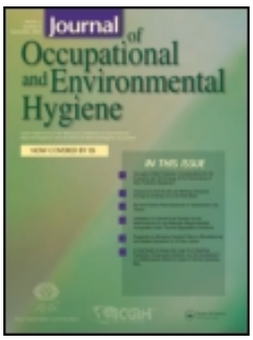

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Monitoring Diesel Particulate Matter and Calculating Diesel Particulate Densities Using Grimm Model 1.109 Real-Time Aerosol Monitors in Underground Mines

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Currently, there is no Mine Safety and Health Administration (MSHA)-approved sampling method that provides real-time results for ambient concentrations of diesel particulates. This study investigated whether a commercially available aerosol spectrometer, the Grimm Portable Aerosol Spectrometer Model 1.109, could be used during underground mine operations to provide accurate real-time diesel particulate data relative to MSHA-approved cassette-based sampling methods. A subset was to estimate size-specific diesel particle densities to potentially improve the diesel particulate concentration estimates using the aerosol monitor. Concurrent sampling was conducted during underground metal mine operations using six duplicate diesel particulate cassettes, according to the MSHA-approved method, and two identical Grimm Model 1.109 instruments. Linear regression was used to develop adjustment factors relating the Grimm results to the average of the cassette results. Statistical models using the Grimm data produced predicted diesel particulate concentrations that highly correlated with the time-weighted average cassette results ($R^2 = 0.86, 0.88$). Size-specific diesel particulate densities were not constant over the range of particle diameters observed. The variance of the calculated diesel particulate densities by particle diameter size supports the current understanding that diesel emissions are a mixture of particulate aerosols and a complex host of gases and vapors not limited to elemental and organic carbon. Finally, diesel particulate concentrations measured by the Grimm Model 1.109 can be adjusted to provide sufficiently accurate real-time air monitoring data for an underground mining environment.

Keywords cassette, diesel particulate matter, DPM, Grimm Model 1.109 aerosol monitor, underground metal mine

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INTRODUCTION

Diesel is used in many industrial applications, but a limiting factor to its use is the resultant emissions, commonly called diesel particulate matter (DPM). Exposure to DPM has been associated with a variety of acute and chronic human health effects.[1]

The underground mining environment is one occupational setting known to have among the highest concentrations of DPM; maximum concentrations underground in both metal and nonmetal mines have ranged from 350 to 1600 $\mu g/m^3$.[2] These concentrations are 10 times higher than usually reported in any other industry and 100 times higher than environmental DPM levels in the most polluted urban areas in the United States.[3] In 2002, the Mine Safety and Health Administration (MSHA) estimated that diesel-powered equipment is used in 14,000 mining operations in the United States.[4] Further, in 2008, the National Institute for Occupational Safety and Health (NIOSH) reported that 34,000 underground miners were potentially exposed to diesel exhaust.[3]

In an effort to better protect the health of underground miners, the MSHA revised enforceable rulemaking regulations for DPM exposures. Effective May 2, 2008, the permissible exposure limit (PEL) was reduced from 350 $\mu g/m^3$ to 160 $\mu g/m^3$ for total carbon (TC).[5] The currently accepted MSHA method for sampling and analysis of DPM is NIOSH Method 5040. There is an inherent lag time from collecting samples to obtaining DPM results from a laboratory when using this method.

The composition and quantity of the emissions from a diesel engine depend mainly on the type and condition of the engine, fuel composition and additives, operating conditions, and emission control devices.[6] Diesel emissions are a mixture of particulate aerosols and a complex host of gases and vapors.

DPM is the particulate aerosol portion of the mixture and consists, in part, of elemental carbon (EC) carrier particles on which hydrocarbon gases are also adsorbed. The hydrocarbon gases are classified as the organic carbon (OC) fraction of the DPM aerosol. The combined sum of the EC and the OC fractions constitutes the amount of TC present in the aerosol (OC + EC = TC), which typically represents over 80% of the DPM.[5,7,8] The MSHA reports that EC concentration ranges from 23% to 100% of DPM in underground mines.[5] The concentration of carbon monoxide, carbon dioxide, nitrogen oxides, polycyclic aromatic hydrocarbons, quinines, acids, and transitional metals (many contained in the OC fraction of DPM) adsorbed onto the EC core depends on many variables but seems to be relatively consistent throughout site-specific sampling campaigns.[9]

Aerosols in mines have a particle size distribution that is a result of both the mining method and the source of the aerosol.[10] The DPM size distribution is influenced by the different sources of DPM. However, the idealized distribution is trimodal (having three modes) and lognormal in form.[11] The smallest particulate diameter mode, the nuclei mode, typically consists of particles in the 0.005 to 0.05 μm diameter range. This typically contains 1–20% of the particle mass and more than 90% of the particle number for DPM. Most of the particle mass (60–94%) exists in the accumulation mode in the 0.05 to 1.0 μm diameter range. The largest diameter mode is the coarse mode, particles larger than 1 μm in diameter, and contains 5–20% of the particle mass. Further, 90% of DPM mass is less than 1 μm in aerodynamic diameter.[9]

Combustion particles are largely present in the form of clusters and therefore difficult to determine their true volume and, hence, their density.[8] Although the bulk densities from some of the individual materials constituting DPM are known, few studies report diesel particle density. Kittleson et al.[8] reported DPM particle densities from particles emitted from a single-cylinder diesel-powered generator ranged from 0.8 to 2 g/cm^3 and were dependent on engine load. Shi et al.[9] reported smaller particle densities ranging from 0.2 to 1.4 g/cm^3 for particles emitted from a heavy duty diesel engine. In addition to engine load, Shi and colleagues also reported that engine technology, fuel quality, and air dilution conditions in the sampling environment also affected measured particle density.

Recent information on health effects and more stringent regulatory standards may have increased interest in respirable particles and development of alternate methods for monitoring particles in air concentrations.[1,5,12–16] Monitoring results for different respirable particles using commercially available real-time instruments have been compared with results from different sampling methods. In 1996, Lehocky and Williams[16] reported that even though coal dust concentration results from two different direct-reading instruments and cyclones and PVC filters were not identical to each other, regression analysis between each of the direct-reading instruments and the respirable samples indicated high coefficient of determination (R^2) values of 0.85 and 0.94 when compared with the filter collection method.

In 2004, Kim et al.[17] reported that logistic regression models indicated log real-time instrument results significantly ($p < 0.01$) predicted log gravimetric results for fine respirable particles ($PM_{2.5}$). Simultaneous monitoring of outdoor tobacco smoke with multiple real-time instruments of both similar and different detection designs allowed Klepeis et al.[18] to achieve a high level of confidence in measured outdoor tobacco smoke levels, and to perform evaluations and comparisons of all sampling instruments in the study ($R^2 = 0.80$–0.99). They concluded in 2007 that real-time particle measuring instruments, especially those based on light scattering for particle detection, provide consistent findings that are useful in characterizing the determinants of outdoor tobacco smoke concentrations. In addition to solid particle detection, Verma et al.[19] reported in 2006 that a real-time instrument was useful in pinpointing the areas for potential exposure to oil- and water-based metalworking fluids.

DPM monitoring strategies with real-time instruments have also been compared with filter cassette sampling methods. Because the use of a filter cassette requires submission of the sample to an analytical laboratory, an inherent lag time exists before workplace exposures are available to mine supervision to act on if appropriate. Thus, mine operators using an MSHA-approved air sampling filter cassette to monitor personal DPM exposures are faced with the possibility of realizing airborne concentrations are above regulatory standards after the exposures have occurred. Use of a validated real-time monitoring method would provide immediate results vs. the delay in receiving results from the filter cassette sampling methods. In addition, the use of an acceptable real-time instrument would allow mine operators to efficiently evaluate effectiveness of control methodologies, such as the addition of a catalytic converter to a piece of diesel equipment or change in ventilation, to control DPM concentrations.

In an effort to address this issue, Stephenson et al.[4] performed a side-by-side sampling technique to investigate the correlation between a DustTrak real-time aerosol monitor (Model 8520; TSI, Shoreview, Minn.) and SKC DPM cassettes (SKC Inc., Eighty Four, Pa.) in an underground mine environment. They reported in 2006 that results of regression analysis between time-weighted averages (TWA) obtained from the two sampling devices suggest a good correlation ($R^2 = 0.91$) exists when measuring submicron particles for the mine environment in which they were used.

Other researchers from the NIOSH Pittsburgh Research Laboratory also addressed the problem of results being unavailable pending analysis. They developed a non-commercially available portable device that measures EC concentrations in real-time by an optical absorbance method. Janisko and Null[20] reported in 2008 that the portable EC monitor provides near real-time analysis of EC concentration ($R^2 = 0.99$) and is highly portable, lightweight, and accurate. Because of these results, the EC monitor may prove to be a vital tool when monitoring DPM in underground mines.

The MSHA initially considered TC as the best surrogate for measuring DPM in underground mines because it typically accounts for over 80% of DPM, and the EC to DPM ratio can change with engine load.[5] However, cigarette smoke and oil mist in the sampling environment can lead to erroneous results in OC measurements that, in turn, can lead to flawed TC measurements.[20] As a result, the MSHA imposed an interim sampling strategy in 2001 for monitoring DPM in mines while a 31-mine study was conducted to investigate sampling procedures for DPM. The interim DPM limit of 350 $\mu g/m^3$ for TC could be determined using EC as the analyte. That is, the EC value from the NIOSH sampling and analytical method is converted to an 8-hr TWA and then multiplied by 1.3 (a conversion factor determined by the 31-mine study, 1.3*EC = TC) to determine compliance.[5]

In 2005, one of the MSHA's conclusions from the 31-mine study stated the analytical method specified by the diesel standard gives an accurate measure of the TC content and is appropriate for making compliance determinations of DPM exposures in underground metal extraction mines.[5] However, there is not a current standardized sampling method that would provide real-time results of exposures to DPM. Therefore, the objective of this pilot study is to investigate if the Grimm Portable Aerosol Spectrometer Model 1.109 (Grimm Technologies, Inc., Douglasville, Ga.) can be used during underground mine operations to provide accurate real-time data of TC concentrations relative to SKC DPM cassettes, an acceptable DPM sample collection device as per the MSHA-approved procedure (NIOSH Method 5040). Although they are not acceptable for compliance purposes, the Grimm results could be valuable to mine operators as an indicator when DPM concentrations in work environments may be of potential exposure concern and to evaluate control methodologies if they are found to be similar to the SKC DPM cassette results. A subset is to calculate size-specific densities of DPM in underground mines. In this article, future reference to the Grimm Portable Aerosol Spectrometer Model 1.109 and the SKC DPM cassette with integral precision-jeweled impactor will be Grimm instrument and cassette, respectively.

METHODS

Study Design

DPM was sampled with cassettes (Method 1) and monitored simultaneously in proximity with the inlet for the Grimm instruments (Method 2) during seven sampling periods—between September 2007 and February 2008—in a Utah mine, and three in a Montana mine, both of which are underground metal extraction mines.. Each sampling period ranged between 2–6 hr. Sampling locations in both mines were approximately 15 ft wide × 16 ft high at the apex.

Although both are hard rock metal extraction mines, each site employs different strategies to reduce the DPM concentrations in the mine workplace. The Utah mine primarily uses ventilation (1–2 m/sec air velocity, 22–44 m/sec air volume) for controlling diesel emission in the work environment. The Montana mine employs a variety of different control strategies including higher ventilation velocity (12–14 m/sec, for an equivalent of 267–312 m^3/sec), use of biodiesel fuel mixture, and catalytic converters on engine exhaust as an after-treatment control.

Materials and Equipment

Description of Method 1 Sampling for DPM: Cassette

Sampling was conducted during underground metal extraction mine operations using the approved cassette method for monitoring DPM. SKC Inc. describes the advantage of using their cassette for the collection of diesel particulate as it differentiates DPM from other respirable dust (such as coal dust) based on particle size, which is accomplished by use of an impactor and is unlike other approved cassettes without an impactor. The single-use cassette, with its precision-jeweled impactor and impaction substrate, has a cut point of 1.0 μm in aerodynamic diameter at a flow rate of 2.0 L/min. The 1.0 μm cut point of the impactor indicates the aerodynamic diameter of particles for which 50% pass out of the impactor with the airstream (i.e., particles 1.0 μm in diameter and smaller collect on a heat-treated low carbon background quartz filter). A GS-1 Cyclone (SKC) was used with each cassette to prevent large particles (4.0 μm cut point) from clogging the cassette impactor. The GS-1 Cyclone is a single-inlet cyclone providing performance equivalent to the Dorr-Oliver Cyclone (Zefon International, Ocala, Fla.) with the added advantage of conductive plastic construction, which eliminates electrostatic energy. Samples were analyzed for OC and EC content using the evolved gas analysis technique with thermal-optical analyzer as specified in NIOSH Method 5040.[21]

Description of Method 2 for Monitoring DPM: Grimm Instrument

The Grimm instrument is a portable unit used for continuous measurement of airborne particles. It is an optical particle counter with 32 different interval sizes (range from 0.25 to 32 μm) associated with the aerodynamic diameter of the particle, a radial symmetric sampling head, and an integrated laser (λ = 675 nm). The interval total was set to record every 6 sec for the sampling period in this pilot study. For aerosol classification, particle counts can range from 1 to 2,000,000 particles per liter, and mass measurements can range between 0.1 and 100,000 $\mu g/m^3$.

The Grimm instrument's collection efficiency at the radial symmetric sampling head does have some sensitivity to wind speed. Particles up to 10–20 μm in diameter are collected with high efficiency at wind speeds up to approximately 8 m/sec (1575 feet per minute or 13.35 miles per hour), but collection efficiency for these particles decreases above this wind speed.[22] Therefore, ventilation rates were recorded during each sampling period to help identify possible errors in sampling due to wind velocities.

Further, the particle count by the Grimm instrument is dependent on the wavelength of the laser. When the diameter of the particle (0.675 μm) is approximately equal

to the wavelength of the light, the specific scattering function reaches a maximum and is nearly proportional to particle volume.[23] Even though DPM particles range in size about the wavelength of the laser, atmospheric particles within the accumulation mode nearly coincide with the maximum of the specific scattering function so that particles within this size range exhibit the greatest sensitivity when detected with optical means.[23] Thus, within the specific DPM size range for this pilot study (0.25 to 1 μm), the light scattering will be near maximum allowing for an accurate particle count, which is used for mass calculation. However, the Grimm instrument will not detect particles smaller than 0.2–0.3 μm in diameter. Also, it is unclear whether the results from the Grimm instruments would reflect the EC or TC fractions because the Grimm instrument is not specifically calibrated for DPM (i.e., different density for DPM vs. other calibration factors).

The data conversion to mass per unit volume from the measured particle number per unit volume for the Grimm instrument is accomplished by the instrument using protocols developed by Grimm Technologies. The particle count distribution obtained is the basis for the mass calculation. Particle diameter data are first converted to particle volume using the mean particle diameter between the thresholds of the 32 different channels and assuming particles are spherical. Then these volume data are converted to a mass distribution using a density factor corresponding to the Grimm Technologies established "urban environment" factor, which is based on the comparison of Grimm Technologies and the U.S. Environmental Protection Agency (USEPA) Federal Reference Method results in several urban environments.[23] Grimm Technologies' protocols assume that aerosols in all urban environments are dominated by similar anthropogenic emissions, which makes it possible to use a constant particle density over the full size range at all locations.[23] However, DPM is a complex mixture of particulates emitted exclusively from diesel engines. Therefore, it may not be feasible to use the same constant particle density over the full size range of DPM.

DPM Sample Collection

NIOSH Method 5040 procedures were followed for the collection and analysis of six cassettes, while simultaneously sampling the same mine workplace area with two Grimm instruments during each sampling period. DPM was sampled during the peak of activity in the mining cycle (drilling and mucking) when the highest concentrations of DPM could be expected. The Grimm instruments were placed side-by-side on a table approximately 3 ft above the mine floor. Cassettes were attached to a cord affixed to poles connected to the ends of the table. Sampling heads and the cassettes were approximately 8 and 16 in. above the surface of the table, respectively.

The table was located away from face of the mine and working area to minimize interference from oil mist and tobacco smoke. Also, it was placed close to the rib of the mine in an area that did not prohibit mining activity and where measurable DPM concentrations were expected to be present. Further, the chosen sampling location was expected to be representative of the DPM concentrations throughout that area of the mine because the location was in a tunnel where heavy-duty diesel-powered mining machinery was operating and exhaust air was flowing past.

The cassettes and cyclones were used with the SKC Air Check 2000 Personal Sampling Pumps at a flow rate of 2.0 L/min. The pumps have a flow fault feature (terminates sampling should the pump be unable to maintain the airflow) and were pre- and post-calibrated with a Bios Dry Cal DC-Lite Calibrator (Pompton Plains, N.J.). Results from pumps that had greater than a 5% difference between pre- and post-calibrations were not included in the DPM analysis. In addition to the sampling cassettes, two field blank cassettes were used to adjust the results as appropriate from the cassettes that were placed next to the real-time instruments during DPM sampling.

The two Grimm instruments were programmed such that one reported in mass per volume or mass concentration ($\mu g/m^3$) and the other in particles per volume or particle concentration (particles/m^3). Mass concentration results were used for investigating the main objective, while mass concentration and particle concentration results were used primarily to estimate size-specific DPM densities. The summation of aerodynamic diameter interval sizes from 0.25 to 1 μm (PM_1) for each Grimm instrument was used to calculate DPM concentrations. Inherent in the use of these interval sizes, a lower fraction of the accumulation mode and the nuclei mode will not be counted due to the lower limit of detection of the Grimm instruments.

Statistical Analysis

The primary objective of this study was to investigate the feasibility of using the Grimm instrument to monitor DPM concentrations with sufficient accuracy. The overall approach was to evaluate the statistical significance of the relationship between the observed TC levels based on the results from the cassette monitoring to the mass concentration readings from the Grimm instrument. Analytical data from the cassettes and PM_1 data from the Grimm instruments were analyzed using Stata version 10 (College Station, Texas) and Microsoft Excel version 11.5 (Redmond, Wash.).

A Wilcoxon Rank-Sum test indicated that the distribution of concentrations from the Montana mine was significantly different from the distribution of concentrations from the Utah mine ($p < 0.01$). Further, due to the very small number of sampling sets in the Montana mine ($n = 3$), only the sampling sets from the Utah mine ($n = 7$) were used to assess the use of the Grimm instrument during underground mine operations to provide accurate real-time data of TC concentrations relative to the cassettes. However, the Grimm instrument data from both mines were used to estimate DPM particle densities.

Due to the variability in cassette sampling in underground metal mines,[5] the six cassette results for TC concentrations during each sampling set were averaged to generate a single TC concentration for that period. Two regression models were developed to assess the relationship between the cassette results and the Grimm instrument readings. In Model 1, the average

TABLE I. Comparison of Sampling Method Results for Monitoring DPM in the Utah Mine

	Cassettes TC Concentration (μg/m^3)				Grimm Instrument Mass Concentration (μg/m^3)
Sampling Set	n	Average	Minimum	Maximum	Average
1	6	170	153	176	44
2	6	208	155	243	23
3	6	311	293	329	28
4	6	264	254	272	39
5	6	1214	1187	1257	167
6	6	354	343	365	43
7	6	115	102	122	58
Average		377			57
Standard Deviation		378			50

cassette TC concentration was used as the dependent variable and the mass concentration from the Grimm instrument as the independent variable. As the Grimm detects only elemental carbon, Model 2 used the EC portion of the cassette results as the dependent variable, with the mass concentration from the Grimm instrument as the independent variable.

To generate site- and size-specific DPM densities, simultaneous data from two Grimm instruments were used, one set to record particle concentration per unit volume and the other set to record mass concentration per unit volume, which is based on Grimm Technologies' proprietary protocol using the "urban environment" density factor. To assess differences between the two instruments, both were run using a common inlet for a total of 15 min during one sampling period. Linear regression was used to assess the differences between the readings. Based on these results, the mass concentration readings were adjusted before being used to estimate the particle density.

Particle concentration results were used with the adjusted mass concentration results to calculate a DPM density for each of the PM_1 interval sizes of the Grimm instrument for the sampling period. The particle diameter for the particle volume calculation was the midpoint between the thresholds of the 11 different PM_1 interval sizes associated with the aerodynamic diameter of the particle. The following equation was used to calculate DPM densities associated with each interval for the sampling periods using the mass concentration measured from one of the Grimm instruments and the particle concentration from the second instrument:

$$\begin{aligned}\text{DPM Particle Density}_i &= \left(\frac{\text{Mass}_{\text{particle}}}{\text{Volume}_{\text{particle}}}\right)_i \\ &= \frac{\left(\frac{\text{Mass}_{\text{particles}}}{\text{Volume}_{\text{air}}}\right)_i}{\left(\frac{\text{Particle Count}}{\text{Volume}_{\text{air}}}\right)_i} * \left(\frac{1}{\text{Paricle Volume}_i}\right) \\ &= \left(\frac{\text{Mass Concentration Result}_i}{\text{Particle Concentration Result}_i}\right) \\ &\quad * \left(\frac{1}{\text{Particle Volume}_i}\right) \end{aligned} \quad \textbf{(1)}$$

where

i = size-specific interval of Grimm instrument associated with the aerodynamic diameter of particle,

Mass Concentration Result_i = Grimm instrument sampling results reported in μg/m^3 for intervals PM_1, and

Particle Concentration Result_i = Grimm instrument sampling results reported in particles/m^3 for intervals PM_1.

RESULTS

Comparison of Particle Density and Cassette Results

The reported mass concentrations from the Grimm instrument for each sampling period were much lower than the observed TC concentrations from the cassettes (Table I). Overall, the average mass concentration from the Grimm instrument was only 13% of the average TC concentration from the cassettes (50 μg/m^3 vs. 377 μg/m^3). There was not much difference in average mass concentrations between the sampling periods, except for Sampling Period 5, which had a mass concentration and TC concentration approximately five times the average of the other periods.

The TC/EC ratios calculated from the cassettes were similar across six of the seven sampling periods, and the average ratio from all sampling cassettes was the MSHA EC correction factor (Table II). Results from the two regression models (Models 1 and 2) are presented in Figures 1 and 2 and Table III. In both models, the slope estimate (Grimm, ß1) is statistically significant, indicating an association between the cassette results and the mass concentration readings from the Grimm instrument. The slope parameter in Model 1 was 7.1, indicating that the Grimm measured a small fraction of TC mass. In Model 2, the slope parameter was much closer to 1.0, which would be expected if the Grimm instrument measured the same mass as the cassette. Based on these results the Grimm measured, on average, approximately 45% of the EC mass captured from the cassette, as opposed to only 14% of the TC mass.

TABLE II. Calculated Cassette Ratios and Standard Deviations

Sampling Set	TC/EC Ratio	Standard Deviation
1	1.24	0.05
2	1.13	0.10
3	1.22	0.02
4	1.13	0.14
5	1.18	0.03
6	1.25	0.03
7	1.87	0.03
Average (n = 42)	1.30	0.26

Calculation of Size-Specific DPM Densities

Linear regression between the particle concentration results from both Grimm instruments when connected to a common inlet is shown in Figure 3. An R^2 value (square of the sample correlation coefficient between the outcomes and their predicted values) of 0.99 suggests the two Grimm instruments have a high correlation when monitoring DPM in the Utah mine. Although the slope estimate (1.07) indicates that the particle count measurement from the first GRIMM instrument (GRIMM1) were, on average, 7% lower than the particle count measurement from the second GRIMM instrument (GRIMM2). This error is not likely to be important given the lognormal nature of the concentration data. Results of calculated size-specific DPM densities from particle concentration and adjusted mass concentration results are presented in Table IV.

Interestingly, the calculated DPM densities within a size range were generally consistent across the three sampling trips. However, there was significant variation in the calculated DPM densities between the size ranges.

DISCUSSION

Ensuring protection of workers' from overexposure to DPM in underground mines is a formidable challenge. This exposure challenge could be reduced with the availability of a real-time air quality monitoring device validated such that it can provide acceptably accurate air monitoring data to guide operational decisions. The results of this pilot study indicate that the Grimm instrument may be a viable and useful tool for monitoring DPM levels in underground mine settings. The Grimm measurements are highly correlated with the TC and EC levels obtained using the MSHA-approved cassette method; however, the uncorrected results are very different. The Grimm instrument may not detect the OC component of DPM and TC does not represent the entire DPM aerosols, which are only two of the reasons underlying these differences.[7–9] As expected, the Grimm detected a much greater proportion of EC than TC (45% vs. 17%).

There are two possible reasons why the Grimm did not detect all of the EC. First, the Grimm does not capture particulates less than 0.2–0.3 μm, and more than 20% of DPM mass may lie in this range.[11] Second, the conversion factor used in the Grimm is based on DPM characteristics from an urban environment.[23] DPM from a mine source may well have different characteristics such that a different conversion factor would be needed to correctly calibrate the Grimm readings to this environment. Using the Grimm to assess workplace air conditions in terms of potential exposures to workers requires that the uncorrected Grimm readings be adjusted (or calibrated) against the MSHA cassette method at each site before using the results to estimate exposure to workers.

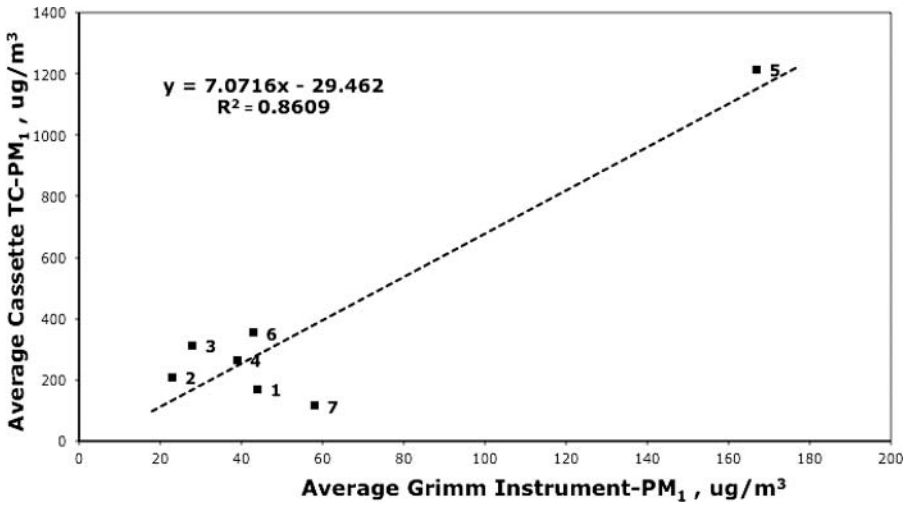

FIGURE 1. Average cassette total carbon concentration as a function of average Grimm instrument mass concentration for each sampling period in the Utah mine.

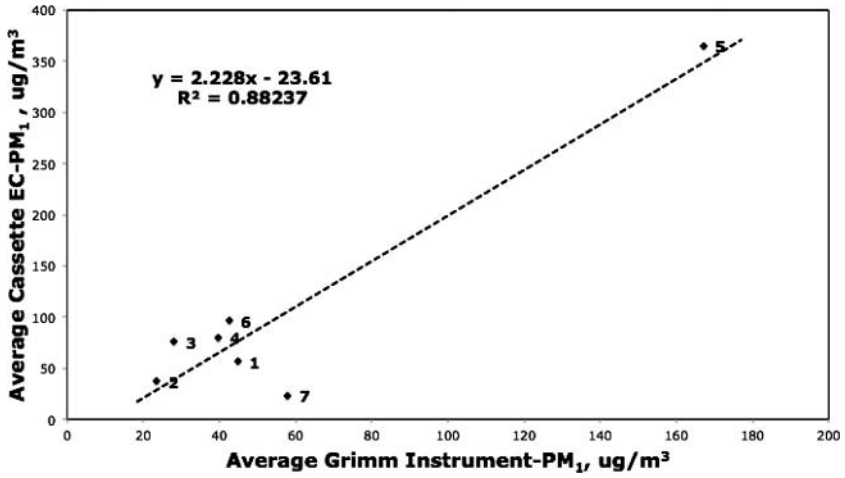

FIGURE 2. Average cassette total carbon concentration as a function of average Grimm instrument mass concentration for each sampling period in the Utah mine.

Clearly, the small number of observations limited the study. This study needs to be replicated with a larger number of observations and from a wider range of mines and DPM sources. Further, results from some of the DPM observations could be used to generate the regression results, and other DPM observations used to validate the models. The statistically significant associations that were found in spite of the small sample size indicate that the Grimm instrument may be a viable screening tool in assisting in monitoring DPM ambient air concentrations in underground mines.

The complexity involved with the implementation of real-time DPM monitoring using the Grimm instrument will depend on how consistent the relationship between DPM levels and Grimm measurements are in different mines and in different environmental conditions within a mine. If these relationships vary considerably, then concurrent sampling, conducted simultaneously with MSHA-required monitoring, will be used to generate the factors needed to adjust the Grimm measurements to approximate DPM levels. Each underground metal mining environment is unique, with site-specific characteristics (e.g., mine equipment, DPM control strategies, environmental conditions) that may possibly affect the correlation between cassette TC concentrations and Grimm instrument results. Therefore, the adjustment model should be calculated for each mining environment when an observed mass concentration from a Grimm instrument is wanted to predict the cassette TC concentration.

The basis of compliance with the MSHA DPM standard is personal sampling; and the study methods used to quantify TC concentrations were based on area sampling. The intent of this study is not to use the adjusted TC results as true compliance estimators. Rather, the adjusted TC concentrations from the Grimm instrument may provide the mining industry with a survey tool that assesses TC concentrations in the air in real-time and can provide information on potential for exposure below or above acceptable concentrations. This information would decrease the lag time between sampling and analytical results and hasten the implementation of DPM control strategies if warranted, as well as provide assurance when exposure controls are found to be acceptable.

Calculated DPM Density

Overall, the range of calculated DPM densities found here (0.9–2.2 g/cm^3) is similar to the results presented by Kittleson et al.[8] and Shi et al.[9] for particles emitted from diesel engines (0.2–2.0 g/cm^3). However, the calculated DPM densities in this study are higher than expected for particles emitted from heavy-duty diesel engines (0.2–1.4 g/cm^3) as reported in Shi et al. This difference may be attributable to different operating

TABLE III. Regression Model Results from Cassette Concentrations vs. Grimm Instrument Mass Concentrations

		Coefficients	Std. Error	t Stat	P-Value	Lower 95 Percentile	Upper 95 Percentile	R^2	Adjusted R^2
Model 1	Intercept	–31.7	94.2	–0.3	0.750	–2.73.8	210.5	0.86	0.83
	Grimm, $\beta 1$	7.1	1.3	5.5	0.002	3.8	10.4		
Model 2	Intercept	–23.6	26.8	–0.9	0.419	–92.5	45.3	0.88	0.86
	Grimm, $\beta 1$	2.2	0.4	6.1	0.002	–1.3	3.2		

TABLE IV. Calculated Size-Specific DPM Densities from Grimm Instrument Results

	Utah Mine		Montana Mine
	Sampling Set		
	1	2	1
Channel (μm)	Density (g/cm^3)		
0.25–0.28	1.8	1.8	1.8
0.28–0.30	1.7	1.7	1.7
0.30–0.35	1.8	1.9	1.9
0.35–0.40	1.5	1.3	1.6
0.40–0.45	1.6	1.3	1.6
0.45–0.50	1.1	0.9	1.1
0.50–0.58	1.5	1.5	1.6
0.58–0.65	2.2	2.1	2.1
0.65–0.70	2.0	1.8	1.9
0.70–0.80	1.6	1.5	1.6
0.80–1.0	2.0	1.8	2.1
Average	1.7	1.6	1.7
Standard Deviation	0.3	0.3	0.3
Range	0.9–2.2		

(i.e., engine load) and environmental (i.e., dilution controls) conditions present in the unique sampling environments.

Variation between the calculated DPM densities for the different particle size intervals suggests that the use of a constant particle density over the full size range of the Grimm instrument[21] may not be adequate for DPM monitoring. The differences in DPM particle densities may reflect differences in the emissions sources in the underground mine environment compared with the emission sources used to calculate the "urban environment" factor used by Grimm Technologies for mass density calculations. Thus, a more accurate correlation may exist if the Grimm instrument was directly calibrated using a density factor specific to the emission sources in an underground metal mine environment.

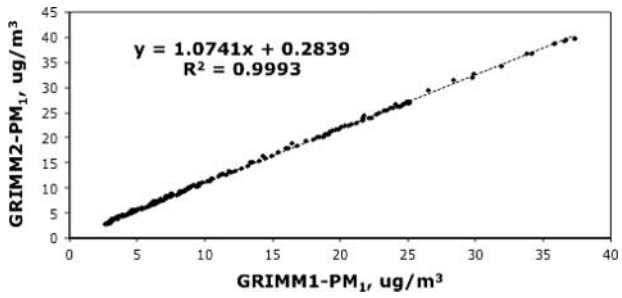

FIGURE 3. Linear regression between particle concentration results from both Grimm instruments when connected to a common inlet in the Utah mine.

Also, the variance of the DPM density by interval size within a sampling period highlights the notion that diesel emissions are a mixture of particulate aerosols and a complex host of gases and vapors not limited to EC and OC, and is dependent on other factors, such as engine load.[9] Different particles or particles with different types of adsorbed OC contribute to different DPM densities at different interval sizes and may affect the correlation between a cassette TC concentration result and a Grimm instrument mass concentration result.

CONCLUSION

An evaluation of the results from this study suggests that monitoring DPM with the commercially available Grimm instrument may provide the capability to rapidly, and with sufficient accuracy, measure underground mine workplace concentrations of DPM emissions compared with traditional cassette sampling and analytical methods. Calculated DPM densities of 1.7, 1.6, and 1.7 g/cm^3 were similar to the published range of 0.2 to 2 g/cm^3 for diesel particles and varied by interval sizes. Variance of the calculated diesel densities by interval size supports the current understanding that diesel emissions are a mixture of particulate aerosols and a complex host of gases and vapors not limited to EC and OC and dependent on other variables.

Further, data from this real-time instrument may help the underground mining industry decrease lag time between sampling and obtaining results that would assist in ensuring that exposure controls are adequate or hastening the implementation of control strategies to more effectively reduce DPM concentrations in air to acceptable or lower levels as regulated by MSHA if warranted. However, more research is needed to more fully explore the capabilities of the Grimm instrument as a surrogate monitoring method in the underground metal mining environment.

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REFERENCES

1. **Cohen, H.J**, **J. Borak**, **T. Hall**, **G. Sirianna**, **and S. Chemerynski:** Exposure of miners to diesel exhaust particulates in underground nonmetal mines. *Am. Ind. Hyg. Assoc. J.* (*63*):651–658 (2002).

2. **Haney, R.A.**, **G.P. Saseen**, **and R.W. Waytulonis:** An overview of diesel particulate exposures and control technology in the U.S. mining industry. *Appl. Occup. Environ. Hyg. 12*:1013–1018 (1997).
3. "Diesel Monitoring and Control Highlights." [Online] Available at http://www.cdc.gov/NIOSH/mining/highlights/programareahighlights8.htm (Accessed March 1, 2008).
4. **Stephenson, D.J., T.M. Spear**, **and M.G. Lutte:** Comparison of sampling methods to measure exposure to diesel particulate matter in an underground metal mine. *Mining Engineering 58*(*8*):39–45 (2006).
5. "Diesel Particulate Matter Exposure of Underground Metal and Nonmetal Miners; Final Rule." *Federal Register* (30 CFR Part 57) *70*(*107*):32868–32964. 2005.
6. **International Agency for Research on Cancer (IARC):** *Diesel and Gasoline Engine Exhaust and Some Nitroarenes*. Monograph 1989; IARC Monographs on the Evaluation of Carcinogenic Risk to Humans: Vol. 46. Lyon**:** World Health Organization. 1989.
7. **Noll, J.D., A.D. Bugarski, L.D. Patts, S.E. Mischler**, **and L. McWilliams:** Relationship between elemental carbon, total carbon, and diesel particulate matter in several underground metal/non-metal mines. *Environ. Sci. Technol. 41*(*3*):710–716 (2007).
8. **Kittleson, D.B.:** Engines and nanoparticles: A review. *J. Aerosol Sci. 29*(*5*):575–588 (1998).
9. **Shi, J.P., D. Mark**, **and R.M. Harrison:** *Characterization of particles from a current technology heavy-duty diesel engine. Environ. Sci. Technol. 34*:748–755 (2000).
10. **Cantrell, B.K.**, **and J.C. Volkwein:** Mine aerosol measurement. In *Aerosol Measurement: Principles, Techniques, and Applications*, P.A. Baron and K. Willeke (eds.). New York**:** John Wiley & Sons, 2001. pp. 801–820.
11. "Review of Diesel Particulate Matter Sampling Methods." [Online] Available at http://www.me.umn.edu/centers/cdr/reports/EPAreport3.pdf (accessed September 1, 2009).
12. **Dong, C.C., X.J. Yin, J.Y.C. Ma, et al.:** Effect of diesel exhaust particles on allergic reactions and airway responsiveness in ovalbumin-sensitized brown Norway rats. *Toxicol. Sci. 88*(*1*):202–212 (2005).
13. **Ferraj, A.K., N. Haykal-Coates, A.D. Ledbetter, P.A. Evansky**, **and S.H. Gavett:** Neurotrophin mediation of allergic airways response to inhaled diesel particles in mice. *Toxicol. Sci. 94*(*1*):183–192 (2006).
14. **Fujimaki, H., Y. Kurokawa, S. Yamamoto**, **and M. Satoh:** Distinct requirements for interleukin-6 in airway inflammation induced by diesel exhaust in mice. *Immunopharmacol. Immunotoxicol. 28*:703–714 (2006).
15. **Chan, R.C., M. Wang, N. Li, et al.:** Pro-oxidative diesel exhaust particle chemicals inhibit LPS-induced dendritic cell responses involved in T-helper differentiation. *J. Allergy Clin. Immunol. 118*(*2*):455–465 (2006).
16. **Lehocky, A.H.**, **and P.L. Williams:** Comparison of respirable samplers to direct reading real-time aerosol monitors for measuring coal dust. *Am. Ind. Hyg. Assoc. J. 57*:1013–1018 (1996).
17. **Kim, J.Y., S.R. Magari, R.E. Herrick, T.J. Smith**, **and D.C. Christian:** Comparison of fine particle measurements from a direct-reading instrument and a gravimetric sampling method. *J. Occup. Environ. Hyg. 1*:707–715 (2004).
18. **Klepeis, N.E., W.R. Ott**, **and P. Switzer:** Real-time measurement of outdoor tobacco smoke particles. *J. Air Waste Manage. Assoc. 57*:522–534 (2007).
19. **Verma, D.K., D.S. Shaw, M.L. Shaw, J.A. Julian, S.A. McCollin**, **and K. des Tombe:** An evaluation of analytical methods, air sampling techniques, and airborne occupational exposure of metalworking fluids. *J. Occup. Environ. Hyg. 3*(*2*):53–66 (2006).
20. **Janisko, S.J.**, **and J.D. Noll:** Near real time monitoring of diesel particulate matter in underground mines. In *Proceedings of the 12th US/North American Mine Ventilation Symposium, Reno, Nevada, June 9–11, 2008*. K.G. Wallace Jr. (ed.). Reno, Nev.: University of Nevada-Reno. 509–513. (2008).
21. "Method 5042, *NIOSH Manual of Analytical Methods (NMAM),* 4th ed. DHHS (NIOSH) Publication, P.C. Schlecht and P.F. O'Connor (eds). [Online] Available at http://www.cdc.gov/niosh/nmam/pdfs/5040f3.pdf (Accessed September 3, 2007).
22. **Grimm, H.**, **and D.J. Eatough:** Aerosol measurement: The use of optical light scattering for the determination of particulate size distribution, and particulate mass, including the semi-volatile fraction. *J. Air Waste Manage. Assoc. 59*:101–107 (2009).
23. **Gebhart, J.:** Optical direct-reading techniques: Light intensity systems. In *Aerosol Measurement: Principles, Techniques, and Applications,* P.A. Baron and K. Willeke (eds.). New York: John Wiley and Sons, 2001. pp. 419–454.