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A real-time, wearable elemental carbon monitor for use in underground mines

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ABSTRACT: ICx Technologies is currently fielding a real-time, wearable elemental carbon monitor designed to determine real-time diesel particulate levels in mines. Diesel particulates are composed primarily of elemental and organic carbon and have been found to present a health hazard. Diesel particulate levels can be particularly high in underground mines. The Mine Safety and Health Administration (MSHA) regulates these diesel particulate levels through total submicron exposure in metal and non-metal mines. The current method of measuring personal exposure to elemental or total carbon nanoparticles involves collecting these particles on a quartz filter followed by a thermo-optical laboratory analysis. This remote laboratory analysis does not allow an understanding of where or when these levels occurred throughout the collection time. In addition, waiting weeks for these results makes it difficult to implement effective exposure reduction mechanisms and only documents that over-exposures have occurred rather than preventing them. This method is used because existing real-time particle monitors are either not sufficiently sensitive for measuring hazardous diesel particulate levels, are too large or costly for routine use in mines, or are subject to interference from other materials commonly present in mines. The ICx Diesel Particulate Monitor is based on a technique developed and tested at the U.S. National Institute of Occupational Safety and Health, Pittsburgh Research Laboratory. The ICx monitor uses real-time particle capture and analysis to yield elemental carbon values that are displayed to the wearer and logged by the compact device. The EC values displayed are based upon a correlation with an established laboratory method (NIOSH Method 5040) for elemental carbon emissions in a mine environment.

1 Introduction

Premature death and illness from particulate air pollution is one of the leading preventable public health problems in the United States. Researchers estimate that as many as 60,000 people in the U.S. die each year due to exposure to fine air particulates (Wilson & Spengler, 1999). A recent study by Abt Associates found that the toll from diesel particulate exposure alone is 21,000 deaths annually in the U.S., as well as 27,000 non-fatal heart attacks, 410,000 asthma attacks, and 2.4 million lost work days, with a total economic cost of $139 billion (Clean Air Task Force, 2005). This cost in lives exceeds that of deaths due to drunk driving and homicide combined. Diesel exhaust is regarded by the U.S. Environmental Protection Agency as a probable human carcinogen (U.S. EPA, 2002). Air particulates have been found to cause cardiovascular disease and mortality (Puett, *et al*., 2008) and large numbers of cases of bronchitis and asthma (Kunzli, *et al*., 2000). PM_{10} and $PM_{2.5}$ are described by the EPA as Criteria Air Pollutants.

These health impacts are particularly severe for populations exposed to high concentrations of air particulates. Underground miners are exposed to some of the highest levels of diesel particulates of any occupation due to the confined workspaces and continuous use of diesel equipment.

The health problems from inhaled particulates are a combination of the size and morphology of the micron and sub-micron particles (mostly carbon) themselves and the often toxic and carcinogenic organic compounds adsorbed on them (Giechaskiel *et al*., 2009). Both epidemiologic and *in vitro* studies have found correlations between particle size and shape and inflammatory potential and immunologic response; often the smallest particles appear to be the most damaging (Wittmaack, 2007). Particles may also be coated with adsorbed polycyclic aromatic hydrocarbons, nitroaromatics, combustion by-products, and heavy metals. These components are independently recognized by the EPA and other agencies as probable human carcinogens and toxic air pollutants (Dellinger *et al*., 2008). This makes diesel particulates particularly dangerous. While the gaseous products of combustion can also have adverse effects on health, most of the health impacts are believed to be due to the particulate component of combustion exhaust (Washington State Dept. of Health, 2008).

Because of this health hazard to miners, in the U.S. exposure of underground metal/non-metal miners to diesel particulate matter (DPM) is regulated by the Mine Safety and Health Administration (MSHA) (U.S. Dept. Of Labor, 2005). DPM is regulated by limiting total submicron carbon (TC) exposure levels to an eight hour time weighted average of 160 µg/m^3.. TC is the sum of elemental and organic carbon (EC and OC). TC exposure is determined from the individual quantification of EC and OC using the NIOSH method 5040. Where a potential overexposure occurs, due to the possibility that the OC could be from non-diesel sources, the confirmation of overexposure is based purely upon the EC fraction. MSHA recommends a method to convert EC into an adjusted TC concentration based upon sampling in an area where it is known that any interference to the OC fraction would be minimal.

Existing instrumentation for real-time air particulate measurement is often expensive, power-hungry, and bulky (such as condensation particle counters and many light-scattering devices). Even with these compromises, instruments (most light-scattering devices) are still unable to detect the most hazardous particles (less than 100 nm diameter) and some are subject to serious interference from the non-carbon particles often found in mine air, such as oil mist, water droplets, dust, and pollen (i.e. any device with a low airflow rate and without a particle size selector). As a result, most particulate air pollution studies use air samplers that trap particles on a filter that must then be sent to an analytical laboratory for subsequent analysis (Lee *et al*., 2006).

For DPM measurement in mines, MSHA stipulates and uses the NIOSH 5040 method. This method employs a pump to draw air through a particle size selector and onto a quartz filter. After a specified period of sampling (typically eight hours) the filter is sent to an analytical laboratory for thermo-optical analysis which yields EC, OC, and TC values.

The NIOSH 5040 method is accurate and reliable, but has serious drawbacks. First, it integrates the exposure to particulates over the entire sampling time. Therefore adapting worker schedules to cycling particulate levels is virtually impossible. Second, if employed as a mobile or personal monitor, all location data is lost due to this constant integration. This data would be invaluable to a mine ventilation engineer wishing to know when and where ventilation is inadequate. Third, the cost and effort of handling the samples and the laboratory analysis discourage frequent use of the method (the cost of a 5040 test is about $100, to generate a single number; this does not include the cost to the mine operation of sampling and filter handling). Fourth and perhaps most seriously, there is a two to three week turnaround time before test results are available to the mine. This prevents any real-time adjustment to the mine's ventilation, personnel, or equipment use to modify DPM exposures. Overexposure to DPM can thus be detected using this analysis method but not prevented. *Such sampling methods are not well suited to the active control of combustion particle generation or for site ventilation to reduce human exposures to hazardous levels of particulates.*

Consequently, a low-cost, sensitive, and accurate elemental or total carbon air particulate monitor for mines could be very beneficial..

2 The ICx Real-time DPM Monitor

2.1 Principle of Operation

The ICx real-time DPM monitor is based on a technique developed by Respiratory Hazards Control Branch at the National Institute for Occupational Safety and Health (NIOSH) Pittsburgh Research Laboratory (Noll *et al*., 2007; Noll & Janisko, 2007),subsequently licensed to ICx. As shown in Figure 1, mine air is drawn by a flow-controlled diaphragm pump through a particle size selector which only permits the passage of submicron particles. These particles are collected on a filter. A laser illuminates the filter and the transmittance of the laser beam is measured in real-time by the instrument. As DPM particles accumulate on the filter, the laser's transmittance decreases. The instrument converts this decrease in transmittance into a real-time concentration of elemental carbon in the air using calibration data obtained by the NIOSH laboratory using NIOSH Method 5040.

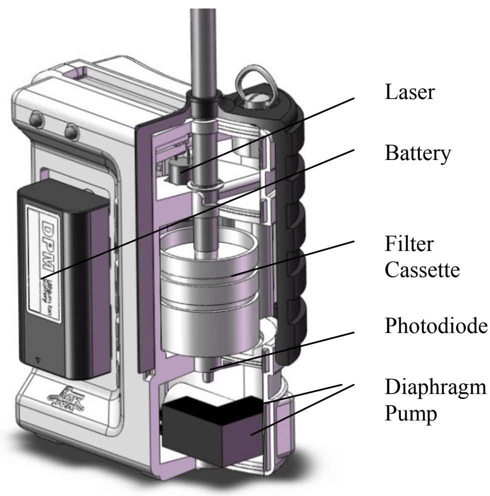

Figure 1 Principal components of the ICx DPM monitor.

The filter on which the particulates are captured is manually replaced (which takes only a few seconds) when it is fully loaded with black carbon. Its capacity is sufficient to operate for at least a full (12 hour)shift even in a very highly contaminated environment. In the event of overloading, a filter saturation alert is given by the instrument. However the low cost of the filter cassette allows its replacement after every shift in a mine.

The instrument manages to preferentially collect and analyze DPM particles by two methods. First, many potential interferents are removed by the particle size selector. Second, the use of light absorbance for the analysis focuses on the detection of highly absorbing materials such as black carbon rather than on less absorbing materials such as silicates or condensed water.

The instrument operates for up to 12 hours on a medium sized rechargeable lithium-ion battery. The unit has a real-time limit of detection equivalent to 15 μg/m^3 EC when using 5-minute averaging at a flow rate of 1.7 liters per minute (lpm). The dynamic range is equivalent to 9 – 300 μg/m^3 at 1.7 lpm and 18 – 600 μg/m^3 at 0.85 lpm expressed as an 8-hour time weighted average. The sensitivity and dynamic range of the instrument may be adjusted for the operating conditions in three ways. First, the rolling averaging time of the instrument may be adjusted to a period of 1 to 60 minutes (values of one or five minutes are typically used in mine environments). Second, the pump flow rate may be set to a low (0.85 lpm) or high (1.7 lpm) value. Third, the photodiode has both high and low gain settings.

The laser transmittance measurement method for black carbon is a technique that has been used for decades and is used in commercial instruments sold by such companies as Magee Scientific and Thermo Fisher Scientific. However, none of these instruments have the combination of portability, ruggedness, sensitivity, dynamic range, and particle selectivity for effectively measuring personal exposure to DPM in a mine environment.

2.2 Output

The unit, a prototype of which is shown in Figure 2, displays real-time EC levels on an LCD display, and can also display TC levels (converted from the EC data using a user-supplied, mine-specific conversion factor as described in MSHA publications). EC can also be displayed as an eight hour time-weighted average. In addition to the real-time display, EC data is logged internally and can be downloaded to a personal computer with a USB port.

Figure 2 A prototype of the DPM monitor. The size selector is not shown.

A nearly linear correlation between the filter absorbance and the EC level as measured by the NIOSH 5040 method is shown in Figure 3. This data was used calibrate the unit to display an EC concentration.

Figure 4 provides an example of the EC data downloaded from a trial in an underground mine. The peaks in EC level correspond directly to the passage of diesel vehicles near the monitor.

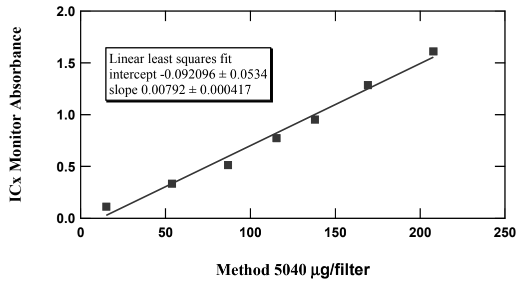

Figure 3 Optical response of the prototype ICx real-time DPM monitor, compared to the standard laboratory method for EC measurement (Method 5040).

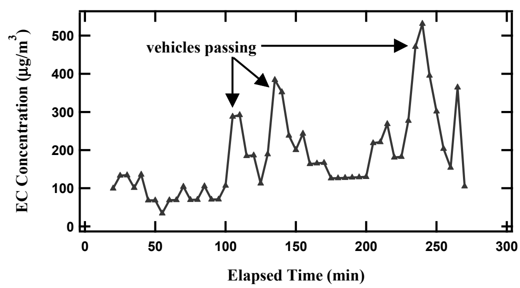

Figure 4 Example of the data from a prototype ICx real-time DPM monitor. Data was taken in a commercial mine; the peaks in the EC data reflect passing diesel vehicles.

2.3 Use of the Monitor in Underground Mines

Detailed discussions of how the monitor can be used to facilitate DPM exposure analysis and reduction in underground mines are given in the papers by Janisko & Noll (2010) and Lethbridge & Good (2010). Briefly, the monitor may be worn on a miner's belt, placed in or on a vehicle, or placed on a wall or table in an area where EC monitoring is desired. The intake and size selector may also be placed on the unit or remotely via conductive tubing. When activated, the unit will display and log the EC concentration until either the battery is exhausted or the filter is saturated. Usually, the battery is limiting, and the operating time of the instrument is determined by the battery capacity. A 4500 mAh battery will operate the unit for over 12 hours, though larger or smaller batteries and AC power may also be used.

The exposure limit alarm on the instrument can be used to alert the user when a set level of EC exposure has been reached. More commonly, the unit will be collected by a ventilation engineer or hygienist at the end of a shift or work period. The integrated exposure may be simply recorded at that time to yield an instant analog to a NIOSH 5040 test, without the need for outside lab analysis and a multi-week wait. Alternatively, some engineers will download the monitor's data (EC concentration as a function of time) to a personal computer, where they can correlate EC levels to the location of the miner, vehicles, or activity near the monitor's location. The locations in the mine or mine activities contributing to the greatest EC levels can be determined. If necessary, changes to personnel, vehicle use, or ventilation may be implemented to reduce EC concentrations. The monitor may then be used to instantly determine if the changes they made are having the desired effect on EC levels or allow them to implement different controls.

2.4 Effect of Real-time Monitoring on Data Collection

The currently used NIOSH 5040 method costs approximately $100 to generate a single EC/TC value. This includes the cost of the quartz filter cartridge and laboratory analysis. The ICx real-time DPM monitor generates dozens, hundreds, or more values for a fraction of the cost, depending on how the mine engineer chooses to use the unit. By any measure, the cost of DPM monitoring is drastically reduced. This cost reduction should allow a corresponding increase in EC sampling.

Real-time sampling allows ventilation engineers and hygienists to develop a comprehensive knowledge of the DPM levels in their mine. This newfound knowledge can be used to institute much more responsive and effective DPM control strategies. For the mine operator, the reduction in DPM sampling and analysis costs go right to the bottom line and a finer control of ventilation rates may be feasible, resulting in reduced energy usage and cost. The greater frequency of sampling enabled by the real-time monitor will also allow the operator to reduce the likelihood of being found out of compliance with DPM regulations and having to suffer the costs of such noncompliance. For the miners, the knowledge that a health threat is being monitored in real-time should be more assuring than only having the chance that this condition could be discovered weeks after it has taken place.

Examples of DPM monitoring in mines show how the real-time data can be more useful than time-averaged results. As shown in Figure 5, samplers for DPM were placed onto a vehicle to determine the concentration of DPM at the working face of the mine where the vehicle was operating. The average concentration (130 µg/m^3) included the time the vehicle was outside of the mine to refuel. The real time data showed that the concentration at the face was actually slightly above the average concentration, and the concentration of DPM when the vehicle was at the face was 200 µg/m^3 though the time weighted average was below the regulatory limit. The periods when the vehicle left the mine are also readily apparent. This information can be important to determine the ventilation rates needed to lower the DPM concentration in this area to below a certain value. In Figure 6, real-time EC data obtained from a monitor prototype is shown for a monitor mounted on a vehicle periodically working near a crusher. While the average concentration was 52 µg/m^3, during the period when the vehicle was located near the crusher (where miners were present), EC values between 80 and 140 µg/m^3 were recorded.

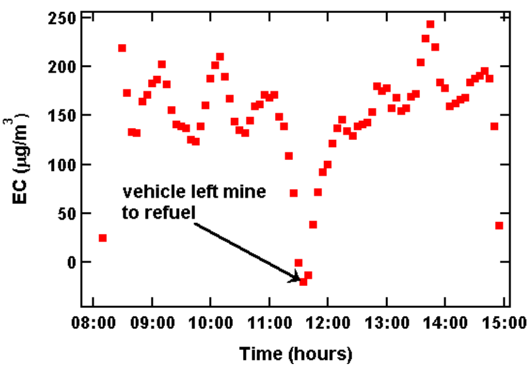

Figure 5 EC data recorded by the ICx real-time DPM monitor prototype operating on a vehicle in an underground mine.

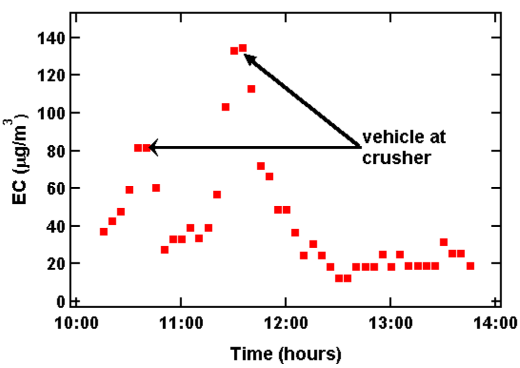

Figure 6 EC data obtained from a prototype of the ICx real-time DPM monitor mounted on a vehicle in an underground mine operating in the vicinity of a crusher.

2.5 Availability of the Instrument

The ICx DPM monitor will be commercially available in mid-2010.

3 Conclusion

The real-time ICx DPM monitor described here accurately replicates the results of the NIOSH 5040 technique used for EC and TC measurements in underground mines. The monitor does so without the multiple-week delay in obtaining results associated with a laboratory analysis method. The ICx DPM monitor provides a large amount of real-time data at a much lower cost and promises to be a useful tool for mine ventilation engineers and hygienists to allow active reductions in DPM concentrations.

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