Near real time monitoring of diesel particulate matter in underground mines

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ABSTRACT: Studies have linked long-term inhalation of diesel exhaust with adverse health effects such as cardiovascular disease, cardiopulmonary disease, and lung cancer. Diesel exhaust levels in underground mines can approach 100 times the environmental level and are therefore monitored closely in the mining industry. Elemental carbon (EC) (a product of diesel combustion commonly referred to as "soot") has proven to be a good indicator of diesel exhaust levels. The current procedure for measuring EC levels involves taking personal samples from a mine worker's breathing zone and/or stationary samples in various parts of the mine and subsequently sending these samples to a lab for analysis by NIOSH 5040 method. Unfortunately, the whole process can take up to several weeks to complete. To address the problem of waiting weeks for results, NIOSH's Pittsburgh Research Laboratory is developing a portable device for measuring levels of elemental carbon. This optical device takes a continuous sample of air in the surrounding environment and measures the absorbance of light passing through a filter that collects diesel exhaust particulates within the instrument. This technology can provide a near real time measurement of EC with accuracy within 10% error. The ability to take near real time measurements, combined with the instrument's portability (currently small enough to be worn on a miner's belt), makes this device extremely useful in the mining industry.

1 Introduction

Diesel exhaust is a complex mixture that contains thousands of compounds. Diesel particulate matter (DPM) constitutes a large fraction of this mixture and has been recognized as a potential occupational carcinogen by the National Institute for Occupational Safety and Health (NIOSH). Therefore, NIOSH has recommended that worker exposure to DPM be limited. Occupations where this exposure is of high concern include mine worker, bridge and tunnel worker, railroad worker, loading dock worker, truck driver, forklift driver, farm worker, and auto mechanic (1). In particular, underground mine workers are exposed to some of the highest levels of DPM on a day to day basis.

DPM itself is made up largely of particulate and particle bound organic carbon (OC) and particulate elemental carbon (EC) (commonly referred to as "soot") (2). Total carbon (TC) is the summation of EC and OC.

The Mine Safety and Health Administration (MSHA) initially considered TC as the best surrogate for measuring DPM in underground mines because it accounts for over 80% of diesel particulate matter and because the EC to DPM ratio can change with engine load (3). However, cigarette smoke and oil mist in the sampling environment can add error to OC measurements which, in turn, can lead to flawed TC measurements (4, 5). As a result, MSHA has imposed an interim technique for monitoring DPM in mines which involves the measurement of both EC and TC.

The interim 2007 DPM limit is 350 μg/m^3 TC, which can also be determined using EC as an analyte. The standard sampling method (see section 2.5) is performed over an entire shift and the filter is analyzed for TC and EC using the NIOSH 5040 method. The concentration of TC is calculated in two ways. In first way, the value of TC from the NIOSH 5040 is converted to an 8-hour shift weighted average (SWA), and in the second way, the EC value from the NIOSH 5040 is converted to an 8-hour SWA and then multiplied by 1.3 (a conversion factor determined by MSHA using the 31-mine study). If either the measured total carbon SWA or calculated total carbon SWA is above 350 μg/m^3 then the mine is out of compliance (4).

This standard method requires samples to be taken in the mine and then be sent to a laboratory for NIOSH 5040 analysis. The process is time-consuming and it can take several weeks before a mine receives the results. If a portion of the mine is out of compliance, ventilation adjustments have to be made and once again, several weeks will pass before the mine obtains the new results. In addition, the standard method can only provide a value for the average EC concentration throughout the sampling period. It is incapable of showing concentration changes due to such factors as vehicle traffic or mineworker travel throughout the day.

NIOSH has developed an instrument capable of measuring EC at typical underground mining concentrations in near real time. This instrument, referred to as the “EC monitor” uses a laser diode absorption technique similar to that used in conventional NIOSH 5040 analysis instruments (Magee Scientific, Berkeley, CA and Sunset Laboratory, Tigard, OR)[i]. However, the EC monitor is portable, lightweight and designed for near real time analysis. This instrument can be attached to a miner’s belt or to a piece of equipment to provide EC concentration analysis on the spot or to plot elemental carbon concentration with time.

2 Methodology

2.1 Design

Please note: Due to pending manufacturing agreements, some design specifications cannot be discussed in depth. Full disclosure of design components will be released in future publications.

The design of the EC monitor consists of four key components: an impactor, a filter, a pump, and an optical measuring circuit. The first component in the sampling train is an impactor through which air is drawn at a set flow rate in order to separate larger dust particles from DPM. This impactor can be placed in a miner’s breathing zone via a lapel holder. The air/DPM mix then passes through a filter within the instrument and EC from the air sample is collected onto the filter. An optical sensing circuit is used to measure the intensity of light transmitted through the filter from a laser diode source. As EC continues to collect on the filter, more light is absorbed and the output voltage of the light sensor decreases. This drop in voltage is compared with a previously established calibration curve to relate laser absorption to EC concentration (see section 2.2). A data logger is used to record these changes in voltage and a microcontroller is used to calculate and output EC values to an LCD screen on the instrument in real time.

2.2 Calibration

In order to establish a relationship between light absorbance and EC concentration, the EC monitors were calibrated in a controlled diesel exhaust laboratory (NIOSH, Pittsburgh Research Laboratory). During calibration, three EC monitors simultaneously sampled from a chamber filled with DPM. The light sensor voltages of these instruments were monitored throughout the test. At the same time, standard NIOSH 5040 sampling was performed to collect EC from the chamber on sets of quartz filters at a regulated flow rate of 1.7 liters per minute. Each set consisted of three DPM cassettes, and each cassette contained two 37mm quartz filters in series (SKC, Inc., Eighty Four, PA). The three EC monitors and the filter sets all began sampling at a common time. The DPM concentration inside the chamber was held steady and the filter sets sampled for different lengths of time so as to collect different amounts of EC on each set of filters. These times were recorded, as were the correlating sensor voltage drops in the EC monitors. Post analysis using the NIOSH 5040 Method was then performed on the filter sets to determine the specific amounts of EC on the filters (see section 2.3). The laser light transmittance was obtained from sensor voltage drop and the laser light absorbance was calculated from transmittance. The EC values were plotted against absorbance to obtain the calibration curve.

2.3 NIOSH 5040 Method

The NIOSH 5040 method is an established technique for measuring both organic and elemental carbon. The process involves drawing sampling air through a DPM cassette (SKC, Inc., Eighty Four, PA) at a flow rate of 1.7 liters per minute to collect soot onto quartz filters inside the cassette. After sampling, punches of these filters are placed inside a 5040 oven for analysis. The oven first measures organic carbon (OC) by progressively ramping its temperature up to 870 °C in four steps in a pure helium environment. The lack of oxygen prevents EC from reacting. OC is oxidized to carbon dioxide and is reduced to methane. The methane is measured using a flame ionization detector (FID). EC is then measured by reducing the oven temperature and then raising it back up to 900 °C in a helium/oxygen atmosphere. EC reacts with oxygen to form carbon dioxide. Once again, the carbon dioxide is reduced to methane and the methane is measured with an FID (6).

2.4 Drop Testing and Sensitivity

To ensure that the monitors are not susceptible to interferences from sudden jerking or shock, a drop test was established to verify the rigidity of the instruments. This testing would also yield data suitable for calculating the limits of detection and quantification of the instruments while in rugged use. During these experiments, one EC monitor was repeatedly dropped from four inches while the other was shaken intermittently at the same rate throughout an eight-hour time period. These motions were achieved via mechanical means. The monitors sampled clean air and the sensor voltages were logged. This test was repeated five times, with monitors rotating positions after each test. The resulting ten blanks (five drops, five shakes) were used to calculate the limits of detection and quantification with a multiplying factor of 3 for LOD and a multiplying factor of 10 for LOQ (7).

2.5 Personal Sampling

The current MSHA method for measuring a mineworker’s exposure to EC involves outfitting the miner with a belt-worn pump that draws air from his or her breathing zone. The air sample is first drawn through a Dorr-Oliver cyclone pre-selector and then through a sampling cassette containing quartz filters (SKC, Inc., Eighty Four, PA). At the end of the mineworker’s shift, the quartz samples are sent to a lab for 5040 analysis. The data obtained represent an aggregate amount of EC exposure throughout the sampling period.

The EC monitors are outfitted with belt loops and are worn in a fashion similar to the pump. The monitors continuously measure EC exposure throughout the day, which is the major benefit over the current method. At the end of a worker's shift, data from the EC monitor can be downloaded and his or her exposure to EC throughout the day can be plotted with time. In addition, real time and shift weighted average exposures to EC are calculated on-board and displayed through an LCD screen on the instrument. This allows the miner to instantly know his or her exposure at any given time.

Personal Sampling Case Study:

Note: An active stone mine was used as the location for all of the case studies in this proceeding.

To obtain personal sampling data, two NIOSH researchers were outfitted with EC monitors while taking ventilation measurements within a stone mine. The researchers were also adorned with standard sampling method equipment for comparison with the EC monitor results. The researchers traveled first to the return (the area where air exits the mine), then to two different working areas (the face), then to the intake (where fresh air is brought into the mine). The researchers exited the mine and the data sets were downloaded from the EC monitors. The standard samples were taken to a laboratory for 5040 analysis.

2.6 Cab Sampling

Environmental cabs are sometimes used in the mining industry to protect vehicle operators from high levels of DPM. These cabs have filtered air conditioning systems to provide a clean working environment for the vehicle operator. The efficiency of cab filtration can easily be tested by mounting one EC monitor on the exterior of the vehicle and placing another EC monitor inside the cab. After the desired amount of sampling time (typically eight hours), the data can be downloaded from the monitors and efficiency can be plotted with time. Standard practice for NIOSH researchers is to include three standard DPM sampling cassettes and pumps with each monitor so that the EC monitor results can be verified with a 5040 analysis. However, this exercise should depreciate with the acceptance of EC monitor readings.

Cab Sampling Case Study:

At the same stone mine used for personal sampling, a Catepillar 980F loader was outfitted with two sampling baskets, each containing an EC monitor and three traditional SKC DPM cassettes with pumps (per the above procedure). The loader was run on its normal working schedule, and after six hours the sampling baskets were removed for analysis. This procedure was followed for five days.

2.7 Area Sampling

The EC monitors can be a useful tool when measuring the effectiveness of a mine's ventilation system. Since the monitors provide EC concentration readings over time, a better observation of mine ventilation changes throughout the day can be obtained. To measure EC levels at a particular location in a mine, the EC monitors are mounted in baskets placed on tripods. Once again, three standard DPM sampling cassettes are typically included to verify the EC monitor recordings. However, as in the case of personal sampling, traditional methods can only supply an aggregate EC number throughout the sampling period, whereas the EC monitors can show how EC concentrations raise and lower with the movement of vehicles throughout the day. In addition, if an area of a mine has suspect ventilation, an EC monitor can be taken to that location to provide a quick measurement without the need for laboratory analysis.

Area Sampling Case Study:

Four areas of the stone mine were monitored to test the mine's ventilation system. Baskets containing an EC monitor and three SKC sampling cassettes were placed at the mine intake, return and two working areas where loading, drilling, roof bolting and scaling were occurring. After six hours of sampling, the baskets were removed for analysis. This procedure was followed for three days.

3 Results

3.1 Calibration Results

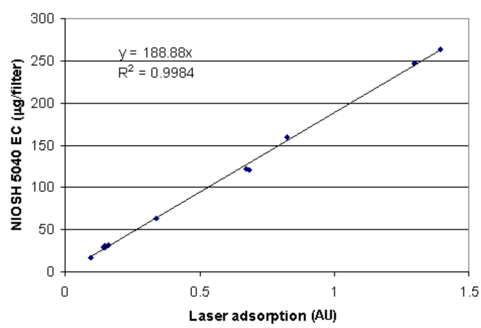

Figure 1 Relationship between EC monitor laser absorption and concentration measured by standard method.

The EC monitor calibration yielded a linear relationship between laser absorption and filter concentration for the concentration range tested (Figure 1). Laser transmittance is first calculated as $\frac{V_i}{V_o}$, where V_i is instantaneous photodiode voltage and V_o is the starting, blank-filter photodiode voltage. Laser absorption is the negative inverse log of transmittance, or $-\log\left(\frac{V_i}{V_o}\right)$. The slope (188.88) is programmed into the EC monitor firmware to convert absorption to concentration in real time.

3.2 Drop Testing and Sensitivity Results

The results of the drop tests demonstrated that the EC monitors are not prone to interferences from sudden shakes or drops. While sampling clean air, the sensor voltages remained stable for both monitors throughout the testing cycle. In addition, the limits of detection and quantification (7) for the following EC measurements are charted in Table 1: time weighted average (TWA), 5-minute average, 10-minute average and 15-minute average.

Blanks using EC Monitors				
	8 hr TWA blank (ug/m3)	5 min average (ug/m3)	10 min average (ug/m3)	15 min average (ug/m3)
Test 1	-1.60	-19.29	-9.65	-12.85
Test 2	-3.98	-1.93	-9.65	-6.43
Test 3	-2.00	0.00	-9.65	-5.14
Test 4	2.02	0.00	-6.75	-6.43
Test 5	0.00	-9.65	-7.72	-6.43
Test 6	-1.00	11.58	5.79	5.79
Test 7	-0.40	-1.93	-9.65	-3.86
Test 8	-2.00	-19.29	-9.65	-12.85
Test 9	-2.00	-19.29	-19.28	-10.29
Test 10	-3.98	-19.29	-4.82	-4.50
stdev	1.80	11.04	6.17	5.36
LOD	**5.40**	**33.13**	**18.51**	**16.08**
LOQ	**18.00**	**110.45**	**61.70**	**53.61**

Table 1. LOD and LOQ results

3.3 Personal Sampling Case Study

The real time readings measured by one of the researcher's EC monitors is shown in Figure 2. The data show that researcher was exposed to approximately 200 μg/m^3 EC in the return, 250 μg/m^3 EC at the first working area (Face 1), 150 μg/m^3 EC at the second working area (Face 2) and 30 μg/m^3 EC at the intake. The EC time weighted average (TWA) from the EC monitor data during this six-hour time period was 110 μg/m^3. Later, NIOSH 5040 laboratory analysis on the standard samples yielded a TWA EC measurement of 112 μg/m^3 for the same time period. However, the results from the EC monitor are much more valuable, because they show the increased or decreased levels of exposure that the researcher encountered as he traveled to different areas of the mine.

3.4 Cab Sampling Case Study

A portion of the cab sampling case study results shows how real time measurement can better account for unforeseen sources of error. The graphs below (Figures 3 and 4) show the interior and exterior EC monitor results from the same cab on the same vehicle but on two days with two different drivers. During the first test, the

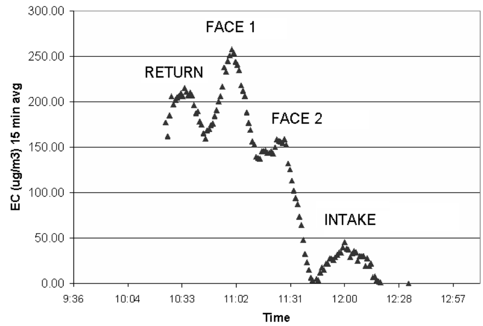

Figure 2 A researcher's EC exposure using a 15-minute running average as recorded by the EC monitor.

measured cab efficiency was about 73% (based on an average EC concentration of 104 ug/m^3 inside the cab and an average EC concentration of 378 ug/m^3 outside the cab) (Figure 3). The measured efficiency for the same cab during the second test was 93% (Figure 4).

Even if there were a leak in the filtration system, we would not expect cab efficiency to change drastically from day to day. However, the real time EC monitor results show large, unexpected peaks in EC concentration levels inside the cab at various times throughout the day (Figures 3 and 4). From this, we can determine that the cab operator in test 1 must have either opened the door of the vehicle or had the window of the vehicle open three times throughout the shift, marked by the three spikes in interior EC concentration. The operator in test 2 only opened the door or window once, as indicated by the spike at the beginning of the test. This simple, but highly pertinent test flaw caused the discrepancy in cab efficiency results. With the EC Monitor in use, these time periods when a cab door or window is open can be recognized and discarded, and thus the actual efficiency can be more accurately determined.

3.5 Area Sampling Case Study

A sample of the EC monitor results from one of the working areas in the area sampling case study is shown in Figure 5. During this particular test, the standard laboratory analysis concluded that the time weighted average (TWA) EC concentration for six hours was 653 μg/m^3. The EC monitor measured a similar TWA of 704 μg/m^3 EC for the same test. However, the EC monitor's real time data show that the EC concentration slowly built up over time (Figure 5).

This might indicate one of two things: either the ventilation was ineffective, slowly causing EC concentration to build up throughout the day or the number of vehicles operating at the working area had increased throughout the day. Since the number of vehicles was known not to change, it was determined that poor ventilation was the cause and that more air needed to be redirected to the working area to further dilute the EC concentration. This analysis would not have been possible with the laboratory results alone.

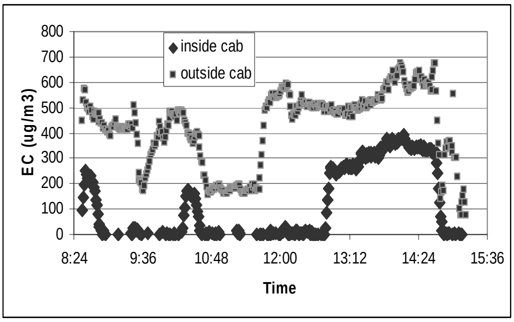

Figure 3 Interior and exterior cab EC concentration using a 5-minute running average during test 1.

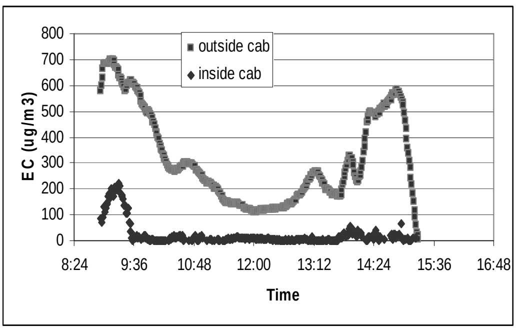

Figure 4 Interior and exterior cab EC concentration using a 5-minute running average during test 2.

4 Conclusion

NIOSH has recently developed a portable device that measures EC concentration in real time by an optical absorbance method. In certain cases, this device may eliminate the need for post laboratory analysis. As shown in the cab sampling case study, errors can occur in the standard method when averaging over an eight-hour time period. These errors may even go undetected. Since the EC monitor provides near real time analysis, it has the ability detect these errors and improve the accuracy of the current system.

This EC monitor can be worn by a mine worker to provide a real time measurement of individual EC exposure as well as shift weighted average. It can also be used to monitor ventilation and measure cab filtration efficiency.

The EC monitor provides important information that is not attainable with the standard method. It is highly portable, lightweight and accurate. Because of these factors, it can prove to be a vital tool when monitoring DPM in underground mines.

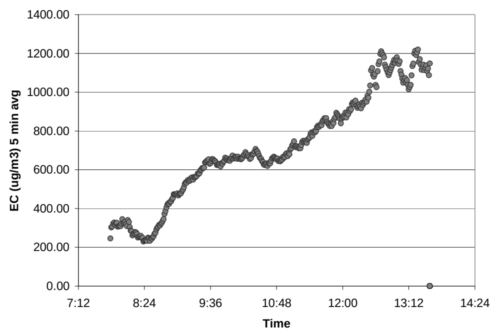

Figure 5 The EC concentration using a 5-minute running average over six hours of a shift at a working area in a limestone mine.

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[i] **Disclaimer:** Mention of any company or product does not constitute endorsement by the National Institute for Occupational Safety and Health (NIOSH).