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REVIEW

Evaluation of Methodology for Real-Time Monitoring of Diesel Particulate Matter in Underground Mines

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Abstract

The results of diesel particulate matter (DPM) monitoring were used by the underground mining industry to mitigate adverse effects of exposure to DPM. NIOSH Method 5040, currently used for ambient and personal exposure monitoring, does not provide needed real-time information. The objective of this study is to develop a methodology for continuous monitoring of DPM concentrations in an underground environment, founded on the application of the Dekati electrical particle sensor (DePS). The DePS, which measures concentrations of submicron aerosol in real time using a diffusion-charging sensor, was evaluated by comparing the results of the concurrent measurements with reference methods at several locations downstream of the diesel-powered equipment. The DePS results were found to correlate well to those obtained by reference methods. However, it was found that dependence of the response on the physical and chemical properties of aerosols necessitates site-specific correlation factors for the targeted matrices. The site-specific factors for number and mass of diesel aerosols were derived using the results of concurrent measurements with TSI NanoScan, FLIR Airtec, and carbon analyses performed on the concurrently collected filter samples. The results showed that methodology based on compensated DePS measurements would be suitable for continuous monitoring of DPM in underground mining operations.

Keywords Diesel aerosols · Mining · Monitoring · Underground

1 Introduction

The extensive use of diesel-powered equipment in underground mining operations contributes to elevated concentrations of submicron aerosols [1, 2] and toxic gases [3, 4]. Due to concerns over adverse health effects associated with exposure to diesel exhaust [5], the underground mining industry, labor, and governments are making major strides to implement various control strategies and technologies [6] to curb diesel emissions and reduce exposures.

Monitoring ambient concentrations and personal exposures to diesel aerosol are critical to identifying and quantifying risk of exposure and for designing and executing control strategies. Measurement of diesel aerosols in underground mining environments is complicated and challenging due to a number of factors, including nanometer size, relatively low mass and high number concentrations, complex physical properties and chemical makeup, and a large number of physical and chemical processes that affect the formation and transformation of diesel aerosols and interaction with other aerosols in underground mines [6].

Mass, number, and surface area are considered as dose metrics for monitoring occupational exposures to submicron aerosols [7, 8]. The other important parameters for establishing toxicity of submicron aerosols are size, shape, phase, and presence of specific inorganic and organic chemical constituents [9–11]. Monitoring multiple metrics might be necessary for proper hazard assessment and risk management of diesel aerosols [12–14].

Currently, due to the prevalence of the epidemiological and toxicological data linking the adverse health outcomes to the mass of diesel aerosols, mass concentration is used as the preferred dose metric to monitor exposure of underground miners to diesel aerosols. The method, based on the various adaptations of NIOSH Method 5040

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[15], is used to monitor mass concentrations of elemental carbon and total carbon (EC and TC), surrogates for diesel particulate matter (DPM), in occupational settings and to enforce personal exposure standards [16–18]. The NIOSH Method 5040 is an offline method which requires collection of the sub-0.8-µm particulates on the quartz fiber filter [19] and subsequent thermo-optical transmittance (TOT) analysis performed by a third-party laboratory provides operators with information on the average concentration over an extended sampling period (e.g., an 8-h or 12-h shift). Because this offline method provides aggregated data with intrinsic delay, it needs to be complemented with a method that provides continuous information needed for timely instituting of engineering controls and protecting workers' health.

Several kinds of portable battery-operated instruments that are using a variety of measurement principles are available for continuous monitoring of mass, number, and lung deposited surface area (LDSA) concentrations of submicron aerosols. The Airtec (FLIR Systems) near-real-time diesel particulate matter (DPM) monitor uses the laser extinction methodology to continuously measure EC mass concentrations [20, 21]. The instrument was designed with monitoring exposure of underground miners to diesel aerosol in mind, and it was demonstrated to produce results equivalent to the NIOSH Method 5040 [21–23]. Real-time, light-scattering photometric instruments that are typically calibrated using Arizona road dust or A1 test dust and used for monitoring mass concentrations of dust in underground operations are occasionally used for monitoring concentrations of diesel aerosols. Benton-Vitz and Volckens [24] showed that due to the presence of a large portion of light-absorbing elemental carbon, photometric instruments tend to underestimate mass concentrations of diesel aerosols. This issue can be potentially resolved by calibrating the instrument with a site-specific aerosol [25, 26].

Since ultrafine (D50 < 100 nm) aerosols do not contain significant mass for gravimetric quantification, the number or surface area appears to be more suitable metrics for monitoring those aerosols [9, 27]. Portable condensation particle counters, such as the CPC 3007 and P-Trak 8525 (TSI, Shoreview, MN), have been used for monitoring number concentrations of aerosols in various occupational settings [27–29]. In the portable CPCs, the sample is flown through a saturator, where the air is supersaturated with isopropyl alcohol, and a condenser, where the alcohol is condensed onto the particles, forming particles sufficiently large enough to be detected by an optical counter. Asbach et al. [29] showed that the accuracy of a handheld CPC is better than ± 20%. The two major issues that limit the use of these instruments for monitoring exposures to diesel aerosols in underground mines would be the necessity to use a working fluid(s) and the need for utilization of a dilutor due to the low upper limit of detection of the instruments ($1*10^6$ for CPC 3007 and $5*10^5$ #/cm^3 for the P-Trak 8525).

The instruments that are using unipolar diffusion charging (DC) were demonstrated to be effective for monitoring particle surface area of particles in ambient air [26, 30] and various occupational settings [27, 31]. In standard DC devices, such as DiSCmini (Testo), nanoTracer (Philips Aerasense, Eindhoven, The Netherlands), and DePS (Dekati, Kangasala, Finland), the aerosols are positively charged at the inlet using a unipolar corona charger; excess ions are removed in the ion trap; and the charged aerosols are measured using electrometers [32, 33]. In the Pegasor PPS-M (Pegasor Oy Ltd., Tampere, Finland), the charged particles are not collected on any filter and do not accumulate on any part of the sensor, but they are directly measured using the current escaping with charged particles [31]. Similarly, in the Partector 2 aerosol dosimeter (Naneos Particle Solutions GMBH, Windisch, Switzerland), particles were measured without contact with any media using the rate of change of the aerosol space charge in a Faraday cage [34]. These instruments are generally less accurate than condensation particle counters but are very compact and simple to use [26, 32]. The intrinsic dependency of the DC sensor response on the particle size and shape is one of the potential sources of the inaccuracy [35]. The DC instruments are suitable for continuous monitoring of concentrations of aerosols in the size range of diesel aerosols but for applications in underground mines where concentrations of diesel aerosols often exceed $10^{6/}$ #/cm^3 with the majority of those instruments requiring the use of a dilutor.

The objective of this study is to evaluate the diffusion charging instrument Dekati DePS as a continuous monitor of concentrations of diesel aerosols in underground environments with relatively high concentrations of submicron aerosols. This study is in support of the efforts in reducing exposure of underground miners to diesel aerosols at the Freeport-McMoRan underground operations.

2 Methodology

The DePS [36] was evaluated by using results of concurrent measurements and sampling in three areas of the underground mine where diesel-powered vehicles were extensively used to support the major parts of the production cycle: (1) mucking at ore pass, (2) ground support by applying shotcrete, and (3) hauling ore from the chute to the crusher. At the first two sites, the measurement and sampling stations were positioned downwind from mucking and shotcreting operations. On the haulage level, the stations were positioned on the side of the haulage drift.

At the mucking level, the Caterpillar R1700 load-haul-dump (LHD) vehicle powered by Caterpillar C11VR engines rated at 242 kW (325 hp) was used to load and haul ore from the draw point to the ore pass. The engine in this vehicle is certified by the EPA (Tier 2) and by Canada Centre for Mineral and Energy Technology (CANMET) (ventilation rate of 8.73 m^3/s, 18,500 cfm). The shotcrete crew was using Normet Spraymec 6050 W powered by a BF4M2012C engine rated at 74 kW (100 hp). This engine was certified by CANMET and approved by the Mine Safety and Health Administration (MSHA). Multiple Sandvik TH680 trucks were used to haul ore from the ore chutes to the crusher. Those trucks are powered by the Detroit Diesel Series 60 engine rated at 317 kW (435 hp). Those engines were certified by EPA (Tier 1) and by CANMET and are approved by MSHA.

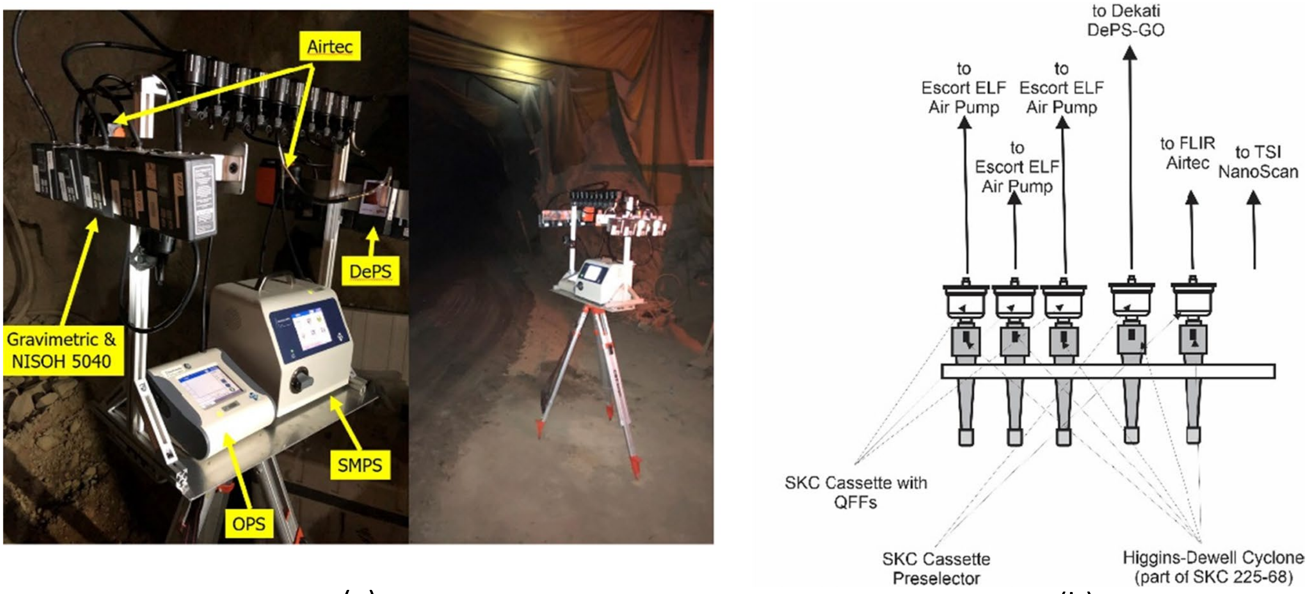
The measurement and sampling stations are shown in Fig. 1a. The layout of the measurement and sampling trains is shown in Fig. 1b. The sampling part of the stations was designed to collect filter samples for gravimetric and carbon analyses. The submicron samples for the carbon analysis were collected on the tandem quartz fiber filters (QFFs) placed in the modified sampling DPM cassettes (SKC, 225–317). In order to minimize organic carbon contamination, the QFFs were pre-baked in a muffle furnace at 800 °C for 4 h, and the cellulose support pads were replaced with stainless steel screens (SKC, 225–26). The cassettes with QFF filters were placed in the DPM samplers (SKC, Eighty Four, PA, 225–68) [SKC, 2013] that use the Higgins-Dewell cyclone to remove micron aerosols from the sampling stream. The Escort Elf (Zefon International, Ocala, Florida) personal sampling pumps operated at 2.0 lpm were used to draw all samples. The DPM samples collected on QFF filters were analyzed using NIOSH Method 5040, a thermo-optical transmittance (TOT) method [NIOSH, 2016]. Concurrent to the sampling, the measurements were paralleled with the Dekati DePS, FLIR Airtec, and TSI NanoScan Model 3910. The DPM Cyclone Sampler (SKC, Eighty-Four, PA, 225–68) with Higgins-Dewell cyclone and modified sampling cassettes (SKC, 225–317) with removed filters and support pads were used at the inlets of all instruments to remove micron-size dust.

3 Results

The results of the measurements with the DePS are shown in Fig. 2. Those were compared with results of the measurements with the Airtec and NanoScan and also with results of the carbon analysis. The results were used to determine the site-specific factors needed to convert DePS electrometer current readings [fA] to the mass [μg/m^3] and number [#/cm^3] concentrations.

The traces of the DePS electrometer signal (fA) were found to correlate well with the traces of the 5-min running average elemental carbon concentrations measured with the Airtec (Fig. 3) and particle number concentration traces measured with the NanoScan (Fig. 4).

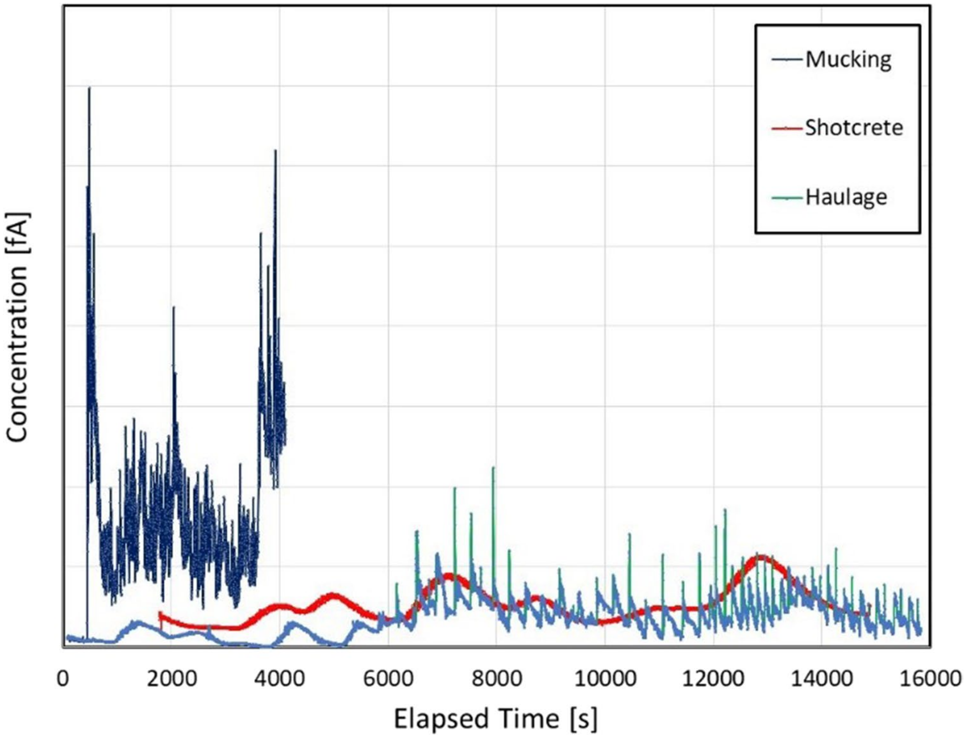
The results demonstrated a close correlation between equipment activity and measured electrical signals (DePS) and mass (Airtec) and number (NanoScan) concentrations of diesel aerosols. The referenced correlation is the linear



(a) (b)

Fig. 1 Measurement and sampling stations: **a** station at two locations and **b** measurements and sampling train layout

Fig. 2 The results of measurements with the DePS



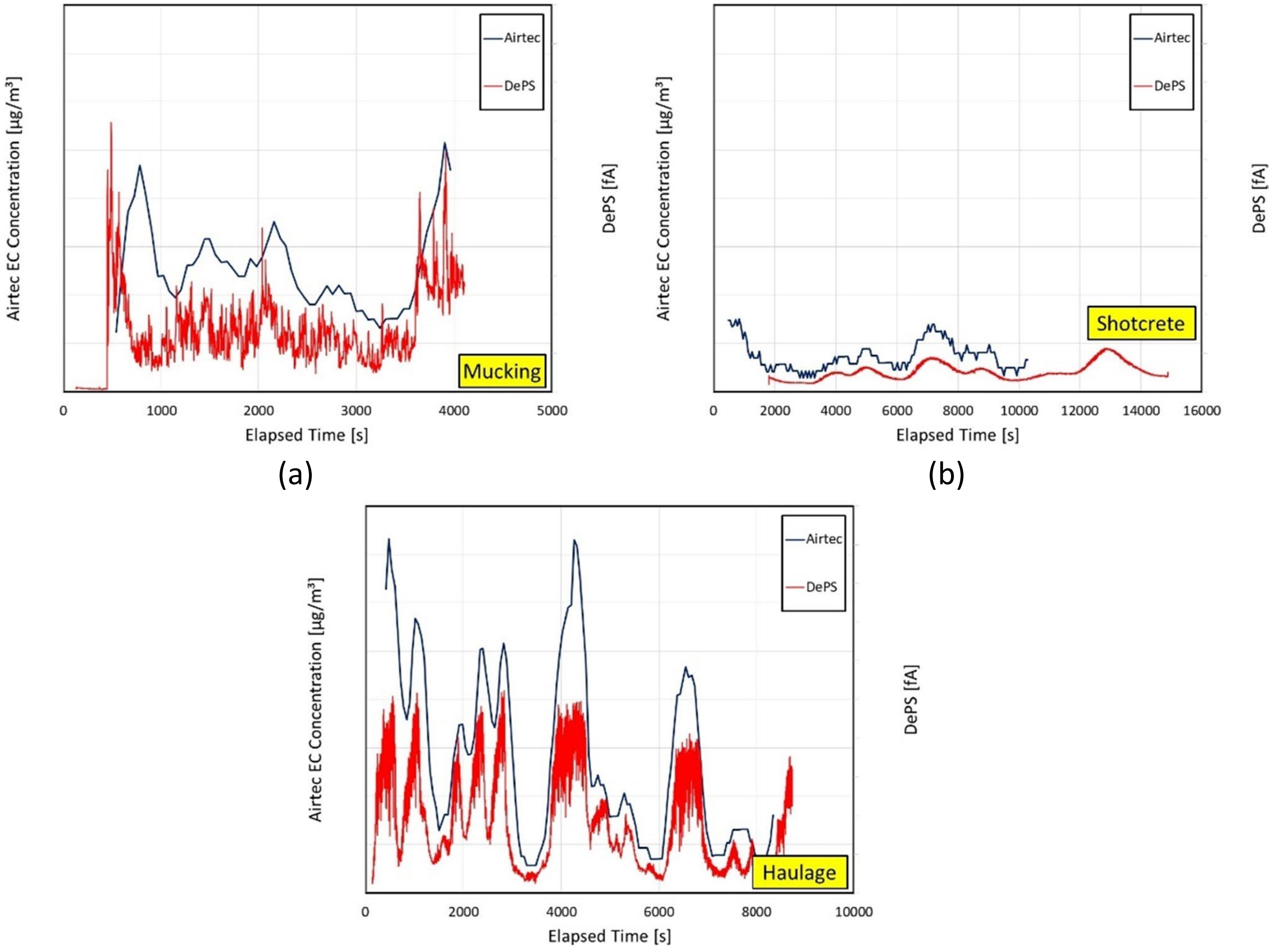
correlation between the magnitudes of the responses of the individual instruments.

The contribution of the vehicles operated at the three test sites to the total mass and number concentrations of aerosols was found to be substantially different (Figs. 3 and 4). The number of concentrations at the shotcrete site were substantially lower than those at mucking or haulage sites. The mass concentrations at the haulage site were substantially lower than those at mucking or even shotcrete sites. The size distribution of aerosols contributed by those vehicles was also substantially different (Fig. 5).

The mass and number conversion factors for DePS determined for these specific operations are shown in Fig. 6a and Fig. 6b, respectively. To determine the DePS conversion factor, the linear relation was assumed. The averages for the specific concurrent measurements were calculated and used to calculate the coefficients.

4 Discussion and Conclusions

The Dekati DePS can be used for monitoring concentrations of diesel aerosols typically observed in underground mining operations. However, since the results could be strongly dependent on the concentrations and physical properties of the measured aerosols, it is critical to understand those of aerosols generated by the specific diesel vehicles and to establish the site-specific factors needed to convert the electrometer current readings [fA] to the mass [μg/m^3] and number [#/cm^3] concentrations. The conversion factors supplied with the instrument should be verified before being applied to the specific sites. This study demonstrated that the results of the NIOSH Method 5040 analysis on the QFF filter samples or measurements with Airtec can be used to establish site-specific conversion factors.

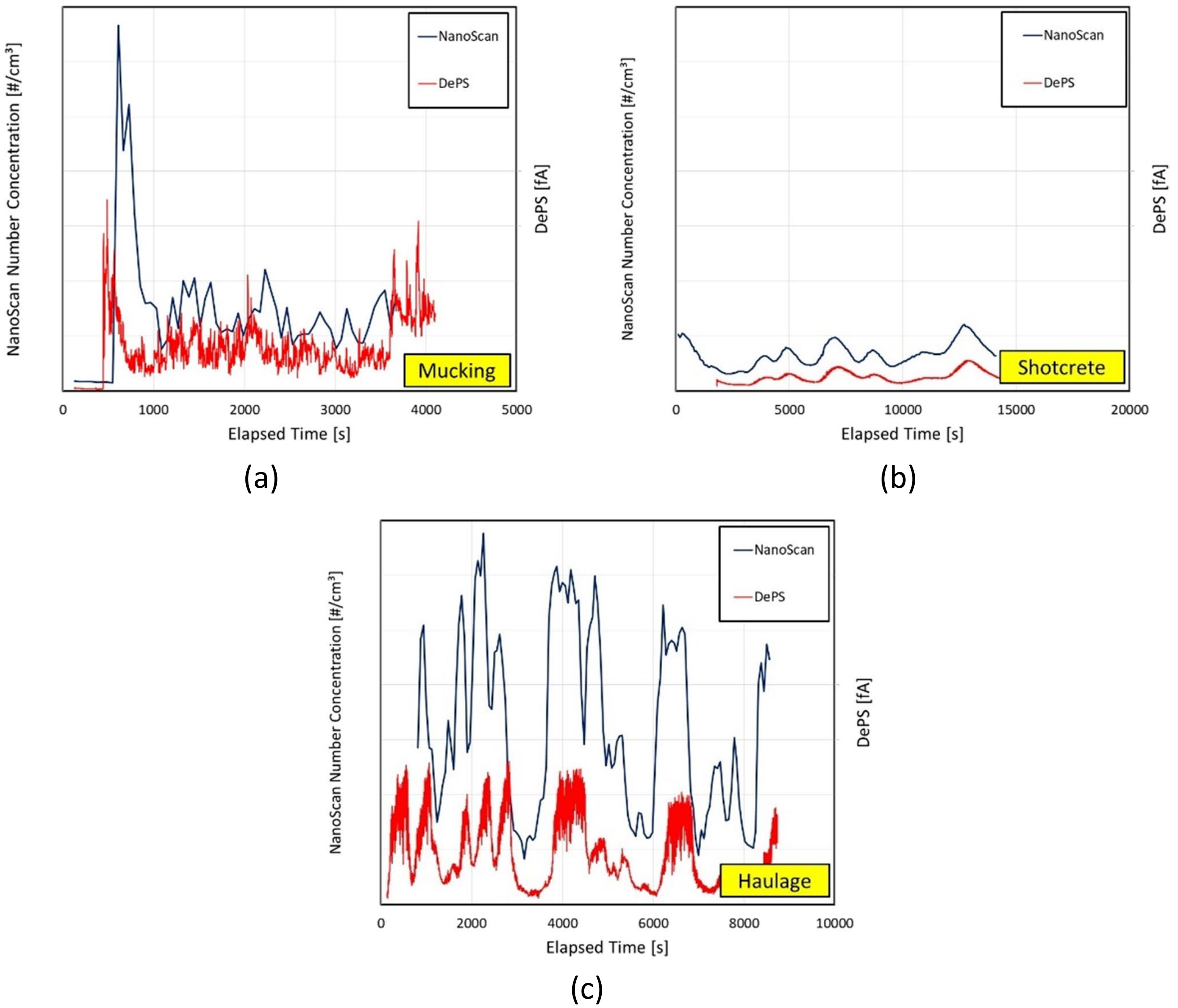


(a)

(b)

(c)

Fig. 3 Comparison of DePS signals with Airtec element carbon concentrations during **a** mucking operation, **b** shotcrete operation, and **c** haulage operation



(a)

(b)

(c)

Fig. 4 Comparison of DePS signal with aerosol number concentrations measured with NanoScan during **a** mucking operation, **b** shotcrete operation, and **c** haulage operation

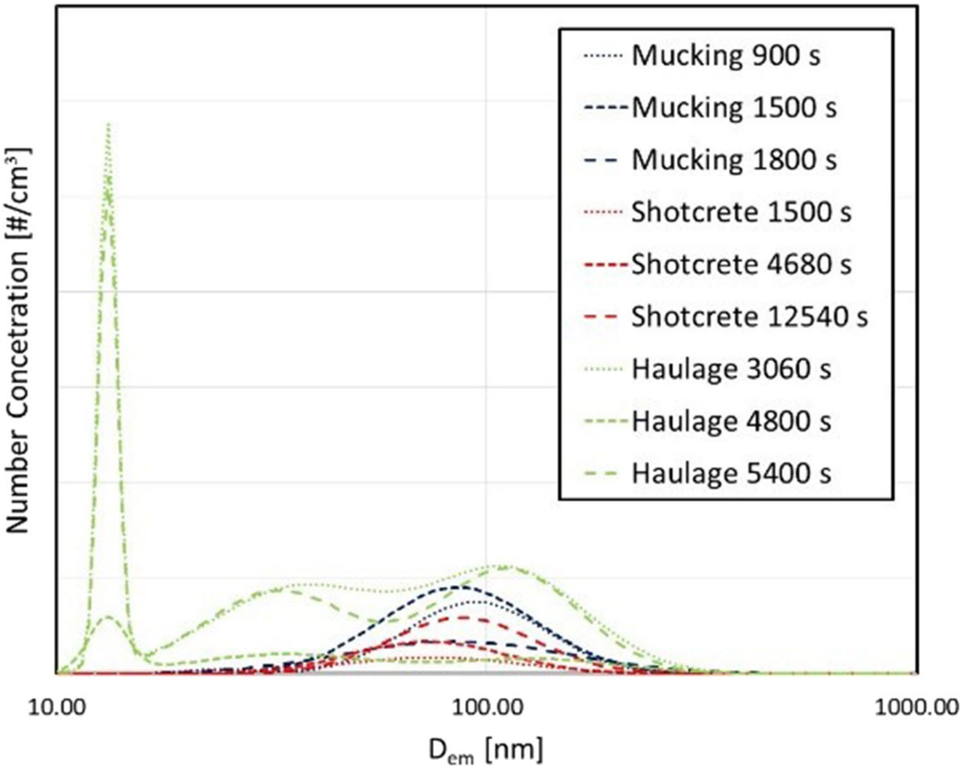


Fig. 5 Size distribution of sub-micron aerosols measured with NanoScan

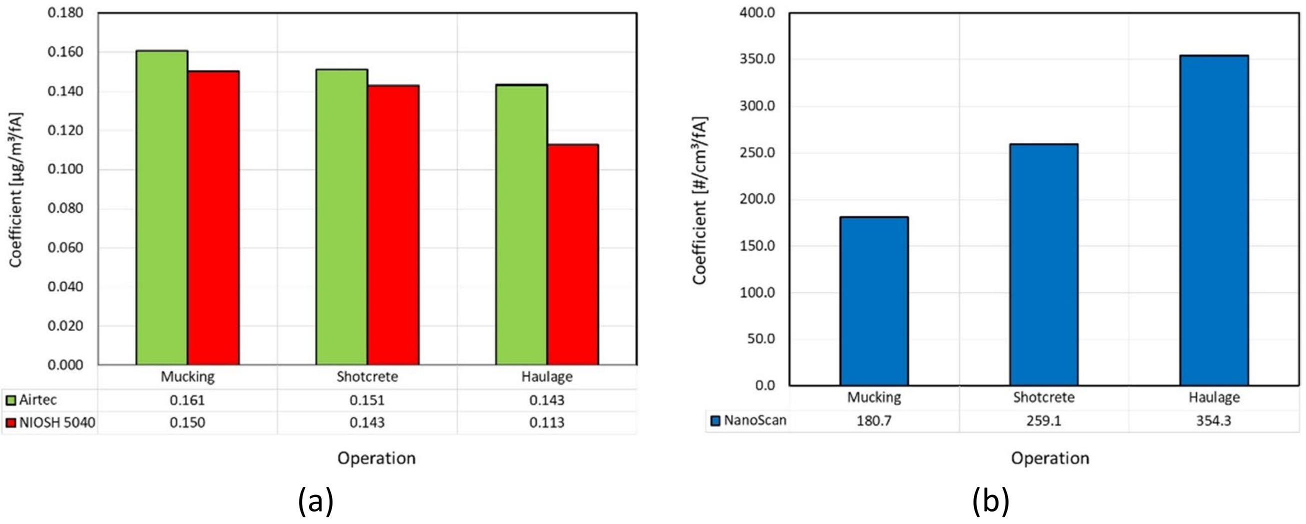


Fig. 6 Mass and number conversion factor for DePS

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Declarations

Disclaimer The findings and conclusions in this manuscript are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC). Mention of company names or products does not constitute endorsement by NIOSH or CDC.

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