Comparison of sampling methods to measure exposure to diesel particulate matter in an underground metal mine

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Abstract

Diesel particulate matter (DPM) continues to be scrutinized as an adverse occupational exposure agent. Currently, the air sampling protocol approved by the U.S. Mine Safety and Health Administration (MSHA) to quantify exposure to DPM in mines designates an SKC impactor as the sample collection device and limits exposure to the total carbon faction of a DPM aerosol. Because use of this impactor requires submission of the sample to an analytical laboratory, it inherently includes a lag time before workplace exposures can be determined. Thus, mine operators who use this MSHA-approved sampling device to monitor personal DPM exposures are faced with the possibility of realizing unacceptable airborne concentrations after the exposures have occurred.

In an effort to scientifically address this issue, this study performed a side-by-side sampling technique to investigate the correlation between a TSI DustTrak real-time aerosol monitor and an SKC impactor when measuring diesel particulate matter concentrations in an underground mine environment. Results of regression analysis between TWA results obtained from the two sampling devices suggest that a good correlation ($R^2 = 0.91$) exists when measuring submicrometer particles. Also, results from triplicate SKC impactor samples showed good precision of the National Institute of Occupational Safety and Health 5040 analytical method compared to published analytical performance criteria. In addition, SKC impactor results appear to validate MSHA's use of a 1.3 multiplier applied to elemental carbon to estimate total carbon in the presence of airborne interferences.

Introduction

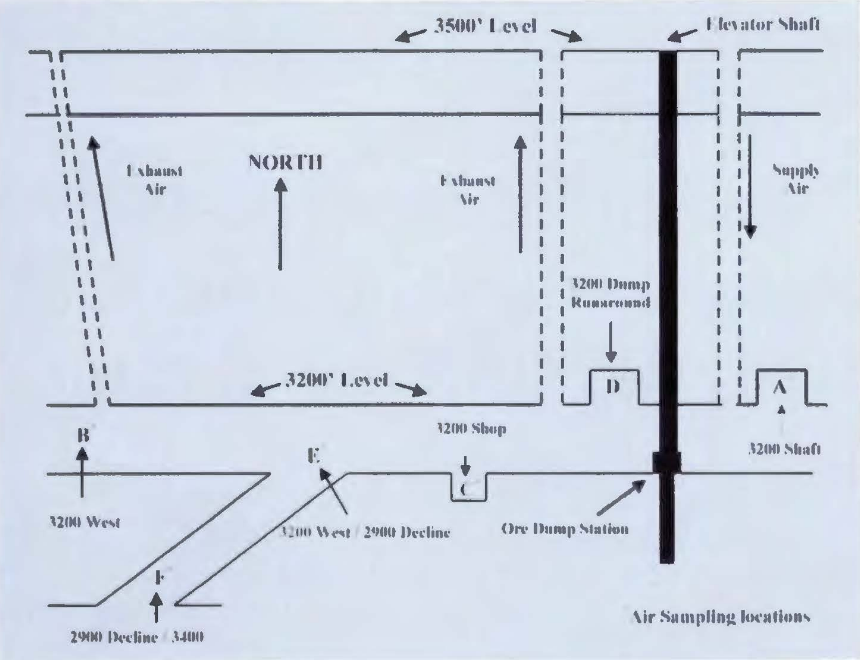
Diesel is an efficient fossil fuel converting a large fraction of its available energy into useable work. Diesel fuel also has a flash point that, when compared to other fossil fuels, lends itself to reduced fire potential. These, among other factors, make diesel a popular choice for many industrial and domestic applications. A negative aspect to the use of diesel fuel is the resultant emissions, which have been implicated as leading contributors to poor air quality and the causative agent associated with a variety of acute and chronic human health effects (IARC, 1989; Cohen and Higgins, 1995; NIOSH, 1998a; Pope et al., 2002).

Diesel emissions are a mixture of particulate aerosols and a complex host of gases and vapors. The particulate aerosol portion of the mixture is commonly referred to as diesel particulate matter (DPM) and consists, in part, of elemental carbon (EC) carrier particles on which hydrocarbon gases are adsorbed. These hydrocarbon gases are classified as the organic carbon (OC) fraction of the aerosol. The combined sum of the EC and OC fractions constitutes the amount of total carbon (TC) present in the aerosol. One occupational setting known to contain high concentrations of DPM is the underground mining environment. The Mine Safety and Health Administration (MSHA) estimates that in the United States diesel-powered equipment is used in 14,000 mining operations and that approximately 230,000 miners are occupationally exposed to DPM (MSHA, 2002). In worst-case environments, it has been confirmed through air sampling that underground miners can be exposed to DPM at a magnitude ten times higher than what is typically seen in other industries (Haney et al., 1997).

In an effort to better protect the health of underground miners, the U.S. Mine Safety and Health Administration (MSHA) has published proposed rule-making regulating DPM exposures (*Federal Register* 2002a). Under this rule, on July 19, 2003, MSHA began enforcement of an interim DPM permissible exposure limit (PEL) for TC of 400 µg/m³. On Jan. 19, 2006, MSHA was scheduled to begin enforcement of a final DPM permissible exposure limit for TC of 160 µg/m³. Both PELs are based on estimation of the average eight-hour equivalent full-shift airborne TC concentration to be determined by the addition of a sample's EC and OC fractions. If a sample's

FIGURE 1

Air sampling locations (included in a separate electronic file).



TC concentration, as determined by the sum of the EC and OC fractions, is above the PEL, then an additional validation step is performed to account for the presence of airborne interferences such as tobacco smoke, oil mist and carbonaceous materials. In this step, the EC fraction becomes the surrogate measure of exposure and the TC concentration is equal to an aerosol's EC fraction multiplied by 1.3. Use of the 1.3 multiplier to estimate TC is based on the assumption that TC is 60 percent to 80 percent EC and analysis of EC using the NIOSH 5040 analytical method is unaffected by the presence of interfering materials (NIOSH, 1998b; *Federal Register*, 2002b).

When performing air sampling to estimate occupational exposure to DPM, consideration must be given to particle size. Published literature has reported that 95 percent of all diesel aerosols are submicrometer in size (ACGIH, 2001). Given this, the collection of DPM is accomplished through the use of a particle size-selective sampling device. The current MSHA-approved air sampling protocol to estimate occupational exposure to DPM employs the use of an SKC impactor (SKC Inc., Eighty Four, PA) having a cut point of 0.9 µm. Implementation of this protocol requires the purchase of one impactor for each sample collected and submission of the impactor and filter media as a single unit to a laboratory for analysis. Thus, when sampling strategies involve the monitoring of all workers in both high and low DPM concentration areas, these single-use impactors can quickly increase sampling costs. In addition, use of these impactors inherently involves a lag time before an exposure determination can be made. During this lag time miners are potentially exposed to unacceptable airborne levels of DPM. Therefore, the availability of a real-time monitor used as a survey tool to instantaneously quantify DPM concentrations aids in identifying areas within a mine where personal sampling is necessary or where immediate implementation of control measures is required. Currently, no standardized sampling method exists that would provide real-time results of exposures to DPM.

The purpose of this study is to investigate the feasibility of using a real-time monitor to measure DPM concentrations through the performance of side-by-side sampling using a TSI DustTrak (TSI Inc., St. Paul, MN) real-time particulate aerosol monitor and SKC® impactors in an underground metal mine. For use in this manuscript, future references to the TSI DustTrak and the SKC impactor will be DustTrak and compliance impactor, respectively. In addition, the sampling results obtained in this study are used to evaluate the precision of the NIOSH 5040 analytical method for DPM and to evaluate the appropriateness of applying a 1.3 multiplier to a sample's EC results to estimate TC (i.e., evaluation of EC/TC ratios in the 60 percent to 80 percent range).

Methods

This study was conducted in a platinum/palladium underground mine that produces approximately 2.25 kt/d (2,500 stpd) of ore and 17.4 t (560,000 oz) of precious metal a year. At this mine, diesel-powered equipment is used during most ore production activities and "ramp and fill" is the primary method employed for ore acquisition. The types of diesel-powered equipment in use during the performance of this study included load-haul-dumps (LHDs/muckers), haul trucks, graders, maintenance vehicles, automatic drillers, pneumatic rock drills and grading tractors. The engine brake horsepower ratings of all diesel-powered equipment ranged from 50 to 277.

The study's field sampling campaign involved air sampling for DPM in an area of the mine that contained active headings and frequent diesel-powered traffic. Care was taken to avoid sampling locations and activities that enhance the collection of DPM-interfering contaminants not associated with diesel combustion. Thus, no sampling was performed in the proximity of oil-mist generating equipment and all miners were asked to refrain from smoking during the sampling phase of the study.

Air sampling for DPM was conducted at six locations in the mine during four consecutive days. Determination of each sampling location was based on the scheduled mining activity for that day, with the intention of collecting samples at locations where low, moderate and high DPM concentrations were anticipated. Figure 1 highlights the specific locations where DPM air sampling was performed during this study. Table 1 provides a brief description of the ambient environment associated with each sampling location and qualitatively identifies the degree of mining activity present during each sampling period.

At the start of each of the four sampling days, three sample collection baskets were loaded with DPM samplers and hung from the ceiling of the mineshaft at different locations on the 3200 level of the mine. Each sample

Table 1

Description of air sampling locations.

Sample location[1]	Location description	Mine activity level
A (3200 Shaft)	• Sampling collection basket placed adjacent to the elevator shaft at the 3,200-ft level in the mine. • Ambient air continuously diluted by fresh air entering from nearby elevator shaft. • Few diesel-powered vehicles passing this sample location during the sampling period.	Low
B (3200 West)	• Sampling collection basket was hung in mine shaft west of the 3200 west/2900. • Near an active mine heading and many diesel-powered vehicles passing this sample location during the sampling period.	High
C (3200 Shop)	• Sampling collection basket was hung inside a maintenance shop. • Some vehicle maintenance performed at this sample location during the sampling period.	Moderate
D (3200 Dump)	• Sampling collection basket was hung adjacent to an ore dump area. • Ambient air at this location was continuously diluted by fresh air entering from nearby elevator shaft. • Few diesel-powered vehicles passing this sample location during the sampling period.	Low
E (3200 West/ 2900 Decline)	• Sampling collection basket was hung at the intersection of the 2900 decline shaft and the 3,200-ft level of the mine. • Near an active mine heading and many diesel-powered vehicles passing this sample location during the sampling period.	High
F (2900 Decline /3400)	• Sampling collection basket was hung at the intersection of the 2900 decline shaft and the 3400-foot level of the mine. • Near an active mine heading and many diesel-powered vehicles passing this sample location during the sampling period.	High

[1] Letters correspond to sample locations identified in Fig. 1.

collection basket contained three compliance impactors and one DustTrak. The height at which each sample collection basket was hung ranged from 1.8 to 3.6 m (6 to 12 ft) above the mineshaft floor and was dependent on the access clearance needed for mine traffic to pass without disruption.

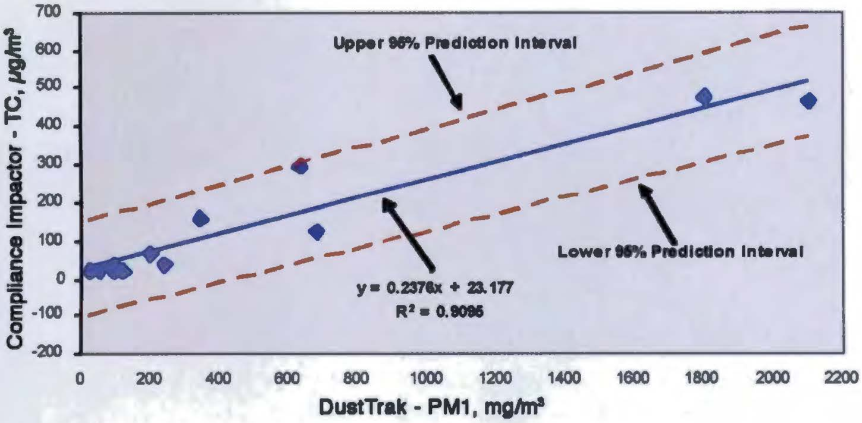
The co-location of the three compliance impactors with one DustTrak real-time monitor in a single sample collection basket was done to evaluate the correlation between the different sampling devices through regression analysis of respective sampling results. The side-by-side placement of three compliance impactor samplers in a single sample collection basket was done to evaluate the precision of the NIOSH 5040 analytical method. Analytical precision was evaluated by calculating the relative standard deviation (RSD) among the results obtained from the side-by-side impactors and its comparison with published analytical performance criteria reported for the NIOSH 5040 method (Birch, 2002). In this published review, it is reported that RSD values ranging from 4 percent to 10 percent for EC and 5 percent to 12 percent for OC have been observed during round-robin sample analyses involving NIOSH and other contract laboratories.

The DustTrak, employed to measure DPM in real-time, is a 90 light-scattering device that directly measures particulate mass concentration in mg/m^3. In an effort to estimate DPM concentrations, the DustTrak was configured using a sampling head that selectively measures particulate mass at a 50-percent cut point of 1 µm (PM1). For estimation of a sampling period's average particulate mass concentration, the logging interval of each DustTrak was set at one minute. Prior to the start of each sampling period, a DustTrak was pre- and post-calibrated to the required flow rate of 1.7 L/min. A Gilian Gilibrator (Gilian Instrument Corporation, West Caldwell, NJ) was used to pre- and post-calibrate the DustTraks. No final flow rates were in excess of ±5 percent of the calibration flow rate.

The compliance impactor is a size-selective sampling device approved by MSHA for the performance of DPM compliance evaluations and at the prescribed flow rate of 1.7 L/min collects particulate matter at a 50-percent cut point of 0.9 µm. For use in this study, each impactor was housed in a 10-mm Dorr-Oliver cyclone (SKC Inc., Eighty Four, PA.) having a 5-percent cut point of 3.5 µm. The inclusion of the Dorr-Oliver cyclone in the sampling train served to remove larger, non-diesel particulate (mine dust) commonly found in underground mines. At the end

FIGURE 2

Relationship of DustTrak vs. Compliance Impactor-TC.



of a sampling period, each cyclone and associated tubing were washed, rinsed and dried in preparation for the next sampling day. Mine Safety Appliances Escort ELF pumps (Mine Safety Appliances Co., Pittsburgh, PA.) were used to provide negative pressure to collect DPM on the compliance impactor filter media. Each pump was pre- and post-calibrated using a Gilian Gilibrator to a flow rate of 1.7 L/min, as prescribed by the NIOSH 5040 method for the collection of DPM. No final flow rates were in excess of 5 percent error of the calibration flow rate.

The research team remained in the mine for the duration of each sampling period. Efforts were made to monitor each sample collection basket and perform pump checks on an hourly basis. At the conclusion of the field sampling campaign, 36 compliance impactor field samples and four compliance impactor field blanks were submitted to an American Industrial Hygiene Association (AIHA) accredited laboratory for analysis of EC and OC using the NIOSH 5040 method. At the end of each sampling day, logged sampling data were downloaded from all DustTraks to a computer hard drive using TrakPro v3.32 software (TSI Inc., St. Paul, MN).

Results

Analysis of the four compliance impactor field blanks yielded concentration results less than the limit of detection (1 µg/cm²) for EC and OC. Analysis of the 36 compliance impactor filter field samples yielded the concentration EC, OC and TC results shown in Table 2. The data in Table 2 summarize the analytical results for OC and EC in triplicate groupings based on their side-by-side placement in a sample collection basket.

Carbon concentrations for both OC and EC are converted from mass per unit area concentrations to mass per unit volume concentrations by application of

$$\textit{Carbon concentration}\left(\frac{\mu\text{g}}{\text{m}^3}\right) = \qquad (1)$$

$$\frac{\textit{Concentration}\left(\frac{\mu\text{g}}{\text{cm}^2}\right)\times \textit{Filter area}\left(\text{cm}^2\right)\times 1{,}000\,\frac{\text{L}}{\text{m}^3}}{1.7\,\frac{\text{L}}{\text{min}}\times \textit{Sample time}\,(\text{min})}$$

To provide a more meaningful summary of the carbon concentrations calculated from analytical results reported as below the limit of detection (LOD), these values are indicated with a (<) sign preceding each value. TC is expressed as the sum of OC and EC. Scrutiny of the results reported above the LOD show that TC concentrations ranged from the 54 to 500 µg/m³, with the highest concentrations associated with locations where mining activity was moderate or high during the sampling period. Evaluation of these same results show that the RSDs for all but three of the triplicate groupings are within the range observed during the laboratory round-robins cited in the published review of the NIOSH 5040 method (Birch, 2002). The exceptions to this finding are the OC results in Groupings 8 and 11 and the OC and EC results in Grouping 12, which showed RSDs values ranging from 21 percent to 34 percent. EC/TC ratios are also provided in Table 2 to assess the percent contribution made by EC to the overall TC fraction of the aerosol. As is shown, 15 of the 18 ratios and the arithmetic mean for all EC/TC ratios combined agree with MSHA's finding that TC is 60 percent to 80 percent EC. The three outliers in this data set showed EC/TC ratios of 50 percent, 55 percent and 59 percent, respectively.

Table 3 summarizes the DustTrak and compliance impactor TWA TC concentration results for each sampling location. The last column of Table 3 provides compliance impactor TWA TC concentrations that have been adjusted due to their association with EC and OC results reported to be below the LOD. Each adjustment was performed by dividing the EC and OC analytical result by the square root of 2 and using the resultant TC value to calculate the TC TWA. This adjustment technique has been recognized in published literature as a reasonable approach for data having relatively low variability (GSD of OC and EC analytical results are both < 3.0) (Mulhausen and Damiano, 1998). The data in Table 3 show that for the results obtained with both the compliance impactor and DustTrak the greatest concentrations were recorded at sample locations where moderate to high mining activity was present during the sampling period. Figure 2 shows the result of a regression analysis between each sampling device's TWA concentration results. Based on the co-location of both sampling devices in the same sampling basket, the regression was performed by pairing a DustTrak TWA with its associated compliance impactor TC TWA. It should be noted that the adjusted compliance impactor TC TWAs were used to perform the regression analysis. As noted in Figure 2, the R^2 value for the regression is 0.91 and the correlation coefficient (0.95) is significant having a p-value less than 0.001 and a statistical power of greater than 0.9.

These statistical results suggest that for the paired data collected, a strong relationship exists between the compliance impactor method of sampling for DPM and the use of the DustTrak to measure submicron particulate mass. Thus, the equation characterizing the best-fit line provides a quantitative mechanism to estimate TC

Table 2

Compliance impactor sample results.

Date sampled	Triplicate grouping #	Sample location[1]	[2]OC,[2] µg/cm^3	RSD,[3] %	EC,4 µg/m3	RSD,[3] %	TC,5 µg/m^3	EC/TC
1/14/03	1	A	<17	–	<17	–	<34	–
1/14/03		A	<17		<17		<34	
1/14/03		A	<17		<17		<34	
1/14/03	2	B	100	4.3	343	6.5	450	0.76
1/14/03		B	95		370		470	0.79
1/14/03		B	100		390		490	0.80
1/14/03	3	C	<19	–	<19	–	<38	–
1/14/03		C	<19		<19		<38	
1/14/03		C	<19		<19		<38	
1/15/03	4	A	<19	–	<18	–	<37	–
1/15/03		A	<19		<18		<37	
1/15/03		A	<19		<18		<37	
1/15/03	5	B	130	4.9	350	2.7	470	0.74
1/15/03		B	140		350		490	0.71
1/15/03		B	130		365		500	0.73
1/15/03	6	C	<19	–	36	0	<54	–
1/15/03		C	<19		36		<54	
1/15/03		C	<19		36		<54	
1/16/03	7	D	<16	–	<16	–	<33	–
1/16/03		D	<16		<16		<33	
1/16/03		D	<16		<16		<33	
1/16/03	8	E	54	21	82	6.7	140	0.59
1/16/03		E	54		72		130	0.55
1/16/03		E	37		81		120	0.68
1/16/03	9	C	<20	–	40	0.69	<60	–
1/16/03		C	<20		41		<61	
1/16/03		C	<20		41		<61	
1/17/03	10	F	51	0	110	9.1	160	0.69
1/17/03		F	51		120		170	0.71
1/17/03		F	51		100		150	0.67
1/17/03	11	E	68	21	220	9.6	290	0.76
1/17/03		E	100		220		330	0.67
1/17/03		E	85		190		270	0.70
1/17/03	12	C	36	34	36	24	72	0.50
1/17/03		C	19		36		54	0.67
1/17/03		C	36		54		90	0.60
							Average[5]	0.68

[1] Capital letter indicates sample location as identified in Figure 1.

[2] LOD = 1µg/cm^2.

[3] Relative Standard Deviation (standard deviation divided by the mean) expressed as a percent;

[4] LOD = 2 µg/cm^2; [e] TC = OC + EC.

[5] Arithemtic average of all EC/TC ratios combined.

Table 3

DustTrak and compliance impactor TWA-TC concentrations at each sampling location.

	DustTrak				Compliance impactor		
Date sampled	duration, min	Sample location1	n[2]	TWA[3] µg/m^3	Triplicate grouping #	TC TWA[4] ug/m^3	TC TWA[5] (µg/m^3
1/14/03	315	A	315	120 (0.22)	1	<34	24
1/14/03	233	B	233	2,100 (0.93)	2	468	–
1/14/03	288	C	288	51 (0.05)	3	<37	26
1/15/03	301	A	301	25 (0.021)	4	<35	25
1/15/03	309	B	309	1,800 (1.1)	5	480	–
1/15/03	297	C	297	93 (0.08)	6	<54	38
1/16/03	321	D	321	97 (0.14)	7	<33	23
1/16/03	300	E	300	680 (2.5)	8	130	–
1/16/03	270	C	270	240 (0.15)	9	<61	43
1/17/03	315	F	315	340 (0.31)	10	160	–
1/17/03	308	E	308	630 (0.48)	11	300	–
1/17/03	296	C	296	200 (0.18)	12	72	–

Letter corresponds to sample locations identified in Fig. 1.

[2] Number of DustTrak concentration values recorded using a 1-minute logging interval.

[3] Values in parentheses reflect the standard deviation of all recorded concentrations.

[4] Arithmetic average TC TWA concentration for each triplicate grouping, < nomenclature reflects TWA concentrations calculated using TC results assumed to be at the LOD (1 µm/cm^2).

[5] TC TWA concentration calculated using TC results assumed to be at the LOD divided by the square root of 2.

concentrations when using the real-time particle monitor. The upper and lower 95 percent prediction intervals enclosing the best-fit line provide a means to extrapolate the range of future TC concentration outcomes, based on the inherent error associated with environmental sampling and the performance of regression analysis having only a sample size of n = 12.

Discussion

Regression analysis of the TWA results obtained using the compliance impactor and the DustTrak suggest that, for the mine environment in which they were used, a good correlation exists between these two aerosol collection devices when measuring submicron particles. The equation characterizing the best-fit line quantifies the relationship and provides an estimate of DPM exposures using the DustTrak. It should be noted that the estimate of future TC concentrations using the correlation equation is limited by statistical error associated with sampling and analysis and the study's small sample size. This error is visually depicted by the 95 percent prediction intervals associated with the regression line. Because the DustTrak is a device that is factory-calibrated to a respirable fraction of standard ISO 12103-1 test dust, true mass concentration values would only be realized by alteration of the instrument's default calibration factor (1.0) based on analysis of a gravimetric sample result taken from the environment to be sampled. Because the intent of this study is to investigate the relative correlation observed between the use of a DustTrak and a compliance impactor, no alteration was made to the DustTrak's default calibration factor. This decision was based not only on the fact that meaningful results could be obtained when using this factory setting, but that instrument use in this manner would provide mine operators with an exposure tool requiring minimal manipulation.

The RSD results for the majority of the compliance impactor triplicate groupings suggest adequate precision based on quality assurance performance criteria observed for the NIOSH 5040 method. No obvious explanation exists for the relatively high RSDs observed in triplicate Groupings 8, 11 and 12. Given the consistency of analytical results in the other groupings, it is assumed that these deviations are likely due to human error associated with the sampling method. It should be noted that precision of the DustTrak was not evaluated in this study. Faced with potentially high intra- and inter-day fluctuations in the exposure environment, the research team determined that an appropriate evaluation of precision for this instrument would require the replication of side-by-side sampling events using two DustTraks co-located at one or more mine locations. This limitation in study design is a result of the limited number of DustTraks (three) available to the research team and the need to co-locate these instruments with compliance impactors at as many locations as possible during the short time frame allotted for field sampling.

Of the 18 EC/TC ratios evaluated in this study, 15 were between the 60 percent and 80 percent range cited by MSHA in the July 2002 federal register publication. Including the three outliers, the overall average EC/TC ratio was 68 percent. These results are in contrast to a recent Cohen et al. (2002) mine study where, although other DPM sampling methods were employed, EC/TC ratios below 60 percent were common. Thus, while the EC/TC ratios observed in this study seem to validate MSHA's use of a 1.3 multiplier, it is clear that more studies are needed to collaborate these findings.

It should be noted that the study methods used to quantify DPM concentrations where based on area sampling and that the basis of compliance with the MSHA DPM standard is personal sampling. It is not the intent of this study to use the correlation results obtained between the two sampling methods as true compliance estimators.

It is the intent of this study's correlation findings to provide the mining industry with a survey tool that can assess, in real time, the degree of personal and area exposures to DPM relative to a given threshold value (i.e., 50 percent of the MSHA TLV-TWA for DPM). Thus, exceeding this threshold would allow for immediate implementation of control measures and offer mine workers better safety and health protection.

Conclusions

This study's correlation results suggest that the DustTrak particulate aerosol monitor can be used to provide a relative estimate of DPM exposures in a manner similar to exposure results acquired using the compliance impactor sampling method. The precision results among the side-by-side compliance impactors show that good analytical consistency can be achieved using the NIOSH 5040 method, but that care should be taken to minimize systematic errors during the sampling process. Finally, the EC/TC ratios observed in this study seem to validate MSHA's 1.3 multiplier applied to EC to estimate TC. Even so, given the sample size of this study and the inconsistent results between this and other studies, it is clear more data are needed to evaluate the appropriateness of using this factor. ■

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