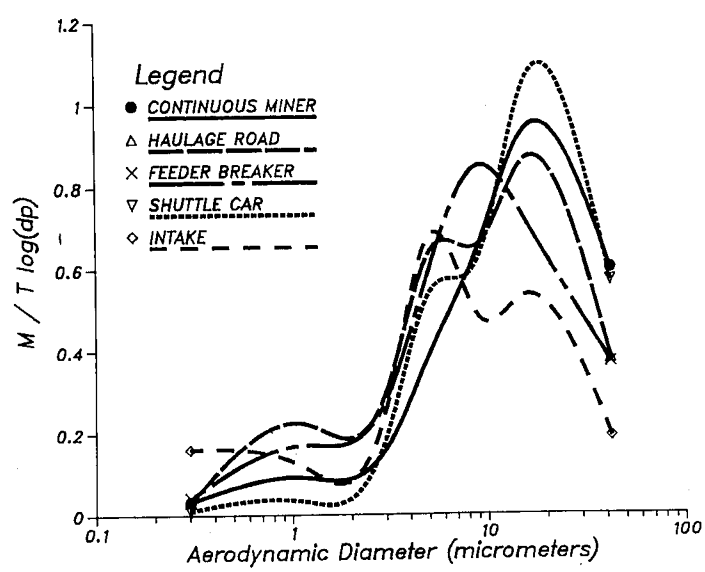

Figure 7 — Relative mass frequency distribution. A spline procedure was used to show the trend in the histogram data.

and precision of those instruments used presently to assure compliance to the dust standard and any instrument that might be proposed.

Finally, from a medical point of view, knowing the particle size distributions in coal mines can provide information on the tracheo-bronchial dose as well as respirable dust levels. This information combined with pulmonary function data can be used to gain a better insight into the entire spectrum of coal mine dust-induced lung diseases.

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21 February 1986; Revised 18 July 1986