Chapter 8

A Personal Diesel Exhaust Aerosol Sampler

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ABSTRACT

Techniques are being developed for measuring the mass concentration of respirable diesel exhaust particles found in underground coal mines. Studies have been conducted over the past five years to investigate size selective sampling techniques to measure the respirable mass concentrations of diesel exhaust and mine dust aerosol particles in underground coal mines. Results from these studies have been used to develop design and performance criteria for a personal diesel exhaust aerosol sampler.

Three personal diesel exhaust aerosol samplers have subsequently been designed and evaluated in both laboratory and field settings. These samplers use size selective classifiers for the determination of the respirable mass concentrations of mineral dust and diesel exhaust particles. Their designs are based on the premise that diesel exhaust particles are predominantly less than 0.8 µm while mineral dust is greater than 0.8 µm.

One design, selected for field evaluation, consists of a 10 mm nylon respirable dust cyclone followed by a 0.8 µm cutpoint impactor and afterfilter. The cyclone removes the large nonrespirable particles while the inertial impactor stage, collects the mineral dust on an impaction plate and allows the diesel particles to penetrate to an afterfilter. The two sample fractions of the respirable particles (<0.8 µm and >0.8 µm) are gravimetrically analyzed to determine the concentrations of the diesel and mineral dust portions in the respirable coal mine aerosol.

INTRODUCTION

Historically, coal mines have used electric-powered equipment to perform mining operations in underground mines. However, in recent years diesel-powered equipment has been introduced because this equipment offers greater flexibility, maneuverability, and efficiency.

One of the current concerns in the use of diesel engines is that the exhaust contains particles in the respirable particle size range. The National Institute for Occupational Safety and Health (NIOSH) 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, 1988). Furthermore, a Mine Safety and Health Administration (MSHA) advisory committee directed MSHA to develop a sampling protocol for assessing worker exposure to diesel exhaust particles (MSHA, 1988).

Since both coal and diesel particles are primarily carbonaceous matter, it was not readily apparent what type of sampling and analysis techniques could be used to determine the fraction of diesel particles in a sample containing both diesel and coal particles. Therefore, the Bureau of Mines initiated a program in 1984 to study methods by which the diesel particles could be discriminated from coal particles in a respirable sample (Marple et al., 1986). A hypothesis was made that the diesel and coal particle size distributions were sufficiently different such that the fraction of diesel particles in the total aerosol could be inferred from the total size distribution. It was felt this may require computer assisted curve fitting techniques to separate the total particle size distribution into the diesel and coal particle size fractions.

Marple et al. (1986) performed studies in the laboratory and in underground coal mines with a microorifice uniform deposit impactor (MOUDI) sampling various mixtures of diesel and coal particles to measure the total particle size distribution. The objective of the study was to determine if the mass concentration of diesel particles, in an airborne mixture of coal dust and diesel exhaust particles, could be determined on the basis of particle size. The MOUDI is a cascade impactor with cut sizes ranging from 0.056 to 18 µm in eight or ten stages to enable obtaining a fairly detailed size distribution analysis in the respirable particle size range (Rubow and Marple, 1988; Marple et al., 1991). Although the MOUDI is not suitable for use as a personal sampler, it was necessary to obtain detailed insight into the particle size distributions before criteria for a personal sampler and sampling strategy could be formulated. The results from these studies showed that the mass concentration of coal dust and diesel particles could be separated and measured on the basis of particle size.

Average particle mass size distributions measured in haulage ways of underground coal mines

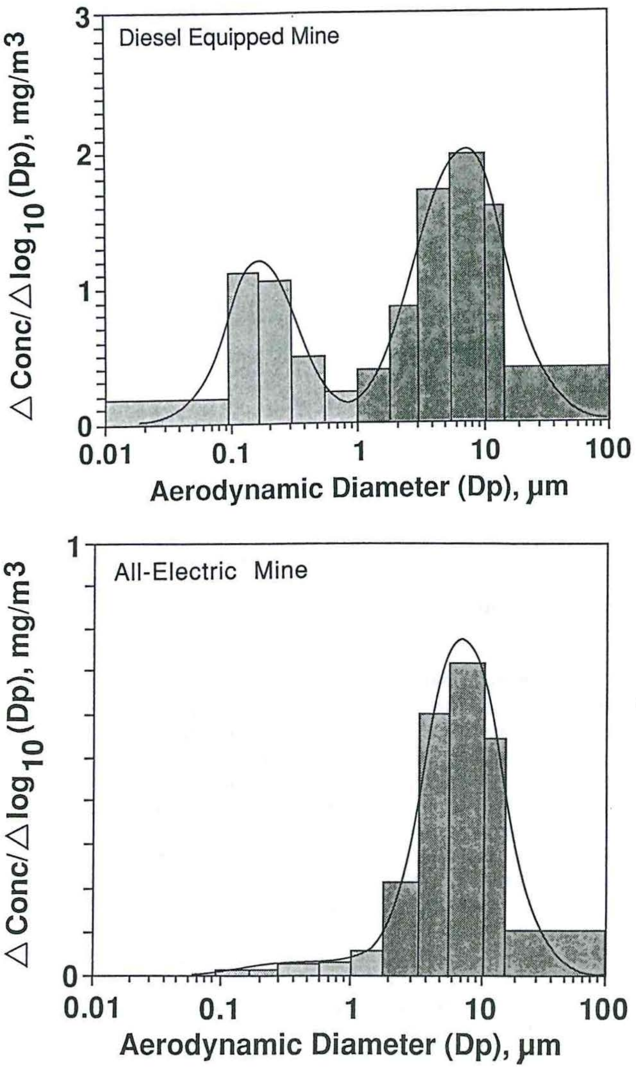

Figure 1. Average particle size distributions measured in haulageways of coal mines utilizing diesel- and electric-powered equipment.

employing diesel-powered and electric-powered equipment are shown in Figure 1. These data were obtained from joint University of Minnesota - Bureau of Mines studies conducted from 1985 through 1990. The steps of the histograms in Figure 1 represents the mass of particles collected on the various MOUDI stages. These distributions indicate the existence of a bimodal particle size distribution in mines employing diesel-powered equipment. However, only the larger particle size (coarse) mode is present in the electric mine, inferring that the lower mode is diesel exhaust particles and the upper mode is coal dust.

Further evidence that the lower mode is diesel exhaust particles was achieved through chemical mass balance (CMB) analysis of respirable particles collected in two size fractions separated at 0.7 μm. Instrumental neutron activation analysis was used to determine the trace element composition in each size fraction. CMB analysis showed that the lower mode consisted of diesel particles (Cantrell, 1987; Rubow et al., 1990).

The analysis of data from several mines and from the laboratory indicated that the separation of the diesel particle and coal dust modes could be achieved by separating the size distribution at 0.8 μm, with the diesel particles being smaller than this size and the coal particles being larger. Size distribution and CMB analysis showed that if the separation was made at 0.8 μm, the uncertainty in the diesel particle concentration, as gravimetrically determined from the mass of material less than 0.8 μm, would be less than 10% (Rubow et al., 1990; Cantrell and Rubow, 1990).

Operating under the hypothesis that the diesel particles are less than 0.8 μm in size and the coal particles are larger, a project was undertaken to develop a personal sampler which would have the capability of separating respirable particles into two size classes: one less than and one larger than 0.8 μm. The object of this paper is to describe the design and calibration of three samplers developed to perform this task and to present data collected in field tests with one of the samplers.

The samplers are designed to separate the respirable fraction of particles into two size classes (<0.8 μm and >0.8 μm) without regard as to the source of the particles. Although there is considerable evidence that particles (in the haulageway) less than 0.8 μm are almost exclusively diesel and those larger are mineral dust, it is realized that some investigators feel that the crossover between the two modes at the 0.8 μm size may be excessive. Therefore, this paper will refer to all of the particles in the lower mode as being <0.8 μm and particles in the larger mode as being >0.8 μm with no further reference to diesel or coal fractions.

CANDIDATE SAMPLERS

The primary design criteria for the personal diesel exhaust aerosol sampler, as indicated in Figure 2, is to sample, classify and collect the respirable fraction of the aerosol particles into those larger and smaller than 0.8 μm. Since the sampler must be personal, the flow rate must be no larger than that obtainable with a personal sampling pump. This places an upper limit on the flow rate at approximately 4 L/min, with most pumps designed to operate at 2 L/min.

The design criteria dictate the use of a three stage sampler. The first stage must remove the large, nonrespirable particles which can be discarded, while the smaller, respirable particles remain airborne. Two possible choices for the first stage classifier are the 10 mm nylon cyclone or a respirable cut impactor. The particles penetrating the first stage must be further classified in the second stage, where the particles >0.8 μm are removed from the airstream. Obvious choices for the second stage separator are impactors, cyclones or virtual impactors. The particles penetrating the second stage are collected on an afterfilter, constituting the third and final stage of the sampler. Only the respirable particles in the size classifications <0.8 and >0.8 μm must be available for analysis.

For the study performed here, personal diesel aerosol samplers based on three combinations of

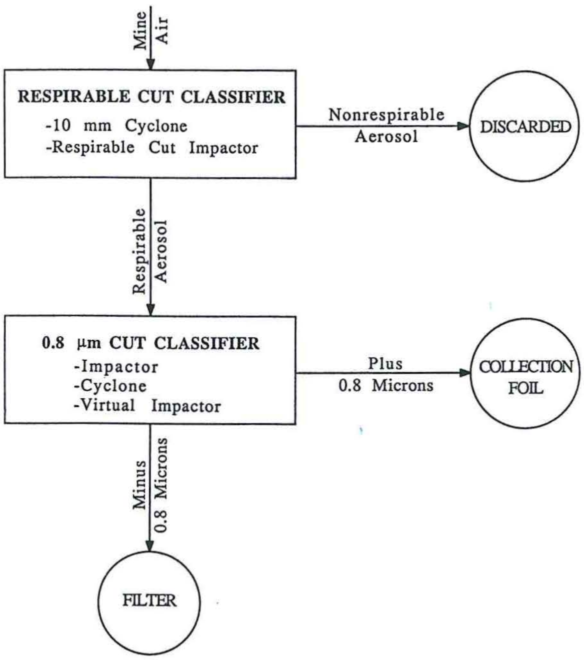

Figure 2. Schematic block diagram of personal diesel aerosol sampler.

particle classifiers were selected for study, as outlined in Table 1. For two of the samplers, the 10 mm nylon cyclone was used as the respirable classifier to remove the large nonrespirable particles. The advantages of this cyclone are that it is currently used in the standard compliance respirable dust sampler and it has high dust loading capacity. The respirable cut impactor is not commonly used but does have the advantage that it can be designed to operate at any flow rate. Therefore, it is possible to design a classifier, operating at 4 L/min, that collects larger quantities of particles for analysis.

Three choices are available for the 0.8 µm cutpoint classifier: a cyclone, an impactor and a virtual impactor. Only the impactor and the cyclone were used for this study since virtual impactors require control of two flows. Since the 0.8 µm cutpoint is a new requirement for a personal sampler, new classifiers were developed.

Table 1

Personal Diesel Aerosol Sampler Design Configurations

Design	Respirable Separator	0.8 µm Cutpoint Inertial Device	Sampling Flow Rate, L/m
1	10 mm cyclone	Impactor	2
2	"	Cyclone	2
3	Respirable impactor	Impactor	4

Samplers were built, calibrated and tested for the three cases listed in Table 1. Details of the designs are described in the following sections. Twelve units of the respirable cut cyclone/0.8 µm cutpoint impactor were designed, constructed, and subsequently used in a variety of field studies. Data obtained with the personal samplers in these studies were compared to those obtained with the MOUDI. These samplers were also used to determine the fraction of respirable diesel particles at a variety of locations in the working sections of three underground coal mines.

Respirable Cyclone/0.8 µm Cyclone Sampler

Cyclones have long been used in personal respirable dust samplers for collecting the large nonrespirable particles. They have the advantage in that they can hold large quantities of collected particles. The 10 mm nylon cyclone is a common classifier for separating the large nonrespirable particles from the respirable particles. The large particles are collected within the cyclone and discarded while the respirable particles penetrate through the cyclone. A natural extension of this respirable dust sampler for the personal diesel exhaust aerosol sampler is the addition of a second cyclone at the exit of the 10 mm nylon cyclone to classify the particles at 0.8 µm. The particles >0.8 µm would be collected in the second cyclone while the smaller particles would penetrate through the cyclone and be collected upon an afterfilter, in the same manner as respirable particles are collected on a filter in the standard personal sampler.

The design of this sampler is shown schematically in Figure 3 and a photograph shown in Figure 4. As indicated in these figures, this sampler consists of two cascaded cyclone classifiers and an afterfilter. Since the second cyclone is collecting the respirable particles >0.8 µm, a method must be devised by which the particles can be weighed or analyzed. The particles <0.8 µm are collected on an afterfilter and can be analyzed in the same fashion as respirable particles analyzed in the standard personal respirable dust sampler. To facilitate the analysis of the particles in the 0.8 µm cutpoint cyclone, a lightweight (70 mg), removable foil insert has been designed to fit into the cylindrical section of the cyclone. After a test, this foil insert, together with the deposited particles, can be removed and weighed to determine the quantity of respirable particles >0.8 µm. The critical dimensions of the 0.8 µm cutpoint cyclone are: cylindrical body of 0.95 cm diameter by 3.0 cm long, tangential inlet of 0.094 cm diameter, and exit of 0.132 cm diameter. The flowrate is 2 L/min, the same as the 10 mm nylon cyclone.

The 0.8 µm cutpoint cyclone was calibrated using monodisperse aerosols. The resulting particle collection efficiency curve is shown in Figure 5. The efficiency curve shows that the cutpoint is at 0.8 µm and the sharpness-of-cut is fairly good. If the sharpness-of-cut is defined as the geometric standard deviation of the curve, analysis of the curve in Figure 5 shows the geometric standard deviation to be 1.24. The geometric standard deviation is defined as the square root of the ratio of the particle diameter corresponding to the 84.1% collection efficiency to the diameter at an efficiency of 15.9%.

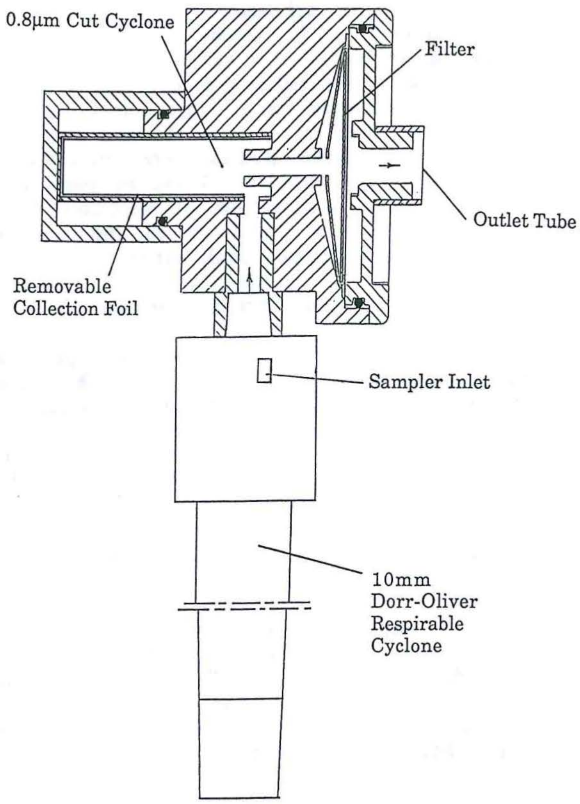

Figure 3. Schematic diagram of personal diesel aerosol sampler- respirable cyclone/0.8μm cyclone.

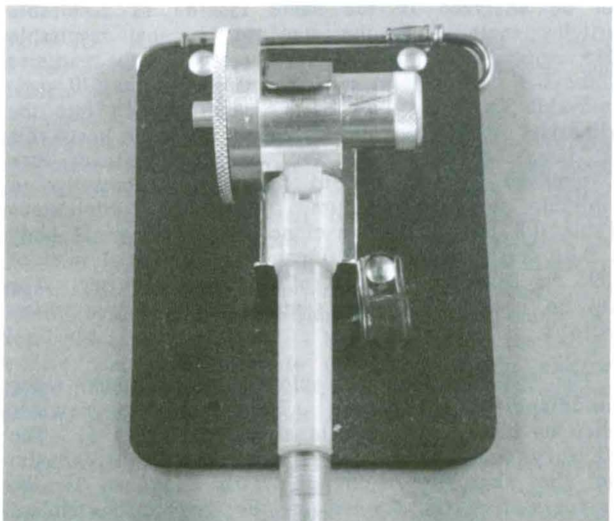

Figure 4. Personal diesel aerosol sampler- respirable cyclone/0.8μm cyclone.

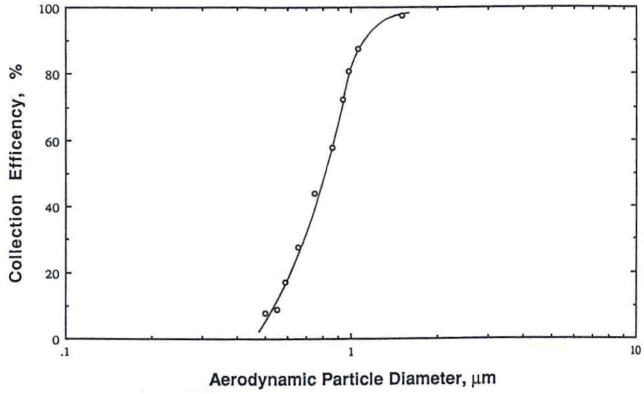

Figure 5. Particle collection efficiency of 0.8 μm cyclone.

Respirable Impactor/0.8 μm Cut Impactor

Although cyclones have been used extensively in personal samplers for the collection of particles, inertial impactors have also been used as personal samplers, especially cascade impactors (e.g., Rubow, et al., 1987). It is, therefore, feasible to design a two-stage cascade impactor with an afterfilter to serve as a personal diesel aerosol sampler. The major difference between this cascade impactor and other cascade impactors is that the first stage of the personal cascade impactor must have a respirable cut.

Respirable cut impactors can be designed for a specific flowrate by using multiple round nozzles of different diameters (Marple and McCormack, 1983; Marple and Rubow, 1983). The technique is shown schematically in Figure 6 where the respirable curve is approximated by a series of steps, with each step being represented by one size of nozzles in the respirable cut impactor. In the example shown in Figure 6, three nozzle sizes have been used to approximate the respirable curve in three steps. The largest nozzle diameters are designed to collect the largest cut of the three steps and smaller nozzles are designed for the smaller cuts. The number of nozzles must be balanced so that 1/3 of the flow will pass through each set of nozzles.

The sampler designed for this study is shown schematically in Figure 7 and a photograph shown in Figure 8. The nozzles for the respirable cut impactor are located in an annular ring so that the impaction plate can be an annular disk. Particles not collected on this plate are directed to the center of the annular disk and then passed through nozzles of a 0.8 μm cutpoint impactor. The particles larger than 0.8 μm are collected upon the impaction plate while the particles less than 0.8 μm penetrate to an afterfilter where they are collected. Since the respirable cut impactor can be designed for any flowrate, a 4 L/min flowrate was chosen to collect more material for analysis. With these design criteria, the two impactor stages were designed following the specific dimensions and operating parameters given in Table 2. The 0.8 μm cutpoint impactor was designed using impactor theory and design guidelines given by Marple (1970), Marple and Rubow (1986) and Rader and Marple (1985).

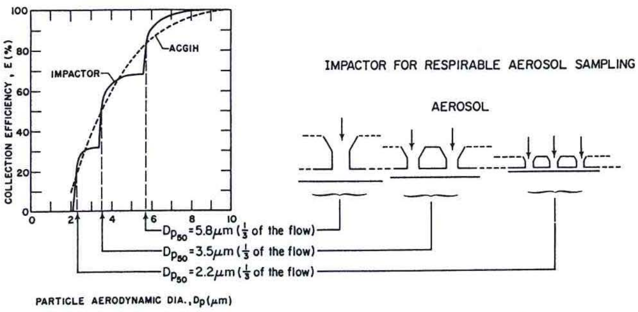

Figure 6. Approximation of the ACGIH respirable dust criteria curve by a single stage respirable impactor with three nozzle sizes.

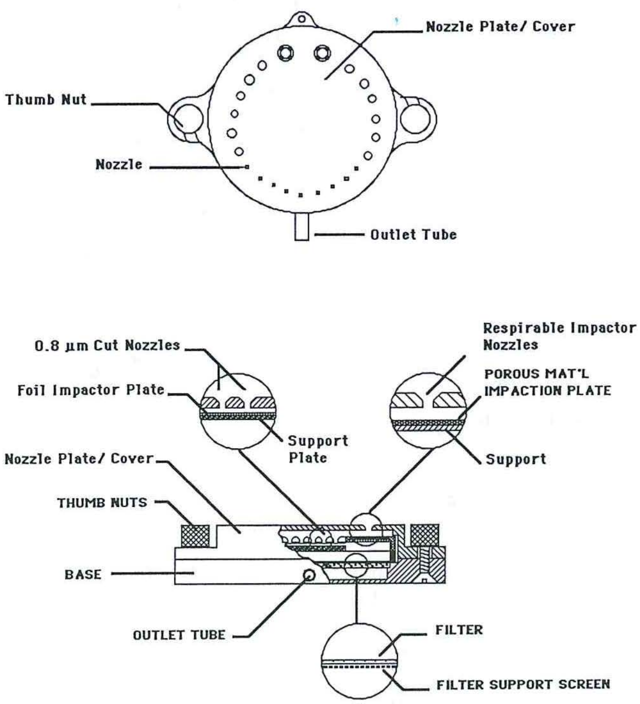

Figure 7. Schematic diagram of personal diesel aerosol sampler- respirable impactor/0.8μm impactor.

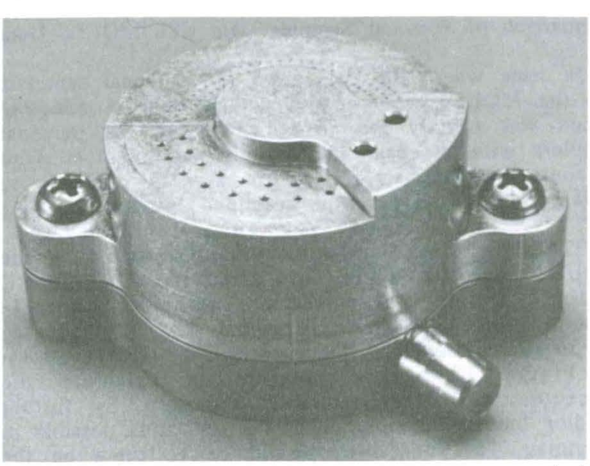

Figure 8. Personal diesel aerosol sampler- respirable impactor/0.8μm impactor.

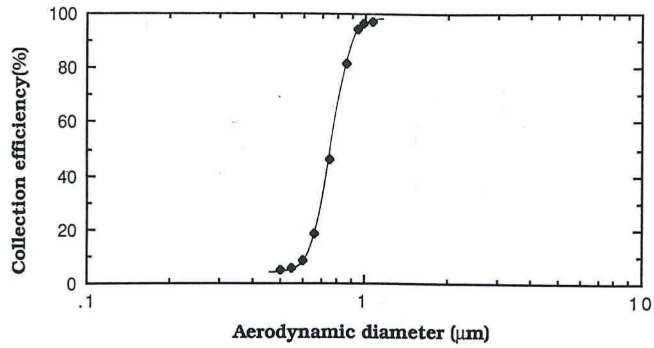

Figure 9. Particle collection efficiency of 0.8 μm impactor.

Table 2

Design Parameters for Respirable Cut Impactor and 0.8 μm Cutpoint Impactor

Cutpoint, μm	Nozzle Diameter, cm	Number of Nozzles	Nozzle Reynolds Number	Jet-to-Plate Distance, cm
ACGIH Respirable Cut Impactor (4 L/m)				
5.8	0.24	2	380	0.24
3.5	0.087	16	130	0.10
2.2	0.033	106	50	0.07
0.8 μm Cutpoint Impactor (4 L/min)				
0.8	0.057	8	1200	0.20
0.8 μm Cutpoint Impactor (2 L/min)				
0.8	0.057	4	1200	0.20

One additional advantage of using an impactor for the respirable classifier is that the impactor can be designed with cutoff characteristics approximating either the American Conference of Governmental Industrial Hygienists (ACGIH) or British Medical Research Council (BMRC) respirable dust criteria. For this particular case, the ACGIH criteria was used for the design.

The 0.8 μm cutpoint impactor was calibrated using monodisperse aerosols in the same manner as the 0.8 μm cutpoint cyclone was calibrated. The calibration curve for this impactor is shown in Figure 9. The sharpness of cut for the 0.8 μm cutpoint impactor, with a geometric standard deviation of 1.15, is sharper than for the 0.8 μm cutpoint cyclone. The cutpoint is at the desired 0.8 μm aerodynamic diameter.

Respirable Cyclone/0.8 μm Impactor Sampler

The first sampler consisted of two cyclone classifiers and the second sampler of two impactor classifiers. However, it is possible to mix the type of classifiers and in the third sampler, the 10 mm nylon cyclone and a 0.8 μm cutpoint impactor were utilized. The advantage of this sampler is that the high dust holding capacity of the respirable cyclone and the

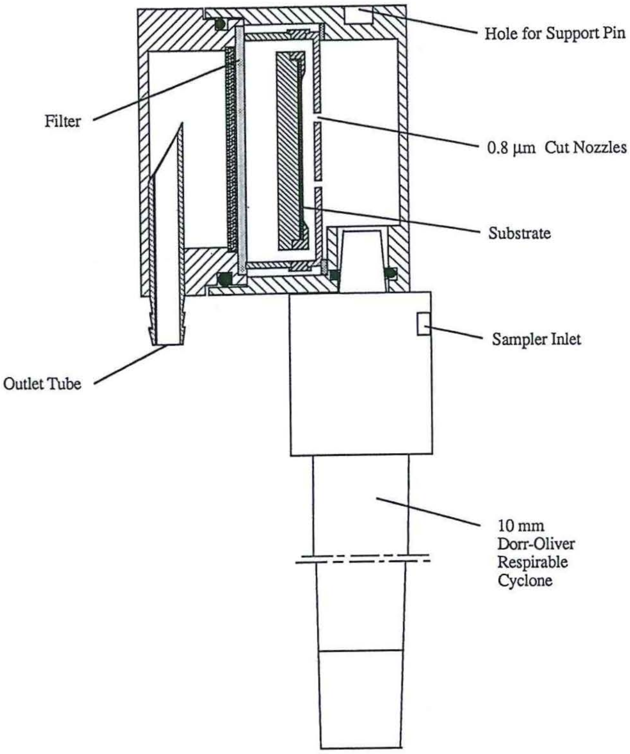

Figure 10. Schematic diagram of personal diesel aerosol sampler- respirable cyclone/0.8µm impactor.

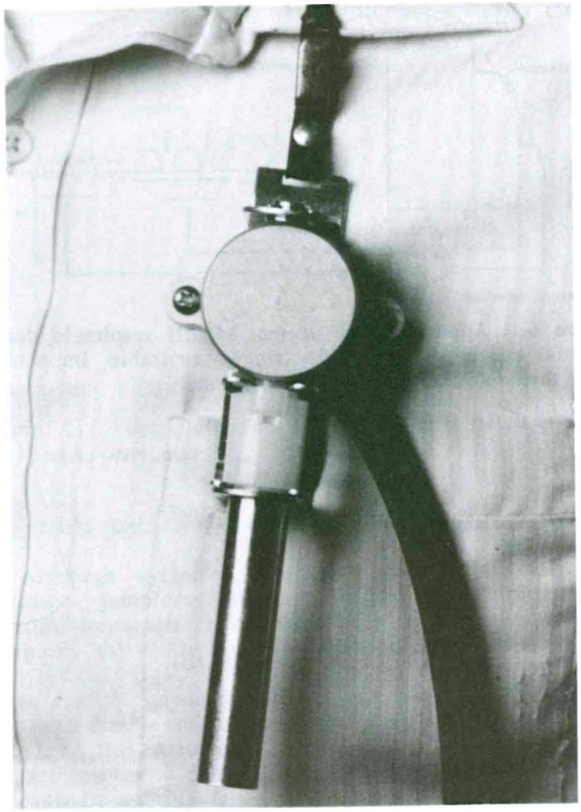

Figure 11. Personal diesel aerosol sampler- respirable cyclone/0.8µm impactor.

good "sharpness-of-cut" of the 0.8 µm cutpoint impactor can be combined. However, the flowrate must now be at 2 L/min because of the respirable cyclone. Therefore, the 0.8 µm cutpoint impactor differs from that in the second sampler in that only four nozzles 0.057 cm in diameter are used rather than 8 nozzles.

A schematic diagram and photograph of this sampler are shown in Figures 10 and 11, respectively. The outlet of the respirable cyclone enters a cavity above the impactor. The particles collected on the impaction plate are the respirable particles larger than 0.8 µm while those particles penetrating to the afterfilter are the less than 0.8 µm.

Calibration of the impactor was performed in the same manner as before and the particle collection efficiency curve shown in Figure 9. This shows the cutpoint is at 0.8 µm and the sharpness-of-cut, as defined by the geometric standard deviation, was found to be 1.15, the same as the impactor for the second sampler.

FIELD STUDIES

Besides laboratory evaluations, the personal sampler has also been evaluated in comprehensive sampling studies performed in three underground coal mines. Twelve personal diesel aerosol samplers based on the 10 mm nylon cyclone/0.8 µm impactor design were constructed and tested in three underground coal mines to determine the applicability of using a personal sampler to measure the concentration of the diesel exhaust and mineral dust particles in the respirable size range. Two to five personal samplers were located adjacent to a MOUDI so that the personal sampler data could be compared to MOUDI data. Samplers were also deployed in five different locations of a continuous mining section utilizing diesel-powered ram cars. These locations were the intake entry, haulageway, return entry, on the ram cars, and in a few instances, worn by one of the research personnel.

Comparison of Personal Sampler Data with MOUDI Data

In tests where the data from the personal samplers and the MOUDI were compared, the MOUDI sampling period was exactly the same as that of the personal samplers with the sampling periods varying from 3 to 6 hours. The sampling periods were selected to correspond to periods with sustained mining activity.

The mass size distribution data obtained from the MOUDI were analyzed to determine the BMRC respirable mass concentration and the respirable mass less than and greater than 0.8 µm. By applying the respirable curve to the size distribution, as shown in Figure 12, it is possible to calculate the concentration of the respirable fraction. By further dividing the size distribution at 0.8 µm, it is possible to determine what quantities should be collected on the impaction plate and the afterfilter of the personal sampler.

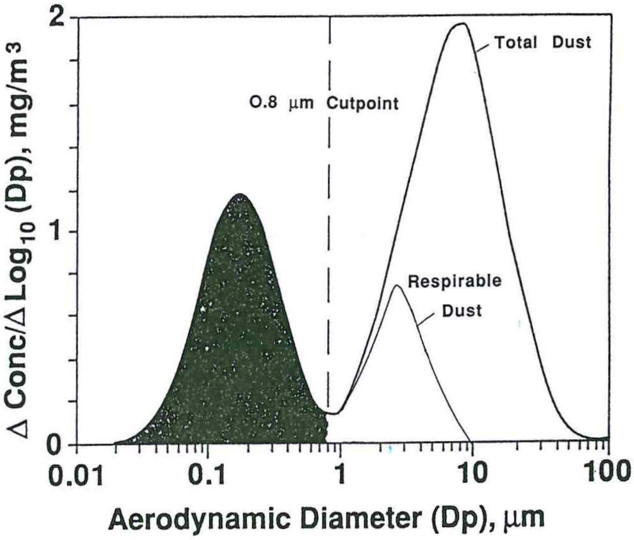

Figure 12. Illustration of the particle size distributions for the total dust, respirable dust and mass fraction less than 0.8 μm.

The BMRC respirable mass concentration for the personal sampler was computed by summing the mass of particles collected on the afterfilter and the 0.8 μm impactor substrate. BMRC respirable mass for particles greater than 0.8 μm was computed by multiplying the mass concentration by the 1.38 factor used by MSHA (Tomb et al., 1973). Data from 30 personal sampler tests were compared to those obtained with 16 simultaneous tests with the MOUDI. Six of these data sets were from tests conducted in the return airways and ten from tests conducted in the haulageway of three different mines, two eastern and one western. The comparison of the data is shown in Table 3. These data indicate, on the average, mass concentration as determined with the personal sampler compared to within 11% of those computed from the MOUDI data. This is considered close agreement since the coefficient of variation for these data is approximately 20%. The quantity of mass collected on the impactor substrate ranged from 0.06 to 0.6 mg and the variation in the ratio of material less than 0.8 μm was found to be independent of substrate mass loadings. Thus, the personal samplers showed no evidence of particle overloading.

Table 3

Comparison of Diesel Personal Sampler Data with MOUDI Data

	Diesel Sampler/MOUDI*		
Mine	<0.8 μm	>0.8 μm	Respirable
J	1.09	0.90	0.92
K	0.96	0.98	0.98
L	1.14	0.80	0.97
Ave	1.06	0.89	0.98

*Corrected for average particle loss of 10% in MOUDI.

**Based on 30 data sets from the 3 mines.

Field Evaluation

Table 4 and Figures 13 and 14 show a comparison of the average respirable mass concentration derived from the personal sampler as well as the mass concentration in each of the two size fractions, i.e. respirable particles >0.8 μm and <0.8 μm. The data include the averages at five locations in three mines: the intake entry, haulageway, return entry, ram cars and one researcher. The researcher spent time at all

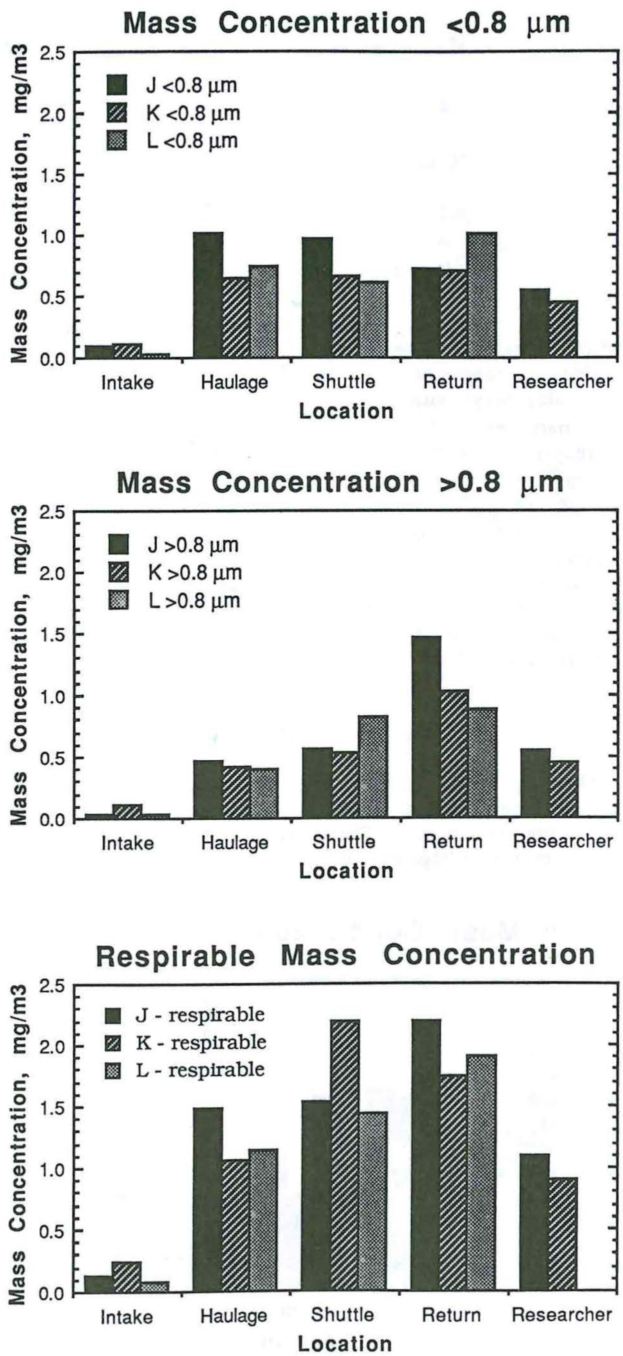

Figure 13. Average mass concentration measured at 4 locations in each of 3 mines for the <0.8 μm, >0.8μm and respirable particles.

Table 4

Grand Average
Aerosol Mass Concentration Data
from Personal Diesel Aerosol Sampler

Location	Mass Concentration, mg/m³						Fraction
	<0.8 µm		>0.8 µm		Respirable		<0.8 µm/
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Respirable
Intake Entry	0.084	0.041	0.063	0.050	0.147	0.080	57%
Haulageway	0.80	0.19	0.43	0.032	1.23	0.23	65%
Ram Car	0.74	0.19	0.98	0.50	1.72	0.42	43%
Return Entry	0.82	0.17	1.13	0.30	1.95	0.23	42%
Researcher	0.50	0.07	0.50	0.07	1.00	0.14	50%

[1]Average for 3 mines
[2]Based on BMRC respirable dust criteria

test sites. The respirable fraction is based on the BMRC criteria. These data indicate that the largest fraction of respirable particles less than 0.8 µm is in the haulageway with 65%. The mass concentration of these particles is 0.74 mg/m^3. The mass concentration of respirable particles <0.8 µm ranged from 0.084 mg/m^3 in the intake entry, which is primarily affected by use of diesel-powered outby equipment, to 0.82 mg/m^3 in the return, which results from diesel-powered equipment in the working sections. A comparison of the ram car and haulageway data show that the mass concentration of the particles <0.8 µm was similar, but that the concentration of particles >0.8 µm about 40% higher at the ram car.

CONCLUSIONS

Three personal diesel aerosol samplers have been designed and tested in laboratory and underground coal mine settings. These three-stage samplers use size selective sampling to separate respirable mineral

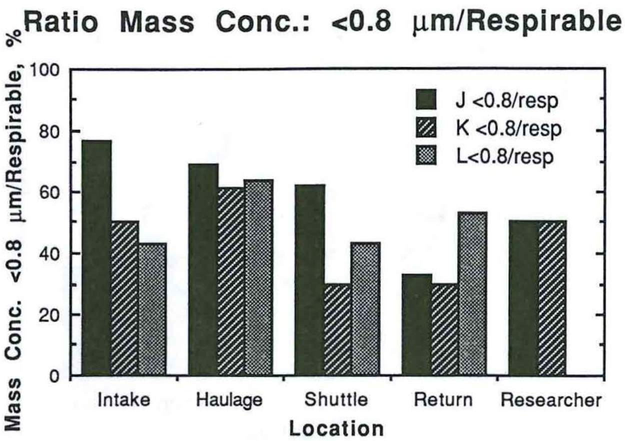

Figure 14. Ratio of the mass concentration of particle <0.8 µm to the respirable particles as measured at 4 locations in each of 3 mines.

dust and diesel exhaust particles into two size fractions at 0.8 µm. The premise is that the material <0.8 µm is diesel exhaust particles while the portion >0.8 µm is mineral matter.

A comparative study of the particle mass concentration data obtained from field studies showed good agreement between those data obtained with the personal sampler and those computed from the MOUDI size distribution data. This comparison holds for particle mass fractions less than and greater than 0.8 µm.

Lastly, the sampler was used to obtain mass concentration data at several locations in the working sections of three underground coal mines utilizing diesel-powered equipment. From the standpoint of worker exposure, this study shows that the haulageways have the highest concentrations of <0.8 µm particles . The data show the average fraction of respirable particles less than 0.8 µm in the haulageways to be 65% with a mass concentration of 0.74 mg/m^3.

ACKNOWLEDGEMENTS

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REFERENCES

Cantrell, B. K., 1987, "Source Apportionment Analysis Applied to Mine Dust Aerosols: Coal Dust and Diesel Emissions Aerosol Measurement", Proceedings of the 3rd U.S. Mine Ventilation Symp., Soc. Mining Eng., University Park, PA, Oct. 12-14, pp. 495-501.

Cantrell, B. K. and Rubow, K. L.,1990, "Development of Personal Diesel Aerosol Sampler Design and Performance Criteria", Annual Meeting of Society of Mining, Metallurgy and Exploration, Salt Lake City, Prepaper No. 90-74.

Marple, V. A., 1970, "Fundamental Study of Inertial Impactors", Ph.D. thesis, University of Minnesota, Minneapolis, MN.

Marple, V. A., Kittelson, D. B., Rubow, K. L. and Fang, C. P., 1986, "Methods for the Selective Sampling of Diesel Particulates in Mine Dust Aerosols", Final Report, Bureau of Mines Contract No. J0145022, Univ. MN, BuMines OFR 44-87, 94 pp.; NITS PB 88-130810.

Marple, V. A. and McCormack, J. E., 1983, "Personal Sampling Impactor with Respirable Aerosol Penetration Characteristics", Am. Ind. Hyg. Assoc. J. 44:916-922.

Marple, V. A. and Rubow, K. L., 1983, "Impactors for Respirable Dust Sampling", Aerosols in the Mining and Industrial Work Environment, Marple, V. A. and Liu, B. Y. H., eds., Ann Arbor Sciences Publishers, Inc., Ann Arbor, MI, Vol III, pp. 847-860.

Marple, V. A. and Rubow, K. L., 1986, "Theory and Design Guidelines", Cascade Impactor: Sampling and Data Analysis, Lodge, J. P. and Chan, T. L., eds., American Industrial Hygiene Association, Chap 4, pp. 79-101.

Marple, V. A., Rubow, K. L. and Behm, S. M., 1991, "A Microorifice Uniform Deposit Impactor (MOUDI)", Aerosol Sci. and Technol., in press.

Mine Safety and Health Administration, 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, 90 pp.

National Institute of Occupational Safety and Health, 1988, "Carcinogenic Effects of Exposure to Diesel Exhaust," Current Intelligence Bulletin 50, Dept. Health and Human Services (NIOSH) Publ. 88-116, 30 pp.

Rader, D. J. and Marple, V. A., 1985, "Effect of UltraStokesian Drag and Particle Interception on Impactor Characteristics", Aerosol Sci. and Technol. 4:141-156.

Rubow, K. L., Cantrell, B. K. and Marple, V. A., 1990, "Measurement of Coal Dust and Diesel Aerosols in Underground Mines", Proceedings of the VIIth International Pneumoconioses Conference, Pittsburgh, PA, Dept. Health and Human Services DHHS (NIOSH) Publ. No. 90-108 Part I, pp. 645-650.

Rubow, K. L. and Marple, V. A., 1988, "Determining the Size Distribution of Coal/Diesel Aerosol Mixtures with the Microorifice Uniform Deposit Impactor", Respirable Dust in the Mineral Industries: Health Effects, Characterization and Control, R. L. Frantz and R. V. Ramani, eds, pp. 71-78.

Rubow, K. L., Marple, V. A., Olin, J. and McCawley, M. A., 1987, "A Personal Cascade Impactor: Design, Evaluation and Calibration", Am. Ind. Hyg. Assoc. J. 48:532-538.

Tomb, T. F., Treaftis, H. N., Mundall, R. L. and Parobeck, P. S., 1973, "Comparison of Respirable Dust Concentrations Measured with MRE and Modified Personal Gravimetric Sampling Equipment", BuMines Report of Investigation 7772.

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