Sampling Results of the Improved SKC Diesel Particulate Matter Cassette

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Diesel particulate matter (DPM) samples from underground metal/nonmetal mines are collected on quartz fiber filters and measured for carbon content using National Institute for Occupational Safety and Health Method 5040. If size-selective samplers are not used to collect DPM in the presence of carbonaceous ore dust, both the ore dust and DPM will collect on the quartz filters, causing the carbon attributed to DPM to be artificially high. Because the DPM particle size is much smaller than that of mechanically generated mine dust aerosols, it can be separated from the larger mine dust aerosol by a single-stage impactor. The SKC DPM cassette is a single-stage impactor designed to collect only DPM aerosols in the presence of carbonaceous mine ore aerosols, which are commonly found in underground nonmetal mines. However, there is limited data on how efficiently the SKC DPM cassette can collect DPM in the presence of ore dust. In this study we investigated the ability of the SKC DPM cassette to collect DPM while segregating ore dust from the sample. We found that the SKC DPM cassette accurately collected DPM. In the presence of carbon-based ore aerosols having an average concentration of 8 mg/m^3, no ore dust was detected on SKC DPM cassette filters. We did discover a problem: the surface areas of the DPM deposits on SKC DPM cassettes, manufactured prior to August 2002 were inconsistent. To correct this problem, SKC modified the cassette. The new cassette produced, with 99% confidence, a range of DPM deposit areas between 8.05 and 8.28 cm^2, a difference of less than 3%.

Keywords carbon, diesel particulate matter, dust, impactor

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The Mine Safety and Health Administration (MSHA) rule governing diesel particulate matter (DPM) exposures in metal and nonmetal mines cites total carbon (TC)—a summation of elemental carbon (EC) and organic carbon (OC) obtained by National Institute for Occupational Safety and Health (NIOSH) Method 5040—as a surrogate for determining DPM exposures.(1–4) MSHA personnel use the 1973 sampling criteria outlined by the American Conference of Government Industrial Hygienists (ACGIH®) for collecting compliance-based respirable and inhalation samples in metal/nonmetal mines.(5,6)

DPM is within the aerodynamic particle size range of the samplers used for respirable and inhalable dust measurements. Therefore, if a sampler used by MSHA to collect inhalable or respirable dust samples in underground metal/nonmetal mines was used to collect DPM, both the DPM and mine ore dust would accumulate on the sample filter. When sampling for DPM in carbonaceous mines, the carbon attributed to DPM would thus be artificially high.

To solve this problem, U.S. Bureau of Mines (BOM) researchers developed a size-selective sampler that allowed only particulate matter with an aerodynamic diameter less than 0.8 μm to pass through the device and be collected on a downstream filter.(7–9) Since the aerodynamic diameter of most ore dust is typically greater than 0.8 μm, and the aerodynamic diameter of most DPM is less than 0.8 μm,(7) the impactor segregates most of the DPM from most of the ore dust and permits only DPM to be collected. Research results show that the classification efficacy, in preventing coal dust to pass through this impactor, is greater than 90%.(9)Currently, SKC Inc. (Eighty Four, Pa.) manufactures the DPM cassette that was designed from the BOM impactor. It has the same cut point and impaction design as the BOM impactor. This device is being used to collect DPM in noncoal mines.

Data confirming the accuracy of the SKC DPM cassette is limited. Some in the mining industry have brought up concerns with SKC DPM cassette performance and possible defects.(10) In this study we examined the performance of the SKC DPM cassette. We first determined the ability of the cassette to collect DPM by comparing DPM samples collected with SKC DPM cassettes with respirable samples (which represent the DPM concentration "standard" since they will collect all of the DPM). We performed these tests in the laboratory and at field locations where the only airborne particulate was DPM. We then tested the efficacy of SKC DPM cassettes to avoid mineral dust by placing the cassettes in a laboratory chamber having an atmosphere that contained only mineral dust and measuring the quantity of mineral dust collected on the filters.

Early in this evaluation we discovered problems with the SKC DPM cassette. In many experiments, the surface areas of DPM deposited on the filters were irregular. These areas also varied between cassettes. The discoveries forced the research protocol to be modified. First, the irregularly shaped DPM deposit area of every SKC DPM cassette filter had to be determined, since the area was different for each filter. Because the deposit area is used to calculate the aerosol concentration, any measurement error will cause inaccurate results when calculating the concentration of TC and EC. Second, the difficulty associated with measuring the irregular shapes could result in some error when determining deposit areas.

To solve the problem, the SKC DPM cassette design was modified to produce a consistent DPM deposit area. Following the modifications, we performed tests to verify that the SKC DPM cassette produced a reliable and uniform deposit area by measuring the deposit areas from DPM samples collected in the laboratory and in the field.

METHODS

Sampler Preparation

The following sections describe the preparation required for each sampler type used in both laboratory and field experiments.

Respirable Sampler/Gravimetric Analysis

This sampler was the same setup used by MSHA to collect respirable samples for dust containing silica (a PVC filter behind a Dorr-Oliver cyclone having a D_{50} cut point of 3.5 μm at a 1.7 L/min flow rate). This methodology is also described by ACGIH®.[5,6]

Gravimetric samples were equilibrated and pre- and post-weighed in a controlled environment that was set at 72°F and 50% relative humidity. Balance precision was better than 5 μg. Blank filters were also weighed before and after each set of samples.

Respirable Sampler/Carbon Analysis

Two prebaked quartz fiber filters were inserted in tandem (a second quartz filter is placed behind the primary filter) into a Mine Safety Appliances Company (MSA) three-piece cassette. Each cassette was sealed with an air compressing system and was attached to a Dorr-Oliver cyclone.

BOM Impactor/Gravimetric Analysis

A BOM aluminum impactor was placed in series between the Dorr-Oliver cyclone and the filter cassette that was described above. Since the BOM aluminum impactor only allows particles with an aerodynamic diameter less than 0.8 μm to pass through unimpeded, only submicrometer particles should contribute to the mass increase of the filter. The particles greater than 0.8 μm collect on a substrate of the impactor and may overload the impaction plate when exposed to high levels of dust. Dust particles greater than 3.5 μm can be eliminated by the cyclone and reduce the chance of overloading the impactor.

BOM Impactor/Carbon Analysis

Two quartz fiber filters were baked for at least 2 hours at 800°C to drive off any OC. These filters were inserted, in tandem, into a three-piece MSA cassette. Each cassette was sealed to prevent air leakage. The MSA cassette was placed immediately downstream of a BOM aluminum impactor and a Dorr-Oliver cyclone.

Design I SKC DPM Cassette/Carbon Analysis

The SKC DPM cassette (Figure 1a) was placed in series downstream of a Dorr-Oliver cyclone. The SKC DPM cassette contained two quartz filters in tandem behind an impactor with 0.8-μm cut point. Each quartz filter was wrapped with an aluminum shield as shown in Figure 1b.

Design II SKC DPM Cassette/Carbon Analysis

This design is similar to Design I except that the aluminum shield is removed. Additionally, a metal gasket is placed in front of the quartz filters as shown in Figure 1c.

Laboratory Experimental Error

An aerosol chamber[11] capable of dispersing DPM and dust uniformly throughout its midsectional volume was used in all laboratory evaluations. Ideally, samplers located in the same plane should be sampling equal DPM mass. However, due to spatial variation, small errors were possible. In addition, the NIOSH Method 5040 analytical method contributed to experimental error. Conversely, the sampler airflow should not be a significant contributor to error since critical orifices, whose fluctuations were negligible, controlled the airflows through all samplers used for all chamber evaluations. Flow rates of the critical orifices were checked periodically with an electronic soap film flow meter calibration device (Gilibrator, Gillian Instrument Group, West Caldwell, N.J.).

The following experiments were run to determine the experimental error when collecting DPM in the chamber. Three respirable samplers with quartz filters for carbon analysis were placed at the same height inside the aerosol chamber. Exhaust emissions from a Kubota diesel engine attached to a 10 kW generator provided DPM in the chamber. Air samples were taken within the chamber for a specific duration. Each sample was then analyzed using NIOSH Method 5040 to determine the uniformity of DPM dispersion across the chamber. This experiment was repeated 11 additional times for different DPM concentrations and different engine loads yielding 12 triplicate samples representing different OC-to-TC ratios.

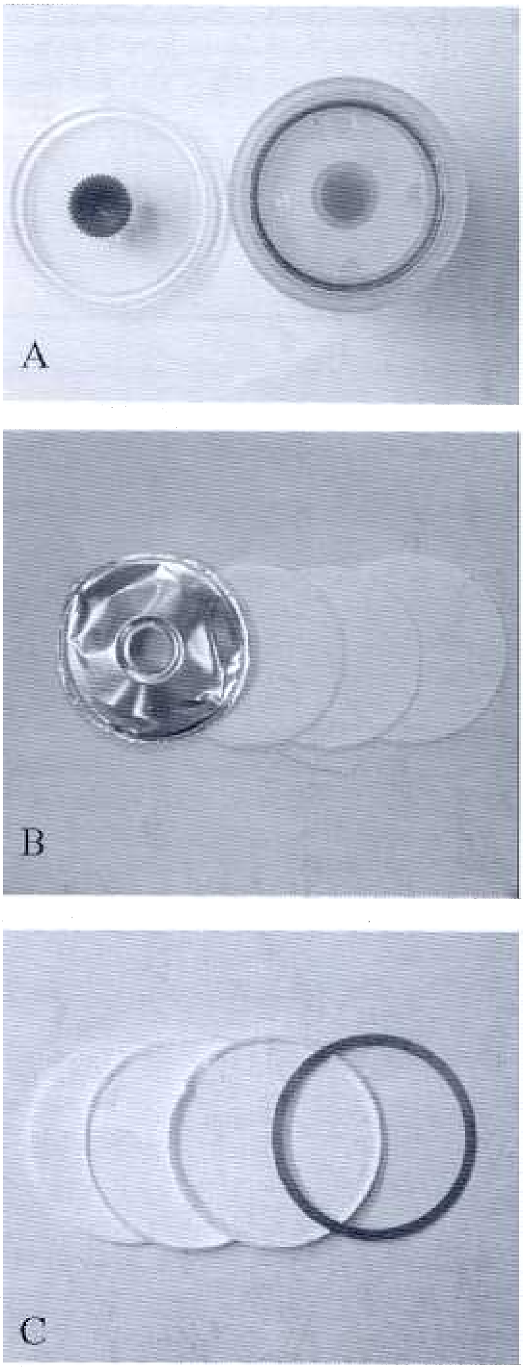

FIGURE 1. SKC DPM cassette: (A) The main casing used for both Design I and Design II. (B) Design I (manufactured before August 2002) and (C) Design II (instead of aluminum shield, a metal gasket followed by two quartz filters and a backing pad are used in this design)

DPM Collection Efficacy

Laboratory Experiments

To determine the efficacy of the SKC DPM cassette to collect DPM, three SKC Design I or Design II DPM cassettes, three BOM impactors (carbon analysis), and four respirable samplers (carbon analysis) were placed at the same height within the aerosol chamber. Because the deposit areas varied among the Design I samplers, we measured the deposit area of each cassette.

For at least an hour, an aerosol chamber sample was collected for carbon analysis at 1.7 L/min by one of the respirable samplers. At the end of the hour, the sampler was removed from the chamber. This sample was considered the chamber blank. It quantified the background OC present in the chamber air before diesel exhaust was added.

The chamber was sealed again and the Kubota diesel engine was started. A tapered element oscillating microbalance (TEOM), designed to measure the ambient particulate mass in real time, was used to monitor diesel exhaust concentration. When the TEOM indicated steady DPM levels inside the aerosol chamber, air pumps drawing on the critical orifices connected to the various samplers were switched on. Sampling continued until a DPM filter loading of between 10 and 40 $\mu g/cm^2$ was attained, as estimated by the TEOM. The air pumps were switched off and the DPM was permitted to exhaust from the chamber. The samples were then removed and plastic plugs inserted into each filter cassette's inlet and outlet to isolate the cassette from the surrounding environment. The above procedure was repeated under different engine loads to achieve a variety of OC-to-TC ratios. Finally, each sample was analyzed for EC and TC using NIOSH Method 5040.

Field Experiments

The ability of the SKC DPM cassette to collect DPM was also tested in an underground mine. In Mine 1, three samples using SKC DPM cassettes and three samples using respirable samplers (carbon analysis) were collected with MSA Elf sampling pumps operating at 2 L/min in an isolated area, a location where no ore dust was produced. The SKC DPM cassette was designed to collect DPM at flow rates of 1.7 or 2 L/min. Impactor cut points were 0.73 μm at 2 L/min and 0.8 μm at 1.7 L/min. MSHA uses a flow rate of 1.7 L/min when sampling aerosols in metal/nonmetal mines and 2 L/min when sampling aerosols in coal mines. The metal/nonmetal regulations were based on the 1973 ACGIH sampling criterion,[5,6] and the coal mine regulations were based on the British Medical Research Council sampling criterion.[12] The 2 L/min flow rate, used in coal mines, was believed to give a better estimate, with a correction factor, of the Mining Research Establishment (London, England) gravimetric dust sampler, which has a four-channel horizontal elutriator. This field data was originally obtained to investigate DPM concentrations in coal mines, so a 2 L/min flow rate was used.

Since the cut point at 2 L/min is smaller than at 1.7 L/min, DPM collection will potentially be more hindered when using 2 L/min rather than 1.7 L/min. Therefore, if most of the DPM is collected at 2 L/min, one would expect even better DPM collection efficiency using 1.7 L/min. When looking at the size distribution of DPM, there does not seem to be a large portion of DPM within 0.73 and 0.8 μm to make a significant difference when using the two different flow rates.[7]

TABLE I. Comparison of DPM Concentrations from SKC and Respirable Samplers in Laboratory Chamber

Sample Set	SKC DPM Cassette EC (μg/m^3)^A	Respirable EC (μg/m^3)^A	SKC DPM Cassette TC (μg/m^3)^A	Respirable TC (μg/m^3)^A	CV^B (%) Between SKC and Respirable for EC	CV^C (%) Between SKC and Respirable for TC
	201	217	242	261	5.4	5.3
	214	225	261	272	3.5	2.9
	274	290	321	344	4.0	4.9
4	302	323	358	360	4.8	0.4
5	737	794	1041	129	5.3	5.7

Each value represents the average of triplicate samples.
CV = (standard deviation (EC [SKC], EC [respirable])/average (EC [SKC], EC [respirable])) × 100, e.g., sample set 1: CV for EC = standard deviation (201 :17)/average (201, 217) × 100.
CV for TC is calculated the same way as the EC.
Design I SKC DPM cassettes were used with this experiment. Design II SKC DPM cassettes were used for the other experiments.

To generate DPM, diesel-powered mining machines were driven back and forth in the isolated area. Each procedure was repeated five times for different vehicles and loads as well as with and without engine exhaust filters. All samples were analyzed for carbon using NIOSH Method 5040.

Ore Dust Collection Efficiency

Laboratory Experiments

To determine how well the SKC DPM cassette rejects non-DPM dusts, we modified the experiments described above by introducing ore dust instead of DPM into the aerosol chamber for 3 hours at an average concentration of 8 mg/m^3. In addition to three SKC Design I or Design II DPM cassettes, one BOM impactor (carbon analysis), and four respirable samplers (carbon analysis) that were mentioned in the previous chamber experiment, three respirable gravimetric samplers and three BOM impactor/gravimetric samplers were also placed into the chamber. The ore dust consisted of actual bulk ore samples that were subsequently crushed at Pennsylvania State University and processed to have the same size distribution as the aerosol found at that particular nonmetal mine. The dust was introduced to the chamber by a fluidized bed aerosol generator.

A comparison of the gravimetric mass collected on the respirable dust filters with that collected on the filters following the BOM impactor yields the effectiveness of the BOM impactor to avoid respirable ore dust from this mine. Since the SKC DPM cassette was designed from the BOM impactor, the efficacy of the BOM impactor should be similar to that of the SKC DPM cassette. SKC DPM cassettes themselves cannot be used in this experiment, since their filters cannot be removed for preweighing. Carbonate carbon analysis of the SKC DPM cassettes would show if a significant amount of ore dust collected on the SKC DPM cassette (described in more detail in the Ore Dust Separation section).

Three respirable samplers with quartz filters (carbon samplers) were used to determine the carbon mass fraction in the ore dust. We determined the percentage of carbon in the ore dust by comparing the carbon obtained through NIOSH Method 5040 analysis of the respirable quartz filter samples to the gravimetric mass of the respirable gravimetric samples. A Marple Series 290 Personal multistage cascade impactor (Andersen Instruments, Smyrna, Ga.) was run at 2 L/min to establish the dust particle size distribution.

SKC Cassette DPM Deposition

To determine the DPM deposition patterns of the Design I SKC DPM cassettes, we collected air samples from two different mines: Mine 1, described previously, and Mine 2, a metal mine where samples were collected at a 1.7 L/min flow rate. The deposit area of each filter was measured and photographed. For each filter, the surface area of DPM deposit was determined by using a calibrated caliper to measure two deposit diameters that were oriented perpendicular to each other. The average of the two diameters was used to compute the approximate area of the deposit using the equation for the area of a circle.

We determined DPM deposition patterns of the Design II SKC DPM cassettes by collecting DPM on SKC DPM cassettes in the laboratory chamber using a procedure similar

TABLE II. Field Data Comparing SKC DPM Cassettes with Respirable Samplers

Sample Set	SKC DPM Cassettes EC (μg/m^3)^A	Respirable EC (μg/m^3)^A	Between SKC and Respirable CV (%)^B	Experimental Error CV (%)
1	409	410	0.2	12
2	670	725	5.6	12
3	335	399	12.3	12
4	3244	3347	2.2	12
5	77	84	6.1	12

^{A}Each value represents the average of triplicate samples.
^{B}CV = (standard deviation (EC [SKC], EC [respirable])/average (EC [SKC], EC [respirable])) × 100, e.g., sample set 1: CV for EC = standard deviation (409, 410)/average (409, 410) × 100.

TABLE III. Particle Size Distribution for Ore Dust Aerosolized into Chamber

Stage	Cut Point (μm)	Preweight (mg)	Postweight (mg)	Correction Factor[A]	Corrected mg Dust	%
	21.30	25.46	25.52	0.52	0.10	3.51
2	14.80	25.84	25.89	0.61	0.08	2.71
3	9.80	25.89	26.02	0.78	0.17	5.75
4	6.00	25.54	25.98	0.89	0.49	16.74
5	3.50	25.32	26.22	0.95	0.95	32.89
6	1.55	25.04	25.93	0.96	0.93	32.04
7	0.93	25.63	25.80	0.97	0.18	6.04
8	0.52	25.21	25.21	0.99	0.00	0.00
Final	0.00	13.49	13.50	1.00	0.01	0.31
				Total	2.90	

[A]The correction factor is a factor to correct for sampling efficiency and internal losses when using the Marple cascade impactor. The mass is divided correction factor on the impactor stage to give the corrected mass.

to that outlined in the DPM Collection Efficacy, Laboratory Experiments section. Each filter was photographed, and the deposit area was measured as described above. The procedure for measuring the deposit area was then followed for DPM samples taken from several mines with SKC DPM cassettes. Field samples using a 1.7 L/min flow rate were taken at different locations in several mines. The deposit areas were measured for each filter. In total, 94 samples were collected to determine the variance of the deposit area.

RESULTS AND DISCUSSION

Interferences

In the laboratory experiments when just DPM was released into the chamber, no sources of EC or TC particulate other than DPM were present. This was shown by the concentrations of EC and TC in the chamber blanks, corrected for vapor phase OC, being below the limit of detection. Vapor phase OC did adsorb onto the quartz filter and caused a positive bias of TC from the DPM results. OC levels on a second filter, inserted in tandem with the first or primary filter, were subtracted from the primary filter OC values to correct for the vapor phase OC.[13,14] In theory, the second filter should not be exposed to the aerosol OC but should adsorb the same amount of vapor phase OC as the primary filter.

In the field study collecting only DPM, no dust was present in the isolated zone; therefore, no sources of EC other than DPM were present in the isolated zone atmosphere. EC results from DPM collected by the SKC DPM cassettes were compared with DPM EC collected by the conventional respirable samplers to indicate whether the SKC DPM cassettes were collecting all of the DPM.

Coefficient of Variation

Laboratory Experiments

To determine the variation of samples in the laboratory chamber, a coefficient of variance (CV) was calculated for the NIOSH Method 5040 results of the three respirable samplers in each of 12 experiments. The 12 CVs were then pooled according to *NIOSH Guidelines for Air Sampling and Analytical Method Development and Evaluation*[15] to obtain an 95% upper confidence limit for an experimental error CV. The Bartlett test was then performed on the data to confirm homogeneity of the data set. The 95% upper confidence limit for experimental-error CV was 7% for EC measurements and 6% for TC measurements.

Field Experiments

Field sampling error was found by taking the root mean square (rms) of three possible sources of error: NIOSH Method 5040, pump flow, and deposit area determination. A NIOSH Method 5040 analytical error CV of 10% (95% pooled CV of 50 DPM samples taken from mines) for EC was taken from the literature.[16] We used a CV of 5% for pump flow error.

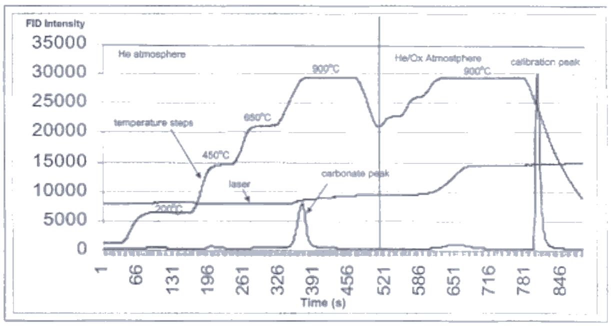

FIGURE 2. NIOSH Method 5040 thermogram of mine ore dust from a respirable sampler: In NIOSH Method 5040, the temperature is ramped up in four steps in a helium atmosphere where carbonate carbon will evolve around 870°C. The laser is used to read transmission and correct for charring. Elemental carbon will evolve when oxygen is added to the gas mixture. As can be seen by the thermogram, most of the carbon in ore evolved at 900°C in the helium part of the analysis. This is the carbonate peak. This sharp peak is not seen in a thermogram of just DPM.

TABLE IV. Laboratory Chamber Data

Sample Type	Total Carbon Concentrations from Mineral Dust OC ($\mu g/m^3$)	EC ($\mu g/m^3$)	CC ($\mu g/m^3$)	TC ($\mu g/m^3$)	LOD ($\mu g/m^3$)
Respirable[A]	97.49	133.77	394.57	625.84	5.59
SKC impactors[A]	9.38	4.41	<3.77	17.21	3.77
BOM impactors[B]	10.05	<5.59	<5.59	15.35	5.59

[A]Each value represents the average of triplicate samples.
[B]These results are from a single sampler.

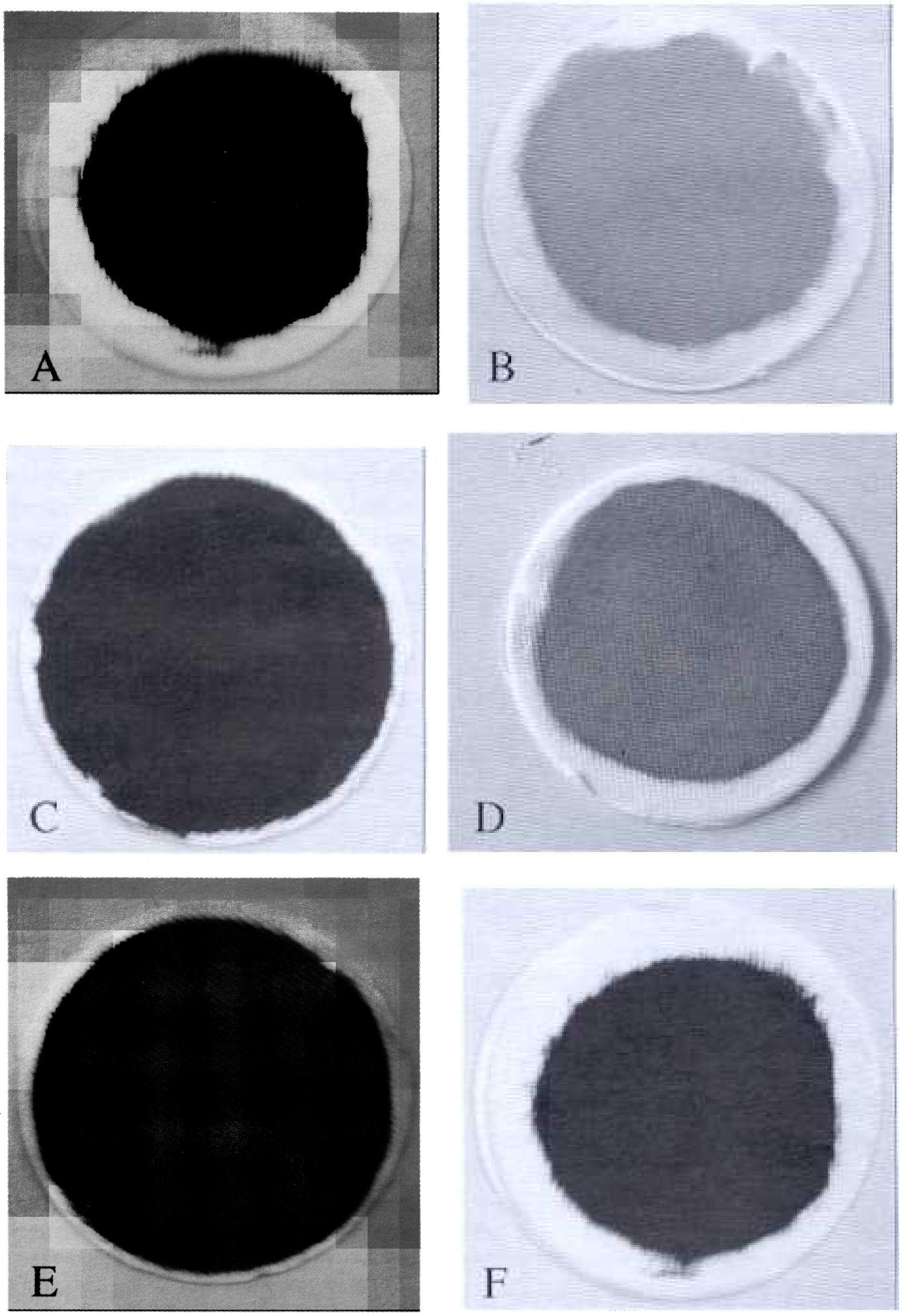

FIGURE 3. Filters that collected DPM from Design I SKC DPM cassette

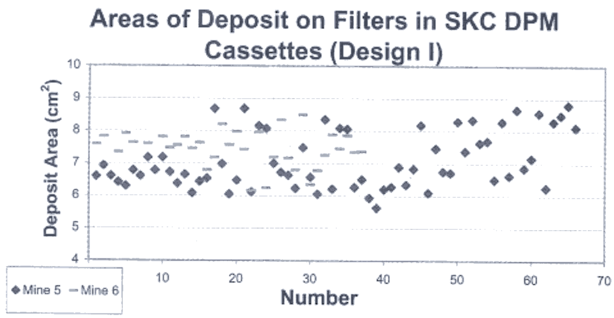

FIGURE 4. Areas of deposit on filters from SKC DPM cassette Design I.

The error in the deposit area was calculated by measuring the diameter of the same deposit area several times and calculating a CV between measurements. The CVs of the measurements from several filters were pooled according to *NIOSH Guidelines for Air Sampling and Analytical Method Development and Evaluation,* and the percent error in measuring the deposit area was about 4%. The rms of the three CVs was 12%.

SKC Cassette DPM Performance

SKC DPM cassettes were found to be very efficient for sampling DPM. In the laboratory experiments where the Design I and Design II SKC DPM cassettes and respirable samplers were exposed to DPM, the variation between EC and TC concentrations of the two sampler types were within the errors of the experiment (the CV between samplers was less than the 95% upper confidence limit for the experimental error), as shown in Table I.

As seen in Table II, field tests also showed that the SKC DPM cassettes collected DPM efficiently. The variation between the EC concentrations derived from air samples containing DPM collected with the Design I SKC DPM cassettes and with the respirable samplers in Mine 1 were less than or equal to the experimental error variation.

EC concentrations were always lower when collected with the SKC DPM cassette. This may have been because agglomerated DPM particles did not pass through the cassette. Nevertheless, EC concentrations measured by the respirable samplers and the SKC DPM cassettes were still within experimental error.

Ore Dust Separation

The SKC DPM cassette also prevented most of the airborne ore dust from passing through the classifier and collecting on the filter. As seen in Table III, about 6% (190 μg) of the ore in the chamber had a particle diameter less than 1.55 μm and approximately 0.31% (10 μg) was less than 0.5 μm. The BOM impactor/gravimetric samplers collected only about 2% (40 μg) of the 2.26 mg respirable dust load. This device was 98% efficient in preventing ore dust from collecting on the filter. We would expect similar results from the SKC DPM cassettes because the two samplers have the same cut point and similar designs.

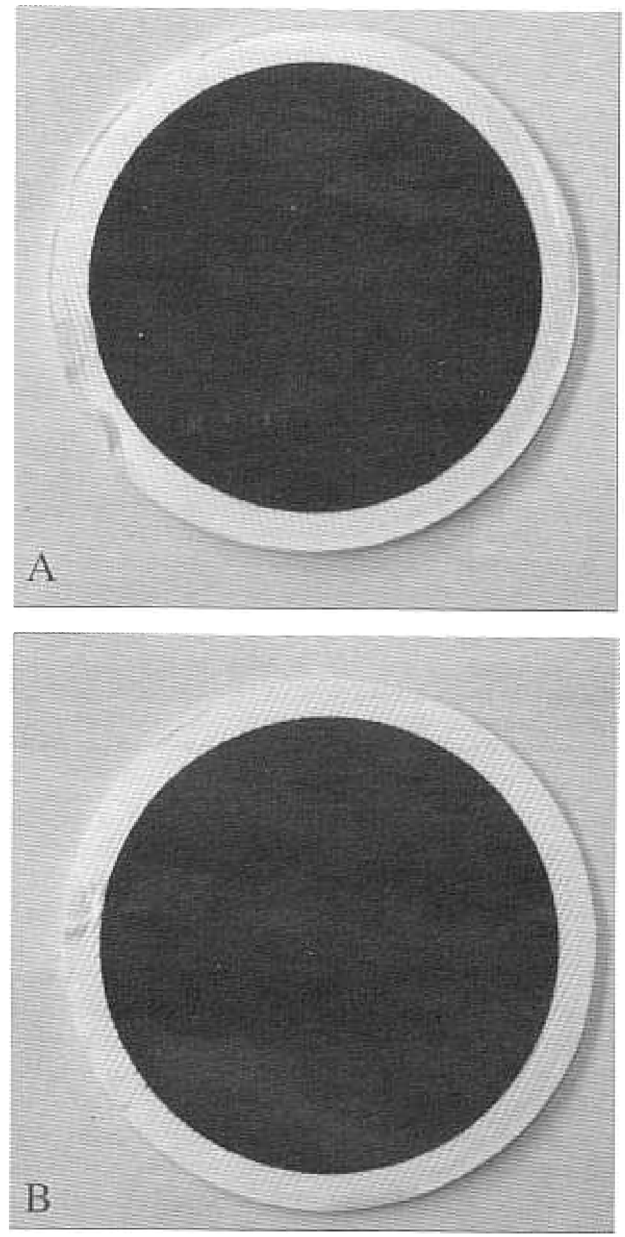

FIGURE 5. Pictures of filters that collected DPM with Design II of the SKC DPM cassette.

Carbon analysis showed similar results. In NIOSH Method 5040, the temperature is ramped up in four steps in a helium atmosphere to evolve all of the OC. When carbonate is present, a sharp peak should be detected when the temperature is about 870°C. This peak is absent if DPM is the only particulate present on the filter.

The carbon present in the ore consisted mostly of carbonate (CC), for the ore dust was 8.49% carbon with 63% of that carbon being carbonate. Because a significant amount of ore dust reached the filter on the respirable dust sampler, a CC peak is readily visible on the carbon analysis thermogram, as shown in Figure 2. In Table IV, CC was detected when respirable

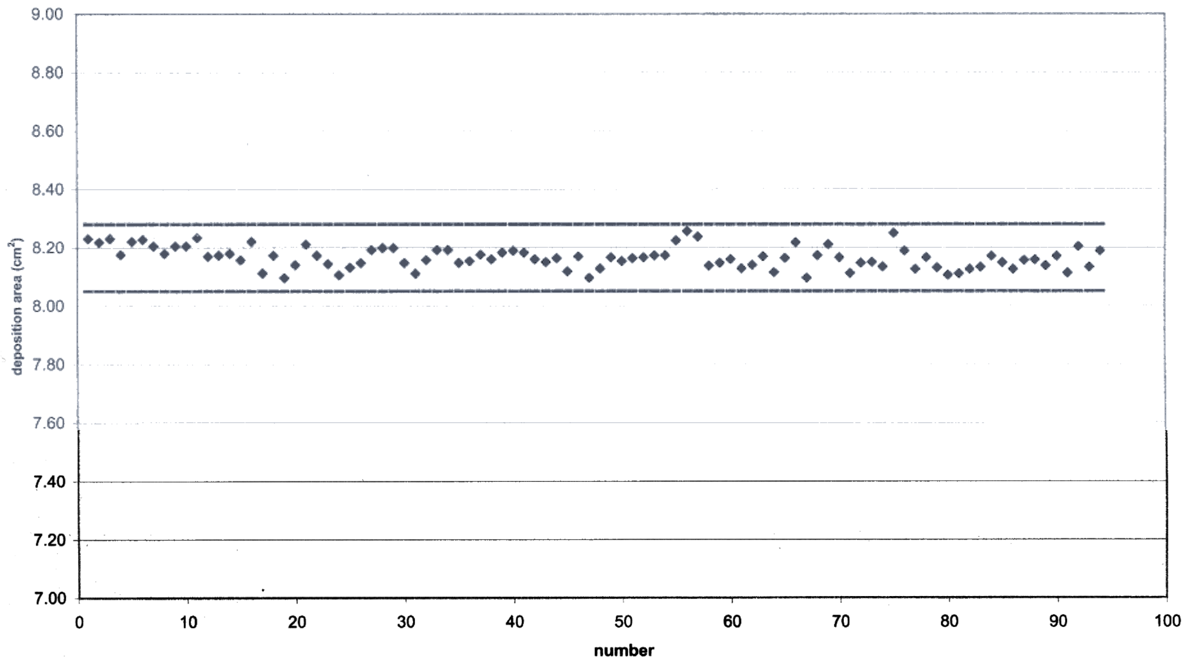

FIGURE 6. Ninety-four deposit areas of filters from Design II SKC DPM cassette (field and laboratory samples). The dotted lines are the upper and lower control limits.

samplers were used, but no CC above the limit of detection (LOD) was found on filters taken from BOM impactors or SKC DPM cassettes. The LOD for NIOSH Method 5040 is 0.2 μg/cm^2 per filter section for a 1.5 cm^2 punch.[4] In Table IV, this LOD was converted to concentration.

These laboratory results confirmed field data obtained in an MSHA four-mine study.[9] MSHA personnel collected samples from four different metal and nonmetal mines. Samples were taken from four areas of each mine. When researchers used the BOM impactor, the mass detected was about 94% less than that found on respirable sampler filters. Ideally, SKC DPM cassettes should behave in a similar manner. Ore samples from operations mining carbonaceous ores had a high percentage of CC; therefore, if ore dust was penetrating the impactor and causing an artificial increase in the carbon detected, a CC peak should have been evident in the thermogram. However, when the SKC DPM cassette was used, no carbonate peak and no TC values significantly above blank values were seen.

Design I SKC Cassette DPM Deposit Area

A problem was observed when using the Design I SKC DPM cassettes. Figure 3 shows that the areas of DPM deposition when using Design I SKC DPM cassettes were often irregular instead of circular. As seen in Figure 4, in Mines 1 and 2 the exposed filter areas for the SKC DPM cassette ranged from about 6 to 9 cm^2. The control limit range, the 3-sigma (3σ) range, of deposit areas for the SKC DPM cassettes in Mine 1 were 4.4 to 10 cm^2. The 3σ range of deposit areas for Mine 2 was 6 to 9 cm^2. Since a constant deposit area is usually assumed (and desirable to avoid the extra effort required to determine deposit area), the 99% confidence range for a sample with 10 μg/cm^2 carbon analysis ranged between 74–110 μg/m^3 for Mine 1 and 54–123 μg/m^3 for Mine 2, a difference of over 40%. Because of this large spread of areas, we decided that the deposition area of each SKC DPM cassette would have to be measured. Even then, slight errors would most likely occur due to the irregular shapes of the deposits. As a result, efforts were made to alleviate the irregular and inconsistent deposition area.

Design II SKC Cassette DPM Performance

The Design I SKC DPM cassette contained an aluminum foil shield to protect the filter. We believe this shield was responsible for the irregular and inconsistent DPM dispersion areas. During cassette assembly, as the two plastic cassette halves were joined, the aluminum shield tended to crimp. This resulted in a deformation of the filter medium and caused varying filter-to-shield contact near the filter perimeter.

The Design I cassette was modified by removing the aluminum shield and placing a thin metal annulus, a 37 mm outer diameter and 32 mm inner diameter gasket, in front of the quartz filter. The area inside the gasket was 8.04 cm^2. The gasket provided strength, reduced filter deformation, and afforded a definite boundary for DPM deposition.

Design II was tested in the laboratory in a DPM-only atmosphere. As can be seen in Figure 5, the cassettes' deposit areas looked regular and consistent. The control limit range of the deposition was between 8.11 and 8.21 cm^2, a difference of less than 2%. After this initial test of the Design II cassette, deposition areas of 94 Design II SKC DPM cassette filters from both field and laboratory experiments conducted for other purposes were measured. As can be seen in Figure 6, the control limit range of the exposed areas was between 8.05 and 8.28 cm^2, a difference of less than 3%. The 99% confidence range for a 10-$\mu g/cm^2$ carbon analysis with the assumption of a constant deposit area would be 99–101 $\mu g/m^3$, a difference of 3%.

CONCLUSIONS

SKC DPM cassettes efficiently collected DPM in both laboratory and field evaluations. In addition, no carbon from ore dust was detected when sampling in an 8 mg/m^3 atmosphere of metal mine ore. Results of the Design I SKC DPM cassette evaluation found irregular and inconsistent deposit areas. If Design I SKC DPM cassettes are used, the exposed filter area should be determined for each cassette. Design II adequately solved this problem and produced regular and consistent DPM deposit areas across the filter surface. The Design II version of the SKC DPM cassette is presently in production.

REFERENCES

1. "Diesel Particulate Matter Exposure of Underground Metal and Nonmetal Miners;" Proposed Rule, *Federal Register 30*:57 (29 October 1998). pp. 58103–58270.
2. "Diesel Particulate Matter Exposure of Underground Metal and Nonmetal Miners;" Proposed Rule, *Federal Register 30*:57 (25 September 2002) p. 47297.
3. **Birch, M.E., and R.A. Cary:** Elemental carbon-based method for monitoring occupational exposures to particulate diesel exhaust. *Aerosol Sci. Tech. 25*:221–241 (1996).
4. **National Institute for Occupational Safety and Health (NIOSH):** *NIOSH Manual of Analytical Methods (NMAM),* 4th Ed. (Pub. No. 94-113). Cincinnati, Ohio: Department of Health and Human Services/NIOSH, 1996.
5. "Safety and Health Standards—Underground Metal and Nonmetal Mines," *Federal Register 30*:57 (1991) p. 393.
6. **American Conference of Government Industrial Hygienists (ACGIH®):** *TLVs Threshold Limit Values for Chemical Substances in Workroom Air Adopted by ACGIH for 1973.* Cincinnati, Ohio: ACGIH, 1973.
7. **Cantrell, B.K., and K.L. Rubow:** Development of personal diesel aerosol sampler design and performance criteria. *Min. Eng. 43*:232–236 (1991).
8. **McCartney, T.C., and B.K. Cantrell:** A cost-effective personal diesel exhaust aerosol sampler. In *Diesels in Underground Mines: Measurement and Control of Particulate Emissions* (Information Circular 9324). Proceedings of the Bureau of Mines Information and Technology Transfer Seminar, Minneapolis, Minn., September 29–30, 1992.
9. **Cantrell, B.K., and W. F. Watts, Jr.:** Diesel exhaust aerosol: Review of occupational exposure. *Appl. Occup. Environ. Hyg. 12*:1019–1027 (1997).
10. "Diesel Particulate Matter Exposure of Underground Metal and Nonmetal Miners;" Proposed Rule, *Federal Register* 30:57 (14 August 2003). pp. 48668–48721.
11. **Marple, V.A., and K.L. Rubow:** An aerosol chamber for instrument evaluation and calibration. *Am. Ind. Hyg. Assoc. J. 44*:361–367 (1983).
12. "Mandatory Health Standards-Underground Coal Mines." *Federal Register 30*:70 (2002).
13. **Eatough, D.J., H. Tang, W. Cui, and J. Machir:** Determination of the size distribution and chemical composition of fine particulate semivolatile organic material in urban environments using diffusion denuder technology. *Inhal. Toxicol. 7*:691–710 (1995).
14. **Kirchstetter, T.W., C.E. Corrigan, and T. Novakov:** Laboratory and field investigation of the adsorption of gaseous organic compounds onto quartz filters. *Atmos. Environ. 35*:1663–1671 (2001).
15. **Kennedy, E.R., T.J. Fischbach, R. Song, P.M. Eller, and S.A. Shulman:** NIOSH Technical Report, *Guidelines for Air Sampling and Analytical Method Development and Evaluation.* DHHS (NIOSH) Pub. No. 95-117. Cincinnati, Ohio: DHHS (NIOSH), 1995.
16. **Birch, M.E.:** Occupational monitoring of particulate diesel exhaust by NIOSH Method 5040. *Appl. Occup. Environ. Hyg. 17*:400–405 (2002).