Metric for exposure monitoring, hazard assessment, and risk management for diesel aerosols in underground mines

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INTRODUCTION

Approximately 30,000 U.S. underground miners are potentially exposed to relatively high concentrations of diesel particulate matter (DPM). In 2001, the U.S. Mine Safety and Health Administration (MSHA) promulgated two rules limiting the DPM emissions from diesel-powered coal mining vehicles [66 Fed. Reg. 27864] and the exposure of underground metal and nonmetal (M/NM) miners to DPM [71 Fed. Reg. 28924]. As of May 20, 2008 exposures of underground M/NM miners to DPM are limited to 160 $\mu g/m^3$ of total carbon. Meeting this performance-based requirement necessitates a multifaceted, technology-forcing, and integrated approach toward reducing miners' exposure to DPM. Critical components of such an approach are likely to include potential use of alternate fuels and implementation of exhaust aftertreatment technologies, such as diesel particulate filter (DPF) systems, disposable filter elements (DFEs), and diesel oxidation catalysts (DOCs).

METHODOLOGY

A series of studies was conducted under controlled conditions at the NIOSH Diesel Laboratory at Lake Lynn Experimental Mine (Figures 1- 3) with the objective of evaluating control technologies and strategies available to the underground mining industry to reduce exposures to DPM. Use of this unique laboratory setting, also enabled direct characterization of the physical, chemical and toxicological properties of DPM aerosols in the underground mine environment.

RESULTS AND DISCUSSION

Influence of Exhaust Aftertreatment System: An example of the dramatic changes in the size distribution of DPM with the implementation of emission control technologies is illustrated in Figure 4. This figure presents a comparison between an engine equipped with an uncatalyzed diesel particulate filter (DPF) system (Figure 4a) and the same engine equipped with a muffler (Figure 4b) operated at heavy load conditions. The engine was fueled with ultra-low sulfur fuel (ULSD, 11 ppm S by weight) for all tests. This DPF system was found to be very effective in controlling total particulate matter and elemental carbon mass concentrations in the mine air (Figure 5). However, the large concentrations of nucleation mode, primarily semi-volatile organic aerosols, shown in Figure 4 resulted in an overall increase in total number concentrations (Figure 5). The LUDEP Software [Jarvis et al., 2000] and the log-normal size distributions data (Figure 4) were used to estimate the alveolar-region-deposited (ARD) aerosol fractions (Figure 6).The average ARD mass concentration was found to be substantially lower when this DPF system was

used in place of the muffler (Figure 7). Nevertheless, the data indicated a substantial increase in ARD aerosol number concentrations (Figure 7).

Influence of Fuel Type: For the cases of the engine equipped with a muffler and DOC, the neat soy methyl ester biodiesel (B100) was found to affect the size distributions (Figure 8) and reduced the concentration of elemental carbon and to a lesser extent the total particulate matter in underground air (Figure 9). Nevertheless, substantial increases in total particulate number and ARD surface area concentrations (Figure 9 and 10), and particularly the particle-bound volatile organic fraction, were observed when B100 replaced the petroleum based ULSD and the engine was operated at light-load operating conditions.

Measurement and Health Implications: These examples demonstrate that the current practice of monitoring exposure of miners in the U.S. underground M/NM mines [71 Fed. Reg. 28924] to nano and ultrafine DPM aerosols in terms of total and elemental carbon mass concentrations might be adequate to predict exposures in the environments where engines are equipped with mufflers and DOCs, but it is relatively insensitive to potentially dramatic increases in the concentrations of nucleation mode aerosols observed after the introduction of contemporary control technologies and strategies. In light of growing evidence suggesting that particle number, surface area, size, or perhaps some associated structural properties and chemical composition may affect nanoparticle toxicity, when compared with larger respirable particles of the same composition [Donaldson et al., 1999, 2001; Frampton, 2001; Schlesinger et al., 2006], additional metrics may be helpful to allow for better monitoring, hazard assessment and risk management related to the exposure to diesel aerosols emitted from contemporary engines and control technologies, particularly those with high mass specific surface area. This information is critical to bridging the major gaps in knowledge about the relative toxicity of particles from various sources, and the relationship between toxicity and particle physiochemical properties [Schlesinger, 2006].

Potentially Viable Methods: Potentially viable methods for supplemental monitoring involve the measurement of aerosol number concentration, by condensation particle counting, and lung deposited surface area concentrations by diffusion charging [Fissan et al., 2007; Shin at al. 2007; Ntziachristos et al., 2007; Asbach et al., 2009]. The results of concurrent measurements performed with the Nanoparticle Surface Area Monitor (NSAM, TSI Inc., Model 3550) and Scanning Mobility Particle Sizer (SMPS, TSI, Model 3936) were used to evaluate the response of the NSAM to a variety of single and bimodal distributed diesel aerosols (e.g. Figure 4 and 8). A strong correlation was found between ARD surface areas measured using NSAM and those calculated using the LUDEP software and log-normal size distributions fitted to SMPS data (Figure 11). The real time NSAM signal was also found to be well correlated (Figure 12) with a total surface area measured by Fast Mobility Particle Sizer (FMPS, TSI Inc., Model 3091). In the presence of high concentrations of nucleation mode aerosols concurrent measurement of number and surface area may be helpful for assessing risk (Figure12). However, additional monitoring methods may be necessary to further characterize the organic fraction of diesel aerosols in an environment were DPFs and biodiesel are used.

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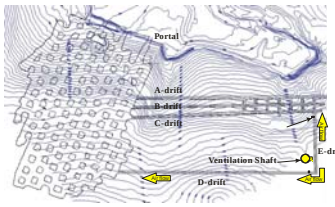

Figure 1. NIOSH Lake Lynn Experimental Mine.

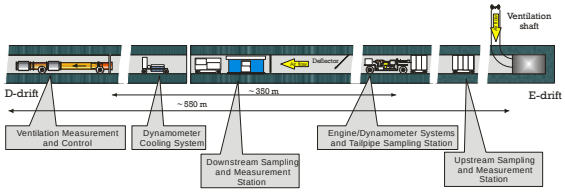

Figure 2. NIOSH Diesel Laboratory in D-drift of the Lake Lynn Experimental Mine.

Figure 3. Downstream Sampling and Measurement Station.

Results and Discussion

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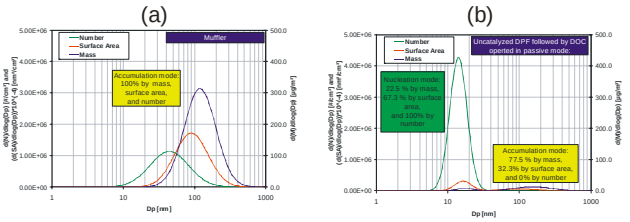

Figure 4. Size distributions (number, surface area, and mass) of diesel aerosols for a) muffler, and b) electrically regenerated uncatalyzed DPF operated in passive mode. Engine was fueled with ULSD and operated at rated speed and full throttle.

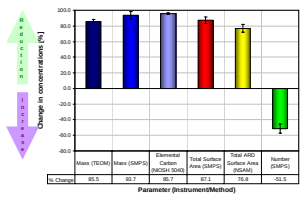

Figure 5. Changes in aerosol concentrations between muffler and DPF cases.

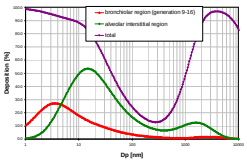

Figure 6. Lung deposition, LUDEP 2 (ICRP Pub 66). Adult male, light exercise, nose breather, ventilation rate 1.5 m³/h, resp. freq. 20/min, tidal volume 1250 cm³, volumetric flow rate 833 cm³/s.

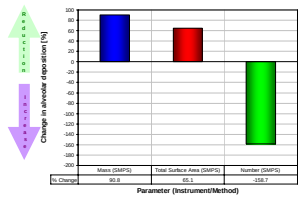

Figure 7. Estimated changes in concentrations of aerosols deposited in alveolar region with replacement of the muffler with the DPF.

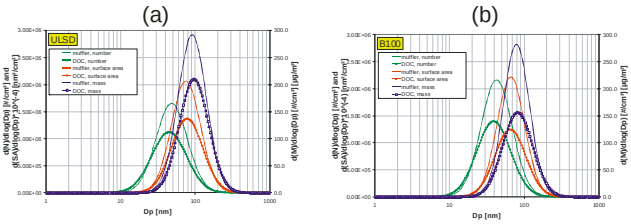

Figure 8. Size distributions (number, surface area, and mass) of diesel aerosols for a) ULSD, and b) neat biodiesel (B100). Engine was operated with muffler and DOC at rated speed and 50% load.

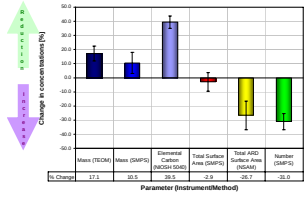

Figure 9. Changes in aerosol concentrations between ULSD and B100 cases.

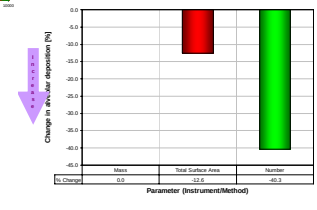

Figure 10. Estimated changes in concentrations of aerosols deposited in alveolar region with switch from ULSD to B100.

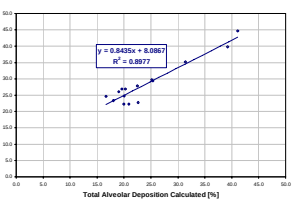

Figure 11. Relation between ARD surface areas calculated using LUDEP and total surface area measured by SMPS and ARD surface area measured using Nanoparticle Surface Area Monitor (TSI Model 3550 NSAM).

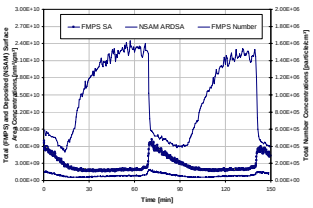

Figure 12. Traces of total surface area concentrations (FMPS), ARD surface area (NSAM), and total number concentrations (FMPS).

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