Area monitoring
and spot-checking for diesel particulate matter in an underground mine

by S. Gaillard, E. McCullough and E. Sarver

Abstract ■ Diesel particulate matter (DPM) has been regulated by the U.S. Mine Safety and Health Administration since 2002 in underground metal and nonmetal mines. To demonstrate regulatory compliance, DPM samples must be collected and later analyzed by the U.S. National Institute for Occupational Safety and Health (NIOSH) 5040 standard method, but the FLIR Airtec DPM monitor can serve as a complementary engineering tool. The monitor is a handheld instrument that offers near-real-time measurements of elemental carbon (EC), which is a primary constituent of DPM. As part of an ongoing field study, the monitor was used to survey EC in an underground stone mine. This effort was aimed at determining spatial and temporal DPM variations in several key locations. The results of prolonged area monitoring—that is, lasting several hours — revealed that DPM concentrations were diluted substantially as air moved away from the primary production zone, but that concentrations could vary quite a bit in a single location from day to day and between seasons. DPM concentrations were generally lower in winter than in summer, which is consistent with increased natural ventilation airflows during winter. Using a modified sampling cassette, an attempt was also made to sensitize the Airtec monitor to allow for "spot-checking" of EC concentrations — that is, measurements made in several minutes. Preliminary field data showed that the sensitive cassette performed well in terms of providing accurate data that could be useful for rapid assessment of DPM.

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Introduction

Diesel particulate matter (DPM) is the solid fraction of the exhaust emissions from a diesel engine. It largely consists of elemental carbon (EC) and organic carbon (OC) (Birch, 2003). The World Health Organization International Agency for Research on Cancer classified diesel exhaust, including DPM, as a carcinogen (World Health Organization, 2012). It is believed to cause and/or exacerbate respiratory illness upon inhalation, deposition and retention in lung tissue. Because DPM exists in both the micro- and nanoparticulate ranges, it can bypass typical autoimmune defense mechanisms that keep larger particles out of the respiratory system (Ristovski et al., 2012).

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Compared with workers in other occupations involving frequent use of diesel-powered equipment, such as dock workers and truck drivers, underground miners are exposed to relatively high DPM concentrations because they work in enclosed environments (Noll and Janisko, 2013; Noll, Janisko and Mischler, 2013). A variety of engineering and administrative controls have been devised to reduce DPM exposures in mines, and increased airflow is often a key component. In large-opening mines, which are most common in the metal and nonmetal sector, DPM abatement through increased ventilation can be quite challenging because moving and controlling large air volumes is difficult (Grau et al., 2002; Grau and Krog, 2009). Dynamic ventilation conditions often result in variable and unpredictable DPM concentrations over space and time.

The U.S. Mine Safety and Health Administration (MSHA) has regulated DPM exposure in metal and nonmetal mines since 2002. Its final rule limits personal exposure to total carbon (TC), which is the sum of EC and OC, to an eight-hour time-weighted average of 160 µg/m^3 (U.S. Mine Safety and Health Administration, 2006). To demonstrate compliance, operators must use the U.S. National Institute for Occupational Safety and Health

(NIOSH) 5040 Method for the analysis of collected DPM samples (Birch, 2003). However, the handheld Airtec DPM monitor (FLIR Systems Inc., Nashua, NH) was developed as a way to provide near-real-time measurements of EC for tracking personal DPM exposures over a work shift (Janisko and Noll, 2010; Noll et al., 2014). The monitor works by capturing DPM on a filter and successively measuring laser extinction as the dark EC particles accumulate. The laser extinction is directly correlated to EC, but the monitor is also programmed to display TC as a time-weighted average (Takiff and Aiken, 2010). For this, an assumed TC to EC ratio of 1.3 is used, as discussed in Janisko and Noll (2008). Based on comparative analysis with NIOSH 5040 Method results, NIOSH confirmed the instrument meets or exceeds its accuracy criteria across a range of EC concentrations expected in mining environments (Noll and Janisko, 2013; Noll, Janisko and Mischler, 2013).

In addition to monitoring personal DPM exposures, the monitor can be used for area monitoring (Janisko and Noll, 2010; Takiff and Aiken, 2010; Noll et al, 2005; McCullough, Rojas-Mendoza and Sarver, 2015). By operating the instrument in a given location for a prolonged period, an understanding of the temporal variation, such as over a shift or over multiple shifts if monitoring on consecutive days, in DPM concentrations can be gained. Such monitoring in multiple locations can further provide valuable information regarding spatial variation in DPM within a mine (Janisko and Noll, 2010; Noll and Janisko, 2007). In the case that a quick assessment is needed, for example, as part of an occasional survey across different mine locations, the monitor might also be used for "spot-checking." However, this application will require sensitization of the instrument in most instances, as the desired time horizon for measurement is much shorter than that for which the monitor was developed — for example, 10 minutes versus 10 hours. To measure over shorter time periods, the monitor must be able to detect relatively smaller changes in EC deposition on the filter.

In this paper, the utility of the Airtec for area monitoring is demonstrated based on data collected in an underground stone mine. Results are presented from prolonged monitoring across multiple mine locations on multiple days, and in opposite seasons. Additionally, the monitor is discussed along with resulting spot-checking data.

Figure 1

Schematic of relative positions of all monitoring locations in the study mine.

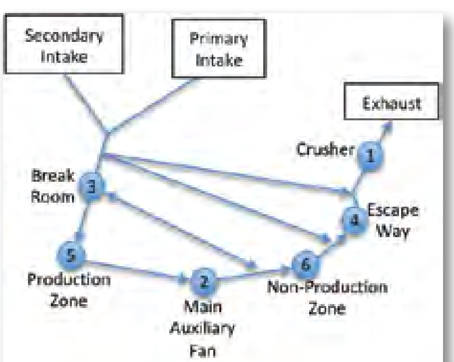


Table 1

Description of monitoring locations in the study mine.

Location	Description
1	Near main mine exhaust and underground crusher operation, moderate traffic (production and non-production equipment/vehicles).
2	Immediately upstream of main auxiliary fan.
3	Outside of portable break room, workers drive to this location for breaks.
4	Escape route far downstream from production zones.
5	Near primary production zone.
6	No production, centrally located, moderate traffic.

Site and experimental details

Study mine and monitoring locations. All data were collected in an underground stone mine with a diesel fleet consisting of about 40 pieces of equipment, including haul trucks, drills, loaders, auxiliary equipment and light-duty vehicles. The mine operates five days a week with two shifts per day. It is considered a large-opening mine, and air velocities are generally very low, less than 0.5 m/s (100 ft/min) in some locations, as is often observed in such operations (Grau et al., 2002; Grau and Krog, 2009). One fan is located on the surface forcing fresh air into the mine at a pressure of about 95 kPa (950 mbar), and the main ramp into the mine serves as another air intake, using natural ventilation. There is also a large auxiliary fan near the production zone and several booster fans, and ventilation tubing and curtains are further used to direct airflow in priority areas. Air exits the mine through a single exhaust.

DPM is the only airborne occupational health hazard known to be of real concern in the study mine. Concentrations of respirable dust, including silica, are quite low, and blast fumes dissipate overnight between shifts. Six distinct locations were selected for this study based on their proximity to activities or airways of interest (Table 1). Figure 1 illustrates the relative positions of the locations within the mine, with arrows indicating airflow direction.

Equipment and data collection. In late July through mid-August 2015, the Airtec was used for prolonged DPM monitoring, with EC concentration measured over time, and spot-checking, with rapid assessments of EC concentration. In December 2015, additional prolonged monitoring was conducted. An Anemosonic UA6 ultrasonic anemometer (TSI, Shoreview, MN; discontinued) or PMA-2008 vane anemometer (Mine and Process Service, Inc., Kewanee, IL) was used during some spot checks to determine the air speed near the monitoring equipment.

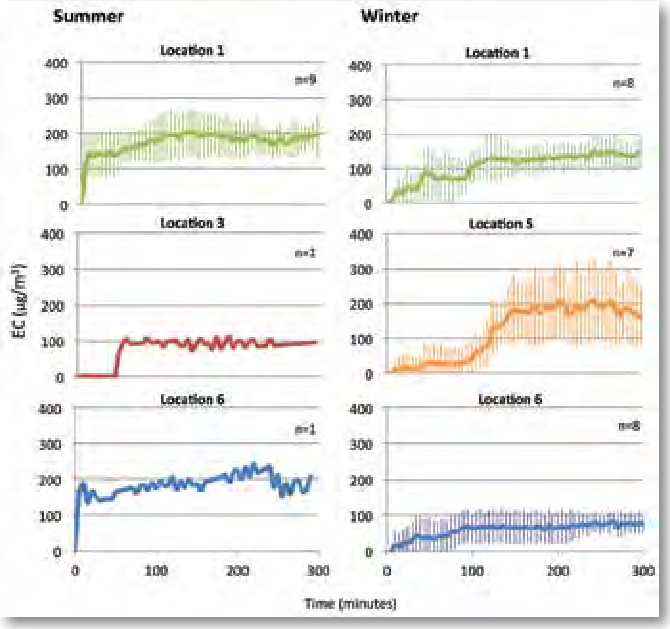
Three Airtec monitors, each calibrated to the standard flow rate of 1.7 L/min, were used with the standard cyclone and impactor, which remove large, non-DPM particles (Noll et al., 2005). The monitor displays data as a five-minute rolling average for either EC or time-weighted average TC concentration, such that it does not display nonzero values until at least minute 6. The sample collection rate of each monitor was set to either one data point or five data points per minute, meaning that a new five-minute average value was displayed every minute or every five minutes, respectively.

For prolonged area monitoring, the monitors were operated with standard cassettes and sample filters, 37 mm in diameter, designed to allow continuous DPM monitoring over an entire work shift, with the main target parameter being time-weighted average TC concentration, which is consistent with evaluating compliance with personal exposure limits. Due to the limits of the optical sensor in the Airtec, this means that when operating the Airtec to monitor a fixed location it may take a relatively long time before enough EC accumulates on the sample filter for the instrument to begin reading stable values. In order to collect spot-check data with the Airtec, it therefore needs to be sensitized.

As a possible approach, NIOSH developed a sensitive cassette that effectively reduces the exposed filter area to a circle about 10 mm in diameter, such that apparent EC collection and thus laser extinction happen relatively quickly. All spot-check data in the study mine were collected using the sensitive cassette, and a preliminary experiment was conducted to compare results from standard and sensitive cassettes.

Figure 2

Prolonged monitoring results from summer and winter. For locations where multiple data sets were collected in the same season, *n* values are given and results are shown as an average with error bars representing the standard deviation.



Results and discussion

Prolonged area monitoring of EC concentrations. During the summer and winter of 2015, 11 and 23 prolonged monitoring data sets were collected, respectively (Fig. 2). The tests were started at roughly the same time of day, near the beginning of a regular work shift, and continued for at least 300 minutes, with data reported only between 0 and 300 minutes to be consistent between all tests. In locations where multiple prolonged tests were conducted, each was on a different day. In all cases, the Airtec was positioned at approximately head height, or 1.8 m (6 ft), and care was taken to monitor about the same point in each location from day to day, either near the center of the tunnel cross section or about 0.6 m (2 ft) off the rib in locations with traffic.

Though the data collected for this study are somewhat limited, several key observations can be made from Fig. 2. First, as may be expected, DPM concentrations, using EC as a proxy, appear to vary both spatially and temporally in the mine. During the summer, locations 1 and 6, which are both along the main exhaust route from the mine, had higher EC concentrations than location 3, which is along the intake airways but is likely affected by some recirculating airflow that picks up DPM near production. From the winter monitoring data, it is clear that location 5, just outby from the main production zone, had the highest DPM concentrations recorded in that season. The DPM appears to be substantially diluted by the time it reaches locations 6 and 1.

Furthermore, DPM concentrations in the study mine seem to vary with season, which is consistent with the well-established understanding of ventilation in large-opening mines (Grau et al., 2002; Grau and Krog, 2009). Comparing summer versus winter data in locations 1 and 6, EC concentrations are clearly lower in the winter, despite no significant known changes in production or ventilation controls. According to monthly airspeed measurements taken by mine personnel in the main exhaust tunnel, where the cross section is small enough to perform a proper traverse, airflows were on the order of 92 m^3/s (195,000 cfm) during the summer tests and 109 m^3/s (230,000 cfm) during the winter tests.

Finally, Fig. 2 also suggests that DPM concentrations can be quite variable within a particular location in the mine. Some variation is likely due to accumulation of emissions with progression of the work shift, and this is demonstrated clearly in the winter data from location 5, but variability between days is also possible.

Figure 3 shows three consecutive weeks of prolonged monitoring data from location 1 from the summer and winter. This location may be expected to have relatively stable DPM concentrations over a work shift as it is located furthest from the primary emissions in the production zone. In the summer, EC values generally tended to increase over the workweek and then drop over the weekend, when there was no production. This may indicate that during summer workweeks DPM was accumulating in the mine faster than it could be exhausted overnight. In the winter, however, the trend of rising EC concentrations over the workweek was generally not observed, though the week 3 data do show an increase from Monday to Wednesday. So, while accumulation of DPM from one day to the next in a given location may explain some variation in prolonged monitoring data, there are surely many other factors at play, including dynamic ventilation conditions. As shown below, air speed measurements made for this study indicated that flows can change dramatically, even over relatively short time horizons such as days.

Spot-checking of EC concentrations. To confirm that the sensitive cassettes produced reliable EC concentration data, a series of basic tests were conducted briefly in the study mine. First, two Airtecs both using the sensitive cassettes were compared side by side. Then, the sensitive cassettes were compared against the standard cassettes. Locations and test times were chosen such that a range of EC concentrations could be sampled, but concentrations were expected to be stable during sampling due to the relative distance between the sampling locations and DPM emissions sources, and anecdotal experience of mine personnel and the research team. In nine side-by-side tests using sensitive cassettes, the absolute difference between the monitors was 13.4 ± 9.5 percent. However, in two of the tests with relatively high differences, 31 and 16 percent, the initial optical sensor value of one Airtec was observed to be very low, only about half that of a typical initial value. This can happen if the exposed filter area on the sensitive cassette is slightly misaligned with the laser and optical sensor, and may have influenced the quality of data collected. Excepting those two tests, the average difference between the monitor was 10.3 ± 7.2 percent. This is well within the range of possible spatial variability, which has been reported to be up to 20 percent (Vinson, Volkwein and McWilliams, 2007).

To compare EC values measured with the sensitive versus the standard cassettes, eight comparison tests were conducted (Fig. 4). For seven tests, a single monitor was used to first collect data on a standard filter, and then it was immediately used to collect data in the same location on a sensitive filter. The total lag time in these tests between the end of the standard cassette data and the data plateau for the sensitive cassette was relatively short, only the 2-3 minutes required to change the cassette and then the time required for the sensitive cassette data to reach plateau, 6-15 minutes. Thus, it is expected that any changes in DPM concentration in the sampling location were minor and should not substantially affect the sensitive and standard cassette comparisons. In test 5, two calibrated monitors were run side by side, one with each filter type. Because the sensitive cassette uses a smaller filter area than the standard cassette, Airtec data from the former must be corrected. In Fig. 4, all sensitive cassette data had been corrected by dividing the EC concentrations by 13.3, the standard-to-sensitive filter area ratio.

The need to sensitize the Airtec for spot-checking is well-illustrated in Fig. 4. While the sensitive cassette data tended to plateau relatively quickly and remain stable, the standard cassette data took longer to plateau, if at all. By comparing the apparent EC concentrations where data plateaued, or fluctuations at least dampened, the sensitive and standard cassette data generally tended to correlate well. In five of the eight comparison tests — tests 1, 2, 3, 5 and 7 — the observed ratio of the apparent EC concentration from the standard cassette to the uncorrected value from the sensitive cassette was 13.5 ± 0.5. This is very close to the expected 13.3 value, suggesting that the sensitive cassettes are indeed performing as intended. In tests 4 and 6, it appears that the standard cassette data did not have a chance to reach plateau within the test period, possibly because the EC concentrations in the test area were too low. This highlights a primary advantage of using the sensitive cassette for short-term measurements. In test 8, the initial optical sensor value on the sensitive cassette run was observed to be very low. All spot-check data shown here had been corrected by the 13.3 factor.

Another important observation from Fig. 4 is that, while data from the sensitive cassettes tended to plateau quickly, the time to the first nonzero values can vary. Based on observations in additional follow-up tests, not shown, this also seems to be related to the initial optical sensory value of the Airtec, which can be influenced by the initial condition of the filter when the instrument begins collecting data. Slightly used filters, such as from a prior spot-check, generally tended to produce data plateaus more quickly, beginning on minute 6, than new filters, which took up to 10 minutes or, rarely,

Figure 3

Results of prolonged monitoring at location 1 by weekday from summer and winter. In both seasons, data were collected on multiple days during three consecutive weeks.

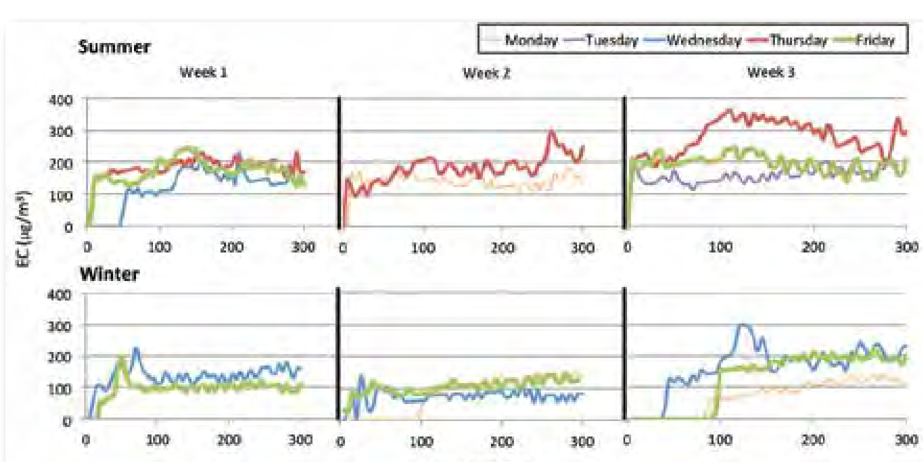
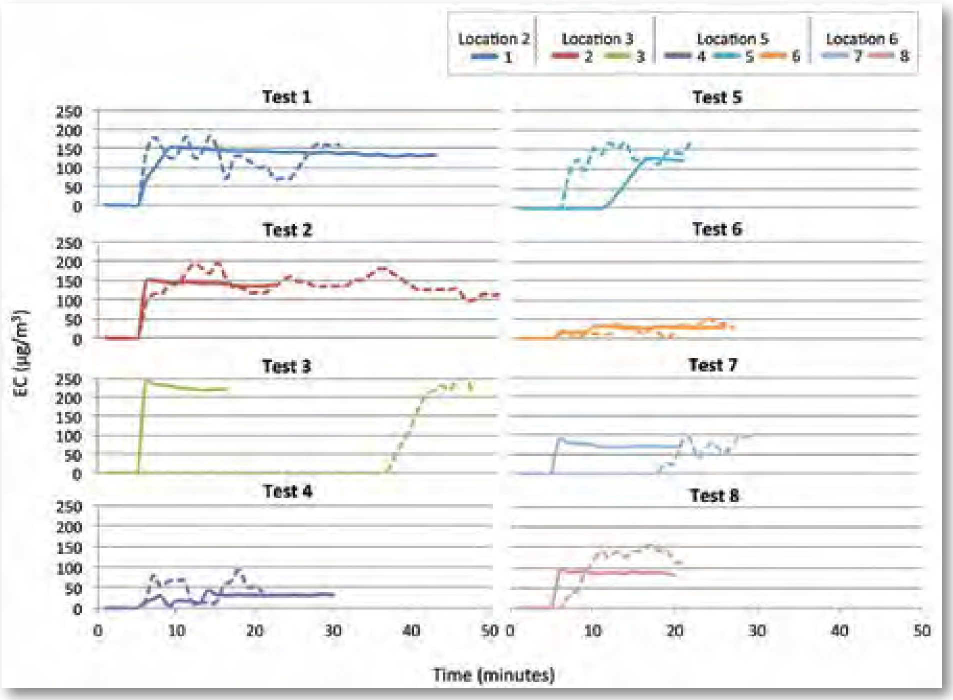


Figure 4

EC concentrations measured in eight comparison tests using standard (dashed lines) and sensitive (solid lines) cassettes. The x-axis represents the relative data collection time for a given cassette, with all data starting at 1 minute. In test 5, the cassettes were tested simultaneously using two Airtec monitors running side by side. In all other tests, the cassettes were tested in back-to-back runs using a single monitor, and data from both runs were overlaid to allow comparison of EC values and time-to-data plateau.



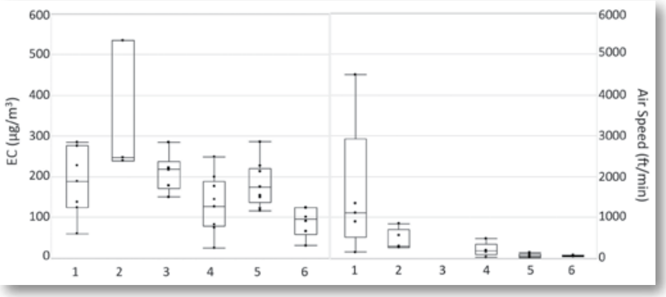
more. With this knowledge, only spot-checking data where a plateau was observed or inferred are reported below.

To demonstrate the utility of spot-check surveying with the Airtec, data were collected at head height in all six locations in the study mine during the summer of 2015. Air speed measurements were also recorded during some of the spot-checks (Fig. 5). In each location, spot-checks were performed on multiple days, during the middle of the workshift at least two hours after the shift began and at least two hours before it ended. Some of the spot-check data shown in Fig. 5 are from tests where the initial optical sensor value was relatively low, but based on our experience to date, data collected under such conditions are expected to vary by only up to about 30 percent versus data collected with a typical initial optical sensor value, with no bias between the two conditions or the specific instruments. Thus, the large variations in reported spot-check data are believed to be real.

In general, the spot-check surveys confirmed that spatial and temporal DPM variations can be significant in the study mine. Consistent with observations from prolonged monitoring, locations 1 and 5, near the exhaust and production zone, tended to have relatively high EC concentrations that were variable from day to day. This was also the case for location 4, along the main air route between production and the mine exhaust, and, somewhat surprisingly, location 3. Based on the single prolonged monitoring data set from that location, it was expected to have relatively low EC concentration, but

Figure 5

Spot-check and air-speed data collected at head height in all mine locations. Air speeds were measured only twice in location 6 and not measured at all in location 3.



spot-checking revealed that the concentration can be fairly high. Because spot-checking was done mid-shift, it is possible that traffic to and from the break room near location 3 caused large but temporary fluctuations in DPM. Also somewhat unexpected are the spot-check results from location 6, which suggest relatively low EC concentrations in contrast to the prolonged monitoring results. The spot-checking results from location 2, near the auxiliary fan, were the most variable. This may be related to movement of concentrated

DPM pockets by the fan. While only a limited amount of air speed data was collected during this study, it illustrates the dynamic ventilation conditions in the study mine.

Spot-check tests were additionally conducted in locations 2, 4 and 5 to compare measured EC concentrations at head versus cab height, or 4.9 m (16 ft), with 14 comparisons made (Table 2). For these tests, a spot-check was done at head height and another was done immediately afterwards at cab height at the same point in the tunnel. Generally, little difference is seen between DPM concentrations within this vertical distance and no real trend in the relative difference between the measurement heights. In 10 of the tests, the absolute difference was less than 10 percent, which is the expected average error in side-by-side spot-check measurements as reported above.

Conclusions

While the NIOSH 5040 Method is required for demonstrating compliance with DPM exposure limits in underground metal and nonmetal mines, the FLIR Airtec DPM monitor is a useful engineering tool that provides the ability to evaluate DPM concentrations in near real time. Using its standard operating parameters and sampling cassettes, it can be used not only to track personal exposures but also to conduct area monitoring. In this work, the area-monitoring application of the monitor was demonstrated in an underground stone mine. The monitor was also studied for a spot-checking application to allow rapid EC measurements. Use of a sensitive cassette, which reduces the exposed filter area, proved to be a simple and effective way to sensitize the monitor for this purpose. In general, the results from both prolonged area monitoring and spot-checking indicate that EC, and thus DPM, concentrations can vary significantly in both space and time within the study mine.

Beyond use in occupational health programs, the Airtec or similar environmental monitoring technologies may also contribute to the improved understanding of mine ventilation systems, particularly in large-opening mines, which are challenged when it comes to airflow modeling and analysis. Such technologies could further provide insights into the fates of airborne particulates as they travel from their sources. ■

Table 2

Results of spot-check tests conducted at head versus cab height.

Test	Spot-checked EC concentration (µg/m³)		Difference (%)
	Head height	Cab height	
1	240	227	5.4
2	239	239	0.1
3	256	232	9.9
4	83	72	14.5
5	177	173	2.3
6	75	88	–15.9
7	145	148	–2.3
8	214	195	9.4
9	134	189	–34.3
10	192	197	–2.7
11	286	265	7.7
12	117	115	1.9
13	161	199	–21.2
14	176	190	–7.6

Acknowledgments

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References

Birch, M.E., 2003, "Monitoring of diesel particulate exhaust in the workplace," NIOSH Manual of Analytical Methods, 4th Edition, U.S. National Institute for Occupational Safety and Health.

Grau, R., and Krog, R., 2009, "Ventilating large opening mines," *Journal of the Mine Ventilation Society of South Africa*, Vol. 62, No. 1, pp. 8-14.

Grau, R., Mucho, T., Robertson, S., Smith, A., and Garcia, F., 2002, "Practical techniques to improve the air quality in underground stone mines," *Proceedings of the 9th U.S./North American Mine Ventilation Symposium*, pp. 123-129, http://dx.doi.org/10.1201/9781439833742.ch19.

Janisko, S., and Noll, J.D., 2008, "Near real time monitoring of diesel particulate matter in underground mines," *Proceedings of the 12th U.S./North American Mine Ventilation Symposium*, pp. 509-513.

Janisko, S., and Noll, J.D., 2010. "Field evaluation of diesel particulate matter using portable elemental carbon monitors," *Proceedings of the 13th U.S./North American Mine Ventilation Symposium*, pp. 47-52.

McCullough, E., Rojas-Mendoza, L., and Sarver, E., 2015, "DPM monitoring in underground metal/nonmetal mines," *Proceedings of the 15th North American Mine Ventilation Symposium*, pp. 325-330.

Noll, J., Cecala, A., Organiscak, J., and Janisko, S., 2014, "Real-time DPM monitoring: NIOSH develops a new tool for assessing and controlling exposure," *Engineering & Mining Journal*, pp. 78-81.

Noll, J., and Janisko, S., 2007, "Using laser absorption techniques to monitor diesel particulate matter exposure in underground stone mines," *Proceedings of SPIE*, Vol. 6759, pp. 67590P-67590P11, http://dx.doi.org/10.1117/12.737790.

Noll, J.D., and Janisko, S., 2013, "Evaluation of a wearable monitor for measuring real-time diesel particulate matter concentrations in several underground mines," *Journal of Occupational & Environmental Hygiene*, Vol. 10, pp. 716-722, http://dx.doi.org/10.1080/15459624.2013.821575.

Noll, J., Janisko, S., and Mischler, S.E., 2013, "Real-time diesel particulate monitor for underground mines," *Analytical Methods*, Vol. 5, No. 12, pp. 2954-2963, http://dx.doi.org/10.1039/c3ay40083b.

Noll, J.D., Timko, R.J., McWilliams, L., Hall, P., and Haney, R., 2005, "Sampling results of the improved SKC diesel particulate matter cassette," *Journal of Occupational and Environmental Hygiene*, Vol. 2, pp. 29-37, http://dx.doi.org/10.1080/15459620590900320.

Ristovski, Z.D., Miljevic, B., Surawski, N.C., Morawska, L., Fong, K.M, Goh, F., and Yang, I.A., 2012, "Respiratory health effects of diesel particulate matter," *Respirology*, Vol. 17, No. 2, pp. 201-212, http://dx.doi.org/10.1111/j.1440-1843.2011.02109.x.

Takiff, L., and Aiken, G., 2010, "A real-time, wearable elemental carbon monitor for use in underground mines," *Proceedings of the 13th U.S. North American Mine Ventilation Symposium*, pp. 137-141.

U.S. Mine Safety and Health Administration, 2006, "Diesel Particulate Matter Exposure of Underground Metal and Nonmetal Miners; Final Rule," Federal Register, Vol. 71, No. 96, pp. 28924.

Vinson, R., Volkwein, J., and McWilliams, L., 2007, "Determining the spatial variability of personal sampler inlet locations," *Journal of Occupational and Environmental Hygiene*, Vol. 4, No. 9, pp. 708-714, http://dx.doi.org/10.1080/15459620701540618.

World Health Organization International Agency for Research on Cancer, 2012, "IARC: Diesel Engine Exhaust Carcinogenic."