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Performance evaluation of diesel particulate filter technology in the underground environment

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ABSTRACT: As part of the Diesel Emissions Evaluation Program (DEEP) consortium, Noranda Inc. has undertaken a field project to evaluate the overall performance of the latest diesel particulate filter technology (DPF) at its Brunswick Mine in Bathurst, New Brunswick. Performance of the filtration systems is evaluated with respect to their ability to reduce tailpipe emissions and concentrations of diesel particulate matter (DPM) and noxious gases in mine air, efficiency of filter regeneration process, maintenance requirements, reliability, and acceptance. Four different particulate filter systems deployed on heavy production vehicles are subjected to an 18-month field evaluation. Over the evaluation period the vehicles will have accumulated approximately 4000 operating hours in production.

This paper presents the results of testing conducted mid way through the 18-month field trials. The 400-meter section of the mine drift at 525-5 sub level, hereinafter referred to as the "isolated zone" was isolated between intake and exhaust fan systems and sealed with bulkheads against leakage. The isolated zone was ventilated at the rate required per CSA Standards and issued by CANMET for the engines tested. Four vehicles, two load-haul-dumps (LHDs) and two trucks, retrofitted with particulate filter systems were tested along with a new identical model LHD and truck equipped with exhaust systems consisting of a catalytic converter (DOC) and muffler. The test vehicles were operated individually inside the isolated zone for approximately 4 hours over simulated production duty cycles.

Measurements of ambient concentrations of particulate matter, tailpipe emissions, and engine parameters were performed for each of the tested vehicles. The DPM samples for carbon were collected at the most upstream end of the isolated zone, at the vehicle next to the operator, and at the most downstream or exhaust end of the isolated zone. The DPM samples were analyzed for total (organic and elemental) carbon using NIOSH Analytical Method 5040. Ambient concentrations of particulate matter at the exhaust end of the zone were also measured using Scanning Mobility Particle Sizer (SMPS), and real time PAH monitor (PAS 2000). Efficiency of the filters was also evaluated on a basis of tailpipe measurements performed using raw exhaust instruments the NanoMet and the UGAS. In addition, relevant engine parameters were obtained using Detroit Diesel Diagnostic Link (DDDL) and from exhaust backpressure and temperature measurements. Results from the tests proved conclusively that diesel particulate filters can significantly reduce the concentrations of airborne DPM, but not without careful monitoring of both ambient and tailpipe emissions and not without careful attention with respect to maintaining the integrity of the DPF systems.

1 INTRODUCTION

The long-term objective of the diesel particulate filter (DPF) evaluation project at Brunswick Mine is to prove the overall performance of the technology in underground mining applications. The performance of the filters is evaluated with respect to their ability to reduce tailpipe emissions and concentrations of particulate matter and noxious gases in mine air, efficiency of the filter regeneration process, maintenance requirements, reliability and acceptance. The criteria with most impact are certainly the efficiency of the filter systems in reducing tailpipe emissions and consequently concentrations of particulate matter and noxious gases in mine air. In 1996 the American Congress of Governmental Industrial Hygienists (ACGIH) derived and recommended the TLV-TWA for diesel particulate matter of 0.15 mg/m^3 based on total carbon (TC). In the notice of intended change for 1998 the proposed limit was lowered again to 0.05 mg/m^3 TC. In the notice of intended change for 2001 ACGIH [ACGIH 2001] recommended an equivalent TLV-TWA of 0.02 mg/m^3 based on elemental carbon (EC). Recently the United States Mine Safety and Health Administration (MSHA) promulgated new regulations [66 Fed. Reg. 5706 and corrections 66 Fed. Reg. 35518 2001] setting an interim limit of DPM exposure for underground metal and nonmetal miners to 0.40 mg/m^3 of total carbon (TC). The rule sets the final limit, effective January 19, 2006 at 0.16 mg/m^3 TC. All current regulations in Canada, where mining is regulated by provincial governments, set the limit for DPM TLV-TWA at 1.50 mg/m^3 determined as the equivalent to TC and measured using the Respirable Combustible Dust (RCD) method [Grenier et al. 1996]. In anticipation of changes in provincial DPM regulations the Canadian mining industry, labor, manufacturers, Canadian and U.S. government agencies formed the Diesel Emissions Evaluation Program (DEEP) consortium.

Recently DPFs have been widely accepted and proven as a very effective technology for curtailment of DPM emissions from diesel powered vehicles [Mayer et al. 1999, Czerwinski et al. 2000, Mayer 2000, Lani et al. 2001]. Unfortunately, very limited data is available on performance of diesel particulate filters working in underground mines [Watts et al. 1995, Postnikoff 1999, Kahlert 1999, Carder 1999]. Although the efficiency of the DPFs was extensively investigated in numerous laboratory and field studies [Larsen 1999, Bugarski 1999], there is almost no data available on the potential effects of DPFs in reducing concentrations of DPM in underground mines. This information is vital in assessing the potential of diesel particulate filters for reducing miner's exposure to DPM.

2 ISOLATED ZONE AND TEST CYCLE

Accurately quantifying the effects of DPFs on concentrations of particles in mine air required isolating an operating zone in the mine with well-defined and controlled ventilation and eliminating interference from other diesel powered vehicles.

The study was conducted at the 525-5 sub level of Brunswick Mine. The mine provided an entire operating level in the mine, which had ceased production activity yet, maintained effective ground control and capabilities for efficient control of ventilation parameters. A 400 meter section of drift on 525-5 sub level, hereinafter referred to as the "isolated zone," was completely isolated from the other parts of the mine by installing two bulkheads and ventilated with fresh, diesel particulate matter free air from the V3 intake fan system. (See Figure 1)

The ventilation flow rate was maintained as close as possible to 30,000 cfm staying above the CSA certified ventilation rate of 63 cfm/bhp yet below the standard ventilation rate at Brunswick Mine of 106 cfm/bhp.

DPM sampling stations were set up inside the zone at the following locations: (1) at the air intake side of the zone, (2) on the vehicles at the operator's compartment, and (3) at the exhaust side of the zone. An additional station was set up at the exhaust side of the zone for measurement of particulate with respect to particle count and size distribution.

All ventilation and vehicle operation parameters relevant for the study were closely monitored and controlled.

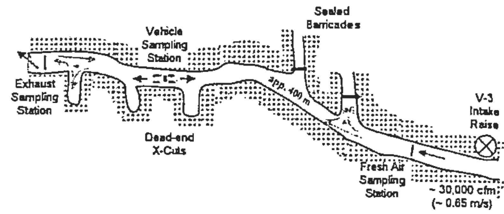

Figure 1. Isolated zone.

2.1 *Test cycle*

A zone was sectioned off between the V3 intake raise and the exhaust raise as shown in Figure 1. Each of the vehicles tested in this study was operated inside the 400-meter zone while repeating an identical simulated cycle. The vehicles were operated with the bucket / box filled with ore. The cycle, developed exclusively for this study, simulated duty cycles observed for LHD vehicles in normal operation at the mine. The cycle consisted of the following operations: (1) At the air intake side of the zone the vehicle was parked for a period of 2 minutes and operated for four times under steady state conditions for 15 seconds at full throttle with torque converter and hydraulic stalled steady state followed by 15 seconds at full throttle with transmission in neutral and no load on engine. This simulated the mucking cycle in repeatable and consistent fashion without producing dust interference normally associated with mucking. (2) The vehicle then trammed for 400 meters along the drift to the exhaust end of the zone where the vehicle was turned around and parked to simulate the dump portion of the cycle; (3) The dump cycle was simply a steady state 30-second run at full throttle with transmission in neutral and no load on engine; (4) After finishing with the dump cycle the vehicle then returned to the fresh air intake gate to repeat the full cycle. The vehicle was operated for a period of 4 hours repeating the described 8-minute cycle. In order to minimize the effects of human error, all tested vehicles were operated in similar fashion, by a single experienced operator.

3 VEHICLES AND PARTICULATE TRAPS

In order to assess the potential of the filter systems to improve air quality in the mine over current existing conditions, emissions from four vehicles equipped with DPFs were compared with emissions from two vehicles equipped with diesel oxidation catalyst (DOC) and silencer as mandated by current New Brunswick provincial regulations [New Brunswick, 1996]. The vehicles being used to test the diesel particulate filter (DPF) technology in the project are the Wagner ST8-B LHDs (Load, haul, dump vehicles also known as Scooptram) and the Wagner MT436-B dump trucks. The LHDs use Detroit Diesel Series 60 model engines rated at 325 HP. The trucks use similar Series 60 model engines with slightly higher output rated at 375 HP. All vehicles are equipped with torque converters and automatic transmissions.

The combinations of the four different DPF technologies and vehicles are shown in Table 1. All other vehicles at Brunswick Mine are equipped with mandated [New Brunswick, 1996] exhaust system configurations consisting of diesel oxidation catalysts (DOC) and in some cases optional silencers. In order to assess the potential for improving the quality of mine air by replacing existing exhaust systems with DPFs, two additional vehicles, an LHD and a truck, each equipped with original DOC configuration were also included in the study. The emissions from vehicles equipped with DPFs were compared to those from identical vehicles equipped with a DOC.

Table 1. Vehicles and exhaust systems.

Vehicle	Exhaust	DPF Technology
VH188 Truck	DOC	--
VH183 Truck	DPF	SiC Monolith with Fuel Borne Catalyst – Passive Regeneration
VH181 Truck	DPF	Wound Fiber Cartridges with Fuel Borne Catalyst – Passive Regeneration
VL254 LHD	DOC	--
VL244 LHD	DPF	Ceramic Monolith – Passive Regeneration
VL247 LHD	DPF	SiC Monolith – Active Regeneration with Electric Heater

At Brunswick Mine all LHDs and trucks are commissioned with identical specifications and configurations. Engine, power train, hydraulic, frame and all other vehicle systems are exactly identical across the ST8-B LHD fleet and similarly for the MT436-B truck fleet. All vehicles tested in the isolated zone study accumulated relatively low total operating hours prior to the testing. The four vehicles equipped with the DPFs had accumulated between 1200 and 2200 total operating hours since delivery from the vehicle manufacturer. The LHD and truck equipped with DOCs were almost brand new with only 500 and 200 operating hours, respectively.

The DPFs (see Table 1) evaluated in this project represents a cross section of the most widely accepted technology being employed in diesel applications around the world.

Wall flow monolith filters have been in use since the 1980s. Three of the four systems in this study employed either ceramic cordierite or silicon carbide (SiC) monoliths as shown in Table 1. The fourth system employs a promising wound fiber technology. In addition to evaluating efficiency of the filters this study also had for an objective to investigate suitability of different filter regeneration schemes for underground mining applications. Three of the tested filter systems, two retrofitted on trucks and one on an LHD, are regenerated passively, using exhaust heat generated during regular duty cycles to combust the soot accumulated inside the filter. In order to lower the regeneration temperature both trucks used a fuel containing a fuel-borne catalyst. The fourth vehicle, VL247 LHD uses an electric heater to actively regenerate the filter between shifts. Diesel oxidation catalyst (DOC) technology in general reduces the carbon monoxide and hydrocarbon emissions and offers relatively small reductions in diesel particulate matter (DPM) emissions, mostly in it's organic fraction. The down side is that DOCs, depending on catalyst activity and engine load, can increase emissions of nitrogen dioxide.

4 MEASUREMENT OF AMBIENT CONCENTRATIONS OF DIESEL PARTICULATE MATTER

A total of seven samples were collected at each of the three sampling stations inside the isolated zone. Five of the samples were collected for carbon analysis using NIOSH Analytical Method 5040. The sampling trains consisted of a cyclone as pre-separator, 37-mm cassette with quartz fiber filter, tubing, and sampling pump calibrated at 1.7 L/min. At the fresh air intake and exhaust sampling stations the samplers were hung onto a 6 X 12 screen positioned to give a cross section representation of the drift ventilation flow across the samplers. The samplers on the vehicle were placed in a screen basket mounted on top of the engine compartment directly in front of and within one meter of the operator. The experts from CANMET's Sudbury U/G Mine Environment Team conducted all DPM sampling and analysis.

In addition, extensive ambient measurements were taken at the exhaust sampling station of the zone. Because of the structured vehicle cycles and the controlled ventilation rate inside the zone, the concentration of airborne diesel particulate matter at the most downstream end of the zone were the heaviest with the most uniform spatial and temporal distribution.

The team from the NIOSH Pittsburgh laboratories used the Scanning Mobility Particle Sizer (SMPS) (TSI, Inc.) and real time PAH monitor, the PAS 2000 (EcoChem Analytics), to measure concentrations of airborne particles at the sampling station located at the most downstream end of the zone. The SMPS instrument was used for direct measurement of ambient concentrations of particles with electrical mobility diameter ranging from 10 – 392 nm. The measurements were performed at three instances during each of the repetitions of the duty cycle: (1) while vehicle was performing load cycle at the most upstream section of the zone, (2) while vehicle was tramming from load to dump location, and (3) while vehicle was performing dump cycle at the most downstream section of the zone. The quasi steady-state measurements were performed using 90-second scans. The results shown in Figure 4 are based on integral count concentrations for each vehicle and the sampling instance averaged over number of measurements performed during the four-hour test period. The PAS 2000 was used to measure in real-time concentrations of DPM at the same location. The instrument uses a photoelectric aerosol sensor to indirectly measure concentration of elemental carbon particles by measuring concentration of particle-bound PAH.

4.1 *Results of EC/OC analysis*

A total of 15 DPM samples for EC/OC analysis were gathered for each of the tested vehicles. Five samples were collected at each of the following stations: (1) The fresh air intake, (2) at the vehicle operator, and (3) exhaust sampling station. The DPM samples were analyzed for total carbon (TC) by CANMET's Laboratory using NIOSH Analytical Method 5040 [NIOSH 1999]. The analysis showed that the fresh air inlet to the zone had very low concentrations of TC. The analysis also showed that the TC concentrations were slightly higher at the exhaust sampling station than at the vehicle operator.

The results of analysis of the five samples collected at the exhaust sampling station are presented in Figures 2 and 3. The results are presented as average concentrations for the 5 samples analyzed per vehicle. In order to illustrate the potential of the DPF systems to reduce DPM concentrations in mine air and to correlate measured concentrations to the current regulations [MSHA 2001] based on TC limits and recommended limits [ACGIH 2001] based on EC limits, results of EC/OC analysis are presented in Figures 2 and 3 as concentrations of total and elemental carbon, respectively. The current and recommended limits appear on the graphs.

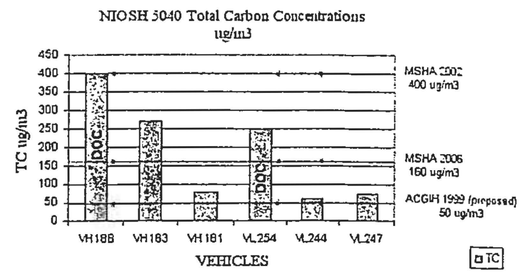

Figure 2. Total carbon DPM concentration.

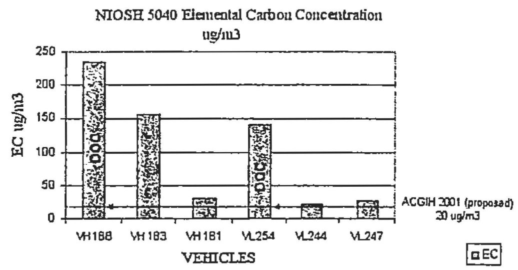

Figure 3. Elemental carbon DPM concentration.

Both LHDs retrofitted with DPFs emitted significantly less TC and EC than the LHD equipped with a DOC. It is important to note that the observed concentrations at the exhaust station for LHDs retrofitted with DPFs were slightly higher than ACGIH recommended limits of 0.05 mg/m^3 of TC or 0.02 mg/m^3 of EC.

The differences in concentrations of TC and EC emitted by the trucks equipped with DPFs and the one equipped with a DOC were somewhat less pronounced. The ambient concentrations of TC measured when filter equipped truck VH183 was operated in the zone were much higher than expected. VH181 truck equipped with a DPF exhibited much lower emissions than the baseline truck, VH188 equipped with a DOC. The concentrations measured when VH181 was operated in the zone were the lowest observed and very close to the ACGIH recommended limits.

In interpreting these results it is also seen as important to take the following into account:

1. The zone was ventilated at a rate below the mandated 106 cfm/bhp by the provincial government [New Brunswick, 1996] but above the certified ventilation rates for the engines of 63 cfm/bhp
2. Time averaged concentrations obtained on the exhaust sampling station should be higher than those measured at the operator. Therefore, obtained values should represent the worst-case scenario used in exposure assessment.

3. All four vehicles equipped with DPFs showed visible signs of exhaust leaks between the exhaust manifold and the filter. It was not possible to quantify these leaks, but assumption is that they contributed significantly to the concentration of DPM in the mine air.

4.2 *Particle distribution measurement*

A scanning mobility particle sizer was used to measure size distributions of the particles in mine air at the downstream end of the zone. The measurements were performed for all tested vehicles three times during each of the 8-minute load-haul-dump cycles: while vehicles were (1) performing load cycle, (2) tramming from load to dump point, and (3) performing dump cycle. During the four-hour test period, more than thirty sets of data were collected per vehicle for each of the aforementioned instances in the duty cycle. The obtained concentrations were corrected for fluctuations in the ventilation rate that occurred between the tests. Figure 6 shows results of size distribution measurements obtained while vehicle VH181 was exercised over load cycles during the four-hour testing. The excellent repeatability of measurements, observed for all vehicles, indicates stability of test parameters influencing distributions, such as ventilation rates, duty cycle, ambient conditions, etc.

The measurements showed that size distribution of particles emitted by vehicles retrofitted with DPFs are bimodal (see Figure 7) with relatively high concentrations of nanoparticles (below 50 nm). The emissions from vehicles equipped with DOCs were characterized with relatively high concentrations of particles below the 100 nm size range.

The efficiencies of tested aftertreatment technologies in curtailing DPM emissions were compared on a basis of the averaged integral number and volume concentrations (see Figures 4 and 5). The results showed that all filtration systems except the one installed on VL247 demonstrated excellent efficiency in reducing the number of particles emitted. For the LHD retrofitted with that particular system, the concentrations of particles by number were even higher than for the similar LHD equipped with the DOC. In addition, according to the SMPS measurements, the filter system on VL247, as well as the filter system on VH183 truck did not offer expected reductions in particle volume of DPM emitted. The

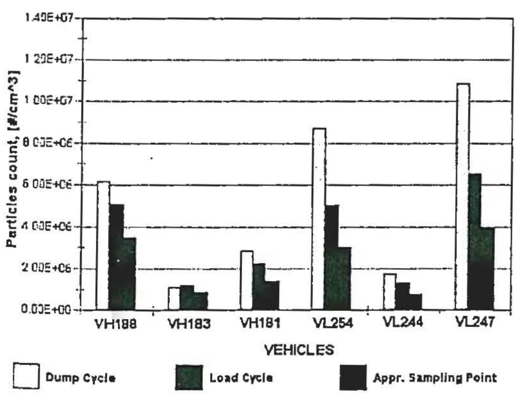

Figure 4. Particle concentrations by number.

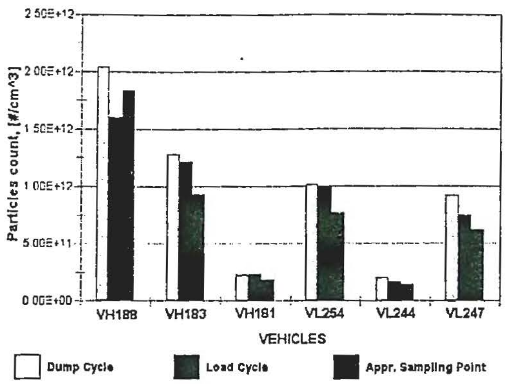

Figure 5. Particle concentrations by volume.

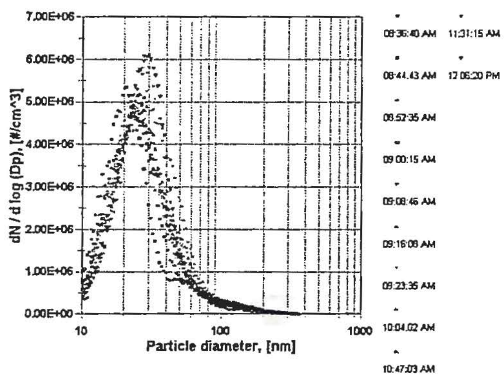

Figure 6. VH181 load cycle size distributions.

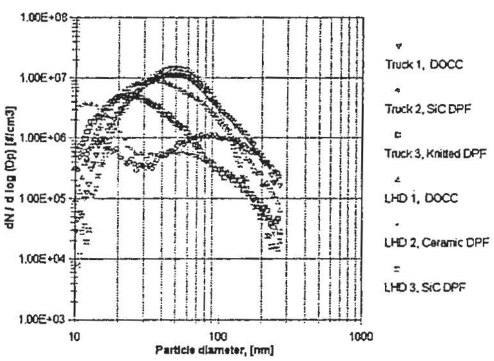

Figure 7. Load cycle particle size distributions.

relatively low efficiency of the VL247 system was attributed to sizeable exhaust leaks between the turbocharger and filter. The results showing poor performance of the system on VH183 truck are in good agreement with the results of carbon analysis.

The measurements with real-time PAH monitor PAS 2000 (EcoChem Analytics 1998) were performed at the same place as those with SMPS. As a real-time instrument, PAS 2000 was used to measure concentrations of elemental carbon particles in mine air throughout the total length of the tests for each of the vehicles. In the instrument, the particles laden sample is passed through a quartz tube and particles coated with PAHs are photo charged (EcoChem Analytics 1998). The charged particles are then collected on the filter element and electrical currents associated with the ion current are measured. Performances of the tested aftertreatment devices are compared on a basis of the integral instrument reading averaged over the test period.

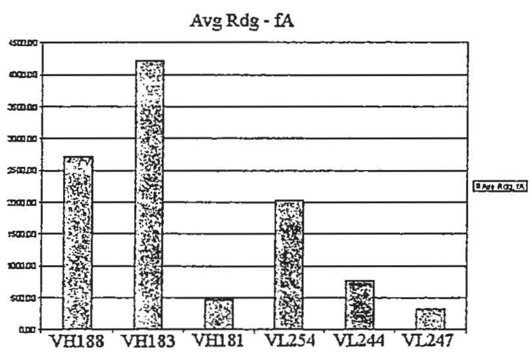

Figure 8. PAS 2000 results.

The overall results shown in Figure 8 illustrates that the particulate traps installed on three of the four vehicles offered significant reductions in particle concentrations when compared to a DOC exhaust configuration. High concentrations of particles observed for vehicle VH183 demonstrated a serious failure of the filter installed on that vehicle.

5 TAILPIPE EFFICIENCY MEASUREMENT

After completion of the four-hour testing inside the isolated zone, each of the vehicles retrofitted with DPFs was subjected to stationary tailpipe emissions measurements. The testing station was set up at the entrance to the isolated zone. The direct tailpipe emissions measurements were conducted after ambient tests to avoid background interference problems. Three methods were used to measure diesel particulate concentration in the tailpipe upstream and downstream of the filters. The results were used to assess the filtration efficiency of the DPFs with respect to raw undiluted exhaust.

The experts from CANMET used the NanoMet instrument (Matter Engineering AG) to measure particulate concentrations upstream and downstream of each of the tested filters. Two sensors are incorporated in the instrument, a diffusion charger (DC) for measuring concentrations of the particles by virtue of their active surface and a PAS 2000 for measuring concentrations of elemental carbon particles. The sampling stream is diluted using a spinning disk diluter, MD19-2E (Matter Engineering AG). In order to minimize thermophoretic losses, the samples are acquired through heated sampling lines. The results of these measurements were used to assess efficiency of the filters.

Measurements were also made using a newly developed method. The method was developed as a result of a search for a relatively inexpensive, simple but still accurate method for evaluating DPFs. The method used for sampling with an ECOM AC (ECOM America) gas analyzer and Bacharach Smoke Number Analysis was slightly modified for collecting DPM samples for EC/OC analysis. The samples were collected on quartz fiber filters and analyzed by CANMET's laboratory using NIOSH Analytical Method 5040. The results of the analysis on filter efficiencies using NIOSH 5040 method are presented in Figure 9.

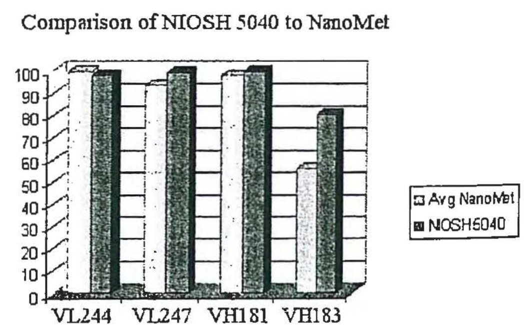

Figure 9. Filtration efficiency determined through NanoMet and NIOSH 5040 analysis.

The results of raw tailpipe measurements were found to correlate well with the results of the airborne concentration measurements. What did become evident during the tailpipe efficiency tests was that the efficiencies of the filters determined on a basis of tailpipe measurements were much higher than those determined on a basis of ambient measurements. This can be mainly attributed to the earlier discussed leaks in the exhaust systems upstream of the filters. When particulate filters were working properly they offered efficiencies in removing elemental carbon particles in the range from 98 to 99% as seen in the NanoMet results shown in Figure 9. What is not accounted for are the potential leaks in the exhaust system between the exhaust manifold and the inlet to the particulate filter. The NanoMet measurements confirmed that three of four tested filters offer above 95% reductions in particulate matter concentrations. The DPF installed on VH183 exhibited efficiencies that are much lower than expected confirming the hypothesis about compromised filter media.

6 CONCLUSIONS

The isolated zone study showed that significant reductions in concentrations of diesel particulate matter in underground mines are achievable with diesel particulate filter technology. The study also demonstrated several measurement and analysis methods available to the underground mining industry for evaluating performance of filter technology.

The extensive measurements showed that three out of four tested filters offered excellent reductions in DPM concentrations. The measurements also showed poor filtration efficiency of the fourth filter indicating premature failure of the filter. The post-test investigation revealed that the filter media had been cracked internally. Traces of black soot were identified at the outlet face of the filter. The premature failure was attributed to uncontrolled regeneration during which exhaust temperatures inside the filter had exceeded 1500°C for an extended period of time.

The comparison of the results of SMPS and tailpipe measurements revealed certain important issues with the complex filter efficiency evaluation process. The SMPS measurements in mine air indicated high number and volume concentrations of particles emitted by VL247 LHD retrofitted with a DPF, which had shown high filtration efficiencies according to tailpipe emissions measurements. This alarming discrepancy in the results of filter evaluation processes based on tailpipe emission measurements and on measurements of ambient concentrations of particles was explained by sizeable leaks discovered in the exhaust system between the engine and the DPF. Apparently estimating the effects of the filter on ambient concentrations of particulates on a basis of tailpipe emissions is not a straightforward process. Introducing a DPF into the exhaust system significantly increases engine exhaust backpressure, which can have the consequence of increased tailpipe emissions. This emphasizes the importance of maintaining integrity of the exhaust system upstream of the filter.

The measurement methods employed in the isolated zone study provided consistent and valuable data necessary for better understanding of processes governing the formation and transformation of diesel particulate matter in mine air. The NIOSH Analytical Method 5040 proved to be a very accurate method for assessment of the exposure levels achievable by DPF technology with respect to both total carbon and elemental carbon. SMPS and PAS 2000 were found to be valuable instruments for obtaining information necessary for better understanding of the processes. The study demonstrated several methods available to the underground mining industry for assessing the efficiency of DPF systems. The methods of different levels of sophistication, varying from simple to very sophisticated offered acceptable levels of accuracy. The down side of relying on tailpipe measurements for evaluations was evidenced with VL247 LHD where the system with a 99% efficient filter offered significantly lower overall system efficiency due to leaks in the exhaust system. The tailpipe measurement instruments were able to measure the 99% efficiency quite accurately but only the ambient measurements were able to detect the effects of the leaks.

The principal conclusions to be drawn from the testing done inside the isolated zone are:

1. Diesel particulate filter technologies were demonstrated to be very efficient in reducing DPM concentrations. At a ventilation rate appropriate for the engine, the ambient DPM concentrations achieved during this study are well below the current and final MSHA regulatory limits and almost meet recommended diesel particulate exposure limits.
2. The ability to attain and sustain diesel equipment within these limits would depend on the ability of operators to measure performance and maintain the systems accordingly.
3. Filter efficiency must be evaluated using *both* tailpipe and ambient measurements. These two types of measurement complement each other.
4. The importance of maintenance cannot be overemphasized – undetected failures and leaks in the DPF system can potentially result in particulate exposure levels that can be higher than current levels.

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