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EVALUATION OF HIGH-TEMPERATURE DISPOSABLE FILTER ELEMENTS IN AN EXPERIMENTAL UNDERGROUND MINE

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ABSTRACT

Filtration systems with disposable filter elements (DFEs) are used in the underground coal mining industry to control particulate matter emissions from diesel-powered permissible and nonpermissible coal mining equipment. This study was conducted in underground mine conditions to evaluate three types of high-temperature DFEs used in those filtration systems. The DFEs were evaluated for their effects on the concentrations and size distributions of diesel aerosols and concentrations of nitric oxide (NO) and nitrogen dioxide (NO_2). Those effects were compared with the effects of a standard muffler. The experimental work was conducted directly in an underground environment using a unique diesel laboratory developed in an underground experimental mine. After an initial DFE degreening period, the filtration system with all three DFEs was found to be very effective at reducing total mass concentrations of aerosols in the mine air. The effectiveness of DFEs in filtering aerosol mass was found to be a function of the engine operating conditions. The efficiency of the new DFEs significantly increased with accumulation of operating time and buildup of diesel particulate matter in the porous structure of the filter elements. A single laundering process did not exhibit substantial effects on performance of the DFE elements. The effectiveness of DFEs in removing aerosols by number was strongly influenced by engine operating mode. The concentrations of nucleation mode aerosols in the mine air were found to be substantially higher for both DPFs and DFEs when the engine was operated at high-load modes than at low-load modes. Initial heating of certain DFEs resulted in visible white smoke and substantially elevated aerosol number concentrations. The effects of the DFEs on total nitrogen oxides (NO_x) concentrations were found to be minor. The NO_2 fraction was found to be generally lower for the DFEs than for the muffler. The engine-out NO_2 fraction of the total NO_x was found to be substantially higher for low-load modes than for high-load modes.

Keywords: diesel particulate matter, underground mining, disposable filter element

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INTRODUCTION

In recent years, health effects associated with exposure to diesel particulate matter (DPM) and other, primarily combustion-generated, nano and ultrafine aerosols have received substantial attention from the public, government agencies, and in academia. Pope et al. (1) established that long-term exposure to combustion-related fine particulate pollution is an important risk factor for cardiopulmonary and lung cancer mortality. There is growing evidence suggesting that particle number, surface area, size, or perhaps some associated structural properties may affect nanoparticle toxicity, when compared with larger respirable particles of the same composition (2). Based on the above evidence, occupational health risks associated with exposure to nano and ultrafine aerosols warrant further study.

Diesel particulate matter (DPM) is a complex mixture of solid and liquid aerosols typically present in nucleation and accumulation modes (3). DPM exposures in underground metal/nonmetal mines are currently being regulated solely on the basis of the total and elemental carbon mass per unit volume of air (4). For coal mines, the total particulate mass emission rate is regulated and requires the use of diesel particulate filtration systems in most cases for compliance (5). Unfortunately, no reference is made in either regulation to exposure to size, number, or surface area of the airborne particles. Mass-based exposure assessments are not always fully predictive of disease risk; in some cases respirable particle surface area and detailed surface compositional or morphological properties better correlate with toxicity, or they offer an explanation of seeming anomalies in epidemiological findings of disease risk (6). In an attempt to assess the adverse health impacts of nano and ultrafine aerosols, past studies indicate the importance of complementing mass-based exposure monitoring with measurements of size, number, and surface area of aerosols (7, 2, 8, 9, 10, 11).

Diesel exhaust filtration systems with low-temperature disposable filter elements (DFEs) have been extensively used to control DPM emissions from permissible heavy-duty diesel-powered coal mining equipment ever since they were developed in the early 1990s (12). Various models of DFEs are currently approved by the Mine Safety and Health Administration (MSHA) (13) for use in conjunction with air-to-water (wet) and air-to-air (dry) heat exchanger systems designed to maintain the exhaust gas temperature at the filter element face below 85 ºC (185 ºF) and 150 ºC (302 ºF), respectively (14). High-temperature DFEs were developed to meet the demand for controlling DPM emissions from non-permissible heavy- and light-duty underground coal mining diesel-powered equipment as required by 30 CFR Part 72. High-temperature DFEs are approved by MSHA for use in applications where the exhaust gas temperature is below 343 ºC (650 ºF). The list of approved low- and high-temperature DFEs is available from MSHA (13). High-temperature DFEs also have found limited used in metal and nonmetal underground mining applications (15).

The majority of the previous work on size-resolved characterization of diesel aerosols was done in laboratory environments (16, 17, 18, 19), on roads (20), and in tunnels (21, 22). Several researchers (12, 15, 23, 24) studied the effects of selected control technologies on concentrations of aerosols in production underground mines. Although DFEs are recognized as very effective at reducing emissions of total diesel particulate matter (13), there is limited information (12) on the effects of DFEs on the number concentration and size distribution of diesel aerosols in underground mine air. Detailed, size-resolved characterization of diesel aerosols in occupational settings is an important step toward a better understanding of the potential health risks associated with worker exposure to nano and ultrafine aerosols, and toward the suitability of different control technologies and strategies for reducing worker exposure, thereby minimizing health risk.

EXPERIMENTAL

This study examined the effects of HT (high-temperature) DFEs, supplied by two manufacturers, and a muffler on the concentration and size distribution of diesel aerosols found in underground mine air. Two of the DFEs were new (DFE-A and DFE-B) and the third was a laundered DFE (LDFE-A). The primary objective of the study was to determine the effects of aged DFEs on the concentrations and size distribution of diesel aerosols, as well as the concentrations of nitric oxide (NO) and nitrogen dioxide (NO_2) in mine air downwind of the exhaust discharge, and to compare these results with the effects observed for a standard muffler. The secondary objective was to use results of number concentration and size selective measurements performed during the first several hours of operation of those DFEs to examine the effects of DFE loading on concentrations and size distribution aerosols in mine air. The tertiary objective was to conduct additional tests to characterize concentrations and size distribution of secondary aerosols generated during the process of off-gassing of the DFE media binder, which takes place during initial heating of never used and freshly laundered DFEs.

Since the size and concentration of diesel aerosol and semi-volatile materials emitted by diesel engines in the workplace are strongly influenced by a number of complex processes defined by ambient conditions (25), the goal was to assess the aforementioned effects directly in the occupational setting of the NIOSH Diesel Laboratory at the NIOSH Lake Lynn Experimental Mine (LLEM). The LLEM is an established but inactive underground limestone mine situated near Fairchance, Pennsylvania (26). The experimental work was performed in the D-drift of the NIOSH LLEM, a tunnel which is approximately 530 m (1750 ft) long, 6 m (20 ft) wide, and 2 m (7 ft) high. A schematic of the laboratory layout is shown in Figure 1. The major components of the laboratory are an engine/dynamometer system, three sampling and measurement stations, and a ventilation measurement and control system.

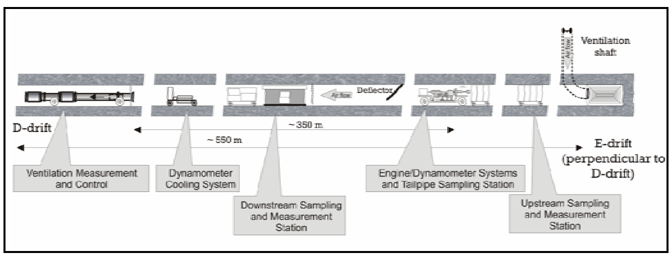


Figure 1. NIOSH Diesel Laboratory in D-drift of LLL (not to scale).

A water-cooled eddy-current dynamometer from SAJ (Pune, India, Model SE150) rated at 150 kW (201 bhp) was used to load and control a naturally aspirated, mechanically controlled Isuzu C240 diesel engine (Isuzu Motors Limited) rated at 41.8 kW (56.0 hp) @ 3000 rpm. This model of the engine is approved by MSHA under 30 CFR Part 7 (approval number 7E-B085) (14). The ventilation rate (VR) rate and particulate index (PI) for this engine are 1.18 m^3/s (2500 ft^3/min) and 2.60 m^3/s (5500 ft^3/min), respectively. The water-to-air heat exchanger used to cool the dynamometer was placed about 30 m (98.5 ft) downwind of the downstream measurement station so as not to add a mode-dependent amount of heat to the ventilation air and potentially affect aerosol characteristics.

The test engine was operated at four steady-state engine operating modes. The engine parameters for the test modes are given in Table 1.

Measurement

Three measurement stations were established in the D-drift. The downstream and upstream stations were used to measure ambient concentrations of aerosols and gases, while the tailpipe station was used to measure concentrations of carbon dioxide (CO_2) and carbon monoxide (CO) in the tailpipe of the test engine immediately upstream of the installed DFE. This procedure provided additional assurance of the consistency of engine operating conditions throughout all of the tests. The downstream ambient monitoring station was located about 60 m (197 ft) downwind of the dynamometer, and the upstream ambient monitoring station was located approximately 60 m (197 ft) upwind of the dynamometer. The corrections for the background concentrations of aerosols were made by subtracting the results of measurements performed at the upstream station from the corresponding results obtained at the downstream station.

Table 1. Parameters for four steady-state engine operating modes.

Mode	Description	Engine speed rpm	Torque Nm	Power kW
R50	Rated speed 50% load	2950	55.6	17.2
R100	Rated speed 100% load	2950	111.2	34.3
I50	Intermediate speed 50% load	2100	69.1	14.9
I100	Intermediate speed 100% load	2100	136.9	30.6

A Tapered Element Oscillating Microbalance (TEOM) Series 1400a ambient particulate monitor from Thermo Scientific (Franklin, MA) was used at the downstream station, and another was used at the upstream station. The monitors measured and logged total particulate matter mass with mean aerodynamic diameter (${}_{50}d_{ae}$) under 0.8 µm. The flow rate of both TEOM instruments was set at 2.0 lpm. A 10-mm Dorr-Oliver cyclone followed by a diesel particulate matter cassette (SKC, Eighty Four, PA) with its collection filter removed were used to pre-classify aerosols entering the TEOM, allowing only particles with an average aerodynamic diameter (${}_{50}d_{ae}$) smaller than 0.82 µm to reach the TEOM.

A Scanning Mobility Particle Sizer (SMPS) (27) from TSI (St. Paul, MN) was used at the downstream station, and another was used at the upstream station, to measure size distribution and number concentrations of aerosols. The SMPS at the downstream station was configured with an electrostatic classifier (EC) Model 3080L and a condensation particle counter (CPC) Model 3025A. The SMPS at the upstream station consisted of an EC Model 3080L and a CPC Model 3776. The CPC Model 3025A and CPC Model 3776 are similar in design and operation. Both SMPSs were used to measure size distribution and number concentrations of particles in the range between 10 and 408 nm. The sample and sheath air flows in both ECs were maintained at 0.6 l/min and 6.0 l/min, respectively. At these flow conditions, the instrument measures only aerosols with an electrical mobility diameter (${}_{50}d_{em}$) below 480 nm.

A Model DAS 3100 Electrical Low Pressure Impactor (ELPI) (28) from Dekati (Finland) was used at the downstream station to classify aerosols according to their aerodynamic diameter. Coarse particles with ${}_{50}d_{ae}$ larger than 1 µm were removed from the ELPI sampling stream by a URG-2000-30EHB cyclone (URG, Chapel Hill, NC). The ELPI was used with greased aluminum collection substrates and a Teflon-coated glass fiber filter (TX40HI20, Pall Corporation) at the filter stage.

The concentration of NO and NO_2 at the downstream station were determined by a Model CLD 700 AL chemiluminescence analyzer (Eco Physics, Duernten, Switzerland). Due to low background concentrations of NO and NO_2 it was not necessary to apply background corrections to NO and NO_2 data.

Ventilation

Fresh air was supplied to the LLL underground facility via a ventilation shaft located in E-drift (Figure 1). A Series 2000 Model 48-26-1770 XP Axivane fan (Joy Technologies Inc., New Philadelphia, OH) was used to push air into the mine from the surface. A portion of this air flows into the test zone via E-drift that is situated immediately upwind and normal to the D-drift. A tightly sealed plywood wall across D-drift was constructed near the extreme downwind end of the drift. A subsonic Venturi meter (Primary Flow Signal, Inc., Tulsa OK) followed by a Series 1000 Model 23017-3450 Axivane fan (Joy Technologies) were installed into a sealed, circular opening and used to pull air across the plywood barrier. This structure provided the means to measure and maintain a constant total air flow through the drift. The flow rate measurements were adjusted for variations in temperature, pressure, and humidity.

A constant flow of fresh air was supplied to the D-drift throughout all tests. The measurements showed the average flow rate of 5.69 ± 0.02 m^3/s (12056.40 ± 87.22 ft^3/min). The very low (0.72%) test-to-test variability in flow rate eliminated the need for normalization of the data with respect to flow rate.

The maximum and minimum values of pertinent ambient parameters observed during the study are summarized in Table 2. The air temperature and relative humidity at the downstream station were found to be strongly affected by engine-generated heat, which varied with engine operating conditions.

Table 2. Ambient conditions during testing.

Mode	Air temp. @ engine intake	Air temp. @ downstream station	Air temp. @ Venturi	Relative humidity @ engine intake	Relative humidity @ downstream station	Relative humidity @ Venturi
	°C	°C	°C	%	%	%
Minimum	13.9	16.4	14.5	34.9	31.8	43.0
Maximum	18.7	22.3	17.0	87.6	79.2	95.5

The average dilution ratios for R50, R100, I50, and I100 engine operating modes were calculated to be 147, 147, 182, and 184, respectively.

Fuel

The engine was fueled with ultralow sulfur diesel fuel. The fuel was supplied to the engine from the 200-liter main fuel tank (Rohmac Inc., Mt. Storm, WV). The results of the analysis performed on that fuel by Core Laboratories, Houston, TX, are given in Table 3.

Table 3. Results of engine fuel analysis.

Test		Method	Result	Units
Btu, Net		ASTM D-240	43468	kJ/kg
Cetane number		ASTM D-613	61.8	-
Density		ASTM D-4052	0.8038	gm/ml
Flash point, PMCC		ASTM D-93A	62.2	°C
Hydrocarbon type	Aromatics	ASTM D-1319	7.2	LV%
	Olefins	ASTM D-1319	1.1	LV%
	Saturates	ASTM D-1319	91.7	LV%
Sulfur Content		ASTM D-5453	11	mg/kg

HTDFEs, Filter Housing, and Heat Exchanger

Three types of HT DFEs were tested in this study:

1. A DFE manufactured by Donaldson Company, Minneapolis, MN, Model P604516 (DFE-A).
2. A laundered DFE, identical to DFE-A, but laundered by Mac's Mining Repair Service, Huntington, UT, following standard protocols (LDFE-A).
3. A DFE manufactured by FST Systems Corporation, Price, UT, Model FST-115-26 (DFE-B).

DFE-A and DFE-B meet MSHA criteria for permissible and non-permissible applications, and they are listed as 83% and 80% efficient, respectively, in the removal of total DPM (13). The laundering or washing process is used by some coal operators to extend the life cycle of the high-temperature DFEs. A short description of the process is available from MSHA (30). The common practice is to launder the DFEs several times over their life cycle. The particular element tested in this study was used and laundered only once.

The maximum exhaust flow rates of 134 m^3/hr (78.9 ft^3/min) and 108.1 m^3/hr (63.6 ft^3/min) recorded for the Isuzu C240 engine while operated at rated and intermediate speed modes, respectively, were significantly lower than the maximum exhaust flow of 679.6 m^3/hr (400 ft^3/min) allowed by the manufacturers for these particular models of DFEs. This fact proportionally extended the time period needed to load a clean filter with DPM from the test engine compared to that for higher emitting engines, and likely affected the duration for initial heating and out-gassing.

Two identical and brand new elements from each manufacturer were used in this study. One DFE from each manufacturer (DFE-A-1 and DFE-B-1) was used in the tests designed to assess the steady-state effects of the DFE on concentrations and size distribution of diesel aerosols in underground mine air. Those elements were conditioned prior to the four-mode test series by operating them for 13 hours at engine mode R50. During the conditioning period, aerosol measurements were performed to assess the effects of increasing filter element loading on the physical properties of aerosols and the DFE mass reduction effectiveness.

A second new DFE from each manufacturer (DFE-A-2 and DFE-B-2) was not conditioned but was used to study the size distribution of secondary aerosols generated during the initial period of operation during the off-gassing of the DFE media binder. In these cases the engine mode was I100. The DFE-A-2 test at I100 was extended to 6 hours so that results could be compared with results obtained with the DFE-A-1.

Only one laundered DFE (LDFE-A) was examined in the study. It was conditioned by being operated at R50 for 6 hours after installation. The results of measurements performed during this conditioning period were used to assess the effects the filter element loading and the effects of off-gassing on physical properties of aerosols and effectiveness of LDFE-A.

The DFEs were installed into a custom housing designed and built by Mac's Mining Repair Service (Huntington, UT). Special precaution was taken to secure a leak-tight fit for the element. Because these model DFEs are approved for use in applications where exhaust temperatures do not exceed 343 ºC (650 ºF), it was necessary to use an air-to-air heat exchanger (supplied by Mac's Mining Repair) between the engine and the DFE housing. The average exhaust temperatures at the inlet and outlet of the DFEs observed for the four test modes are summarized in Table 4.

Table 4. Average exhaust temperatures at the inlet and outlet of the DFEs

Mode	Exhaust temperature at inlet to DFE	Temperature at outlet from DFE
	°C	°C
R50	203	154
R100	328	238
I50	157	120
I100	313	230

The observed pressure drops across the DFEs varied as they accumulated DPM during the test and also varied with engine mode, but they were well below the manufacturer-recommended maximum limit of 14.95 kPa (60" H_2O) for all test modes. A butterfly valve, installed in the exhaust pipe between the engine and the heat exchanger, was used during muffler tests to generate pressure drops comparable to those observed during corresponding DFE tests.

After DFE conditioning, the initial hour of each test was dedicated to achieving system equilibrium. The measurements were initiated at the beginning of the second hour.

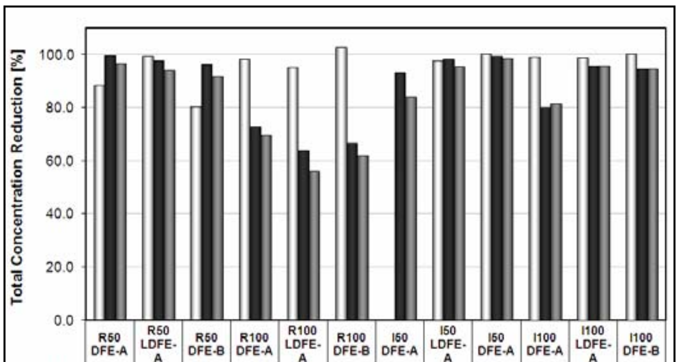
RESULTS AND DISCUSSION

Effects of DFEs on Concentrations and Size Distribution of Diesel Aerosols.

The total aerosol mass concentrations measured by the TEOMs and the total aerosol number concentrations measured by the SMPSs and ELPI at their respective sampling locations are given in Table 5 (see Appendix). The result of the TEOM measurements for the DFE-A test at I50 mode is not reported because of problems with the instrument. All concentrations are reported as averages (AVG) and their corresponding standard deviations of the mean (SDOM) of actual measured values during the last hour of the test at prevailing ventilation conditions.

During the majority of the runs the mass and number concentrations at the upstream station were close to the lower detection limits of the instruments. Nonetheless, these upstream concentrations had a significant effect on some of the DFE filtration efficiency calculations. This was especially true for the light engine load modes (R50 and I50) where, in several cases, the downstream concentrations, due to high DPM removal efficiency of the DFEs, were found to be comparable to the upstream concentrations. For example, at the I50 mode, the average total number concentration at the upstream station was 31.3% of the total number concentrations at the downstream station, with a maximum of 47.4 % for the LDFE-A run. It is important to note that, on average, the aerosols had a slightly larger $_{50}d_{em}$ at the upstream than at the downstream station. The effects of upstream number concentrations on the results were much less significant for the R100 and I100 modes in which engine emissions and, therefore, DFE DPM emissions were greater. In these cases the downstream concentrations were substantially higher so that the average upstream concentrations were only 1.1% and 11.0% of the downstream number concentrations. The results of number concentration measurements performed with the SMPS and ELPI at the downstream station indicate a relatively good agreement between those two instruments.

The relative efficiency of a DFE in reducing a particular contaminant is calculated by comparing the contaminant concentrations observed for the DFE with those observed for the muffler at the same engine mode. In all cases, the upstream background data have been subtracted out of the downstream data (except for the ELPI and nitrogen oxides data, which had no corresponding upstream data). The results of these DFE efficiency calculations, expressed as a percentage for aerosol mass and number, are summarized in Figure 2.



	R50 DFE-A	R50 LDFE-A	R50 DFE-B	R100 DFE-A	R100 LDFE-A	R100 DFE-B	I50 DFE-A	I50 LDFE-A	I50 DFE-A	I100 DFE-A	I100 LDFE-A	I100 DFE-B
TEOM	88.4	99.4	80.3	98.4	95.1	102.7		97.7	100.2	99.2	98.9	100.2
SMPS	99.6	97.7	96.3	72.8	63.9	66.8	93.2	98.3	99.3	80.2	95.9	94.7
ELPI	96.6	94.2	91.7	69.8	56.3	61.9	84.0	95.6	98.5	81.4	95.8	94.8

Figure 2. Percentage of reductions in total mass (TEOM) and number concentrations (SMPS and ELPI)

The results show that, in all cases, the DFEs reduced the aerosol mass concentrations for R100, I50, and I100 modes by a factor of 20 or more (>95% reduction). However, at R50 the reductions were less than 90% for both DFE-A and DFE-B, and the possible reasons are discussed in more detail later in this paper.

The engine operating modes were found to have a more pronounced effect on the total particle number than on the total particle mass. The reductions observed in the total number concentration of aerosols measured by the SMPS were between 93.3% and 99.6% for the low-load modes (R50 and I50). Significantly lower number reductions were observed, ranging from 65.5% to 75.0%, for all DFEs at R100 and for DFE-A-1 at I100.

The efficiencies calculated using the ELPI data were found to be, in general, slightly lower than those calculated using the SMPS data. This is most likely due to fact that the SMPS data was background corrected, while the ELPI data was not. Nonetheless, it can be concluded that ELPI results corroborate relatively well the aforementioned conclusions based on the SMPS results. The effectiveness of LDFE-A in the removal of aerosol mass and number was found to be comparable to that of a new non-laundered DFE-A.

The results of size distribution measurements performed at the downstream sampling station with the SMPSs are summarized in Figure 3. The presented distributions are not corrected for dilution ratio or for background concentrations. Figure 3 shows that the size distributions of DFE-A and DFE-B for mode R50 are bimodal with two accumulation modes. DFE-A and DFE-B at R50 exhibited a relatively high concentration of secondary accumulation mode aerosols with $_{50}d_{em}$>100 nm, which were found to originate from background air. Due to high background concentrations the total mass reductions for these particular cases were found to be less than 95% for that mode. Figure 3b, on the other hand, shows the opposite effect; it shows relatively high concentrations of nucleation mode aerosols ($_{50}d_{em}$<50 nm) for all DFEs at R100, which explains the observed lower total particle reductions for all DFEs at this mode.

The results of size distribution measurements indicate a positive correlation between concentrations of nucleation mode aerosols in the mine air and exhaust temperatures. The concentration of nucleation mode aerosols was found to be substantially higher when the engine was operated at the higher load and higher exhaust temperature modes—R100 and I100 shown in Figure 3b and Figure 3d—than at the lower load and lower temperature modes—R50 and I50 shown in Figure 3a and Figure 3c.

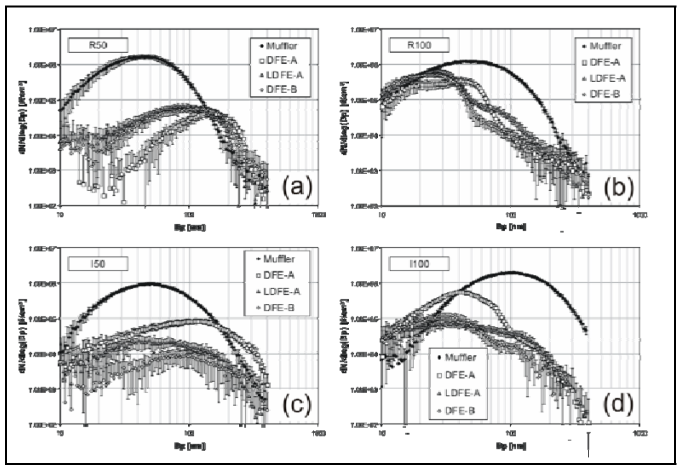


Figure 3. Size distributions for DFEs: (a) R50, (b) R100, (c) I50, and (d) I100 mode.

When engine was operated at high load modes (R100 and I100), all three types of DFEs were found to be very effective at the removal of accumulation mode aerosols ($_{50}d_{em}$>50 nm) (Figure 3b and Figure 3d). The concentrations of accumulation mode particles were found to be significantly higher in the case of R50 and I50 modes—Figure 3a and Figure 3c—than in the case of R100 and I100 modes—Figure 3b and Figure 3d. It can be hypothesized that the unfiltered ventilation air contributed partially to the accumulation mode particles.

Effects of DPM Loading on Concentrations and Size Distribution of Aerosols in Mine Air

A series of tests were conducted in order to assess the effects of DPM loading on performance of the new and laundered DFE elements. Once a DFE was installed, the engine was operated at R50 mode for a period of thirteen hours (DFE-A-1 and DFE-B-1) or six hours (LDFE-A) and aerosol data were collected during those periods. All measurements were initiated after a one-hour equilibration time. Changes in concentrations and size distributions with operating time are evident from the examples of SPMS-measured distributions

(Figure 4 and Figure 5) captured during DFE-A and DFE-B initial tests, respectively. The size distribution for the LDFE-A exhibited a similar behavior.

The gradual decrease in total concentration of aerosols over the first several hours of operation of the DFEs after installation of fresh elements is reflected in total count concentration traces shown in Figure 6.

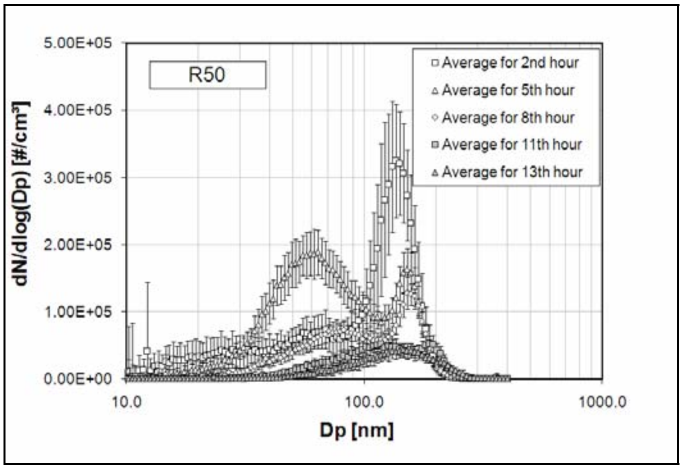


Figure 4. Selected one-hour average size distributions of aerosols during the first thirteen hours of operation of DFE-A for engine operated at R50 mode.

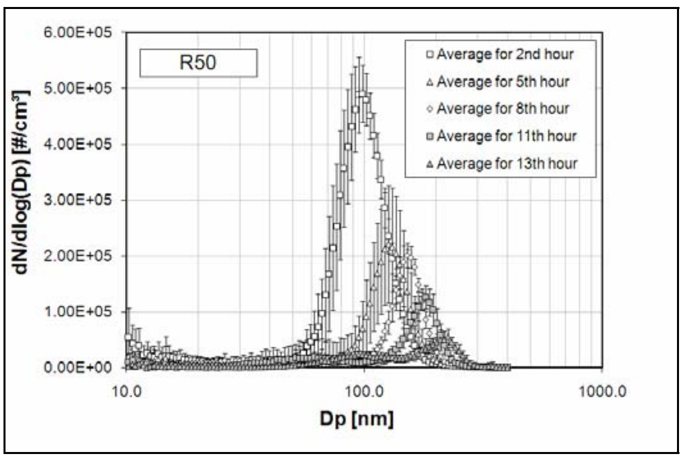


Figure 5. Selected one-hour average size distributions of aerosols during the first thirteen hours of operation of DFE-B for engine operated at R50 mode.

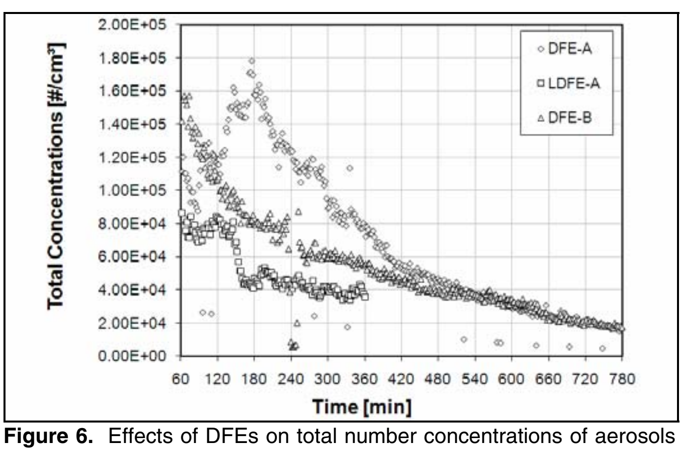


Figure 6. Effects of DFEs on total number concentrations of aerosols in mine air in the first several hours after installation of fresh elements.

Figure 6 illustrates the gradual increase in efficiency of the DFEs with accumulation of operating time and buildup of DPM within the structure of the filter elements. Typically the lowest efficiencies were observed during the first hours of the DFE life. It appears that tested DFEs asymptotically approached but never reached their terminal efficiency over the test periods. The results showed that the laundered DFE-A had higher initial number efficiency than the new DFE-A. At R50 conditions, DFE-A and DFE-B were found to be equally effective at removing aerosols by number at the end of the 13-hour period.

It is important to note that actual time scale for these processes is affected by relative size of the element with respect to engine exhaust flow rate and DPM emission rate. The tested DFEs are designed to handle a volumetric exhaust flow rate up to 0.189 m^3/sec (400.0 ft^3/min) (28) while the volumetric flow rate during the R50 tests was approximately 0.039 m^3/sec (82.0 ft^3/min).

Concentration and Size Distribution of Aerosols in Mine Air during Initial Heating of DFEs

Additional set of tests were conducted with the objective of characterizing aerosols in mine air during the first few minutes of operation of each DFE. All efforts were made to minimize the effects of transient processes occurring in the drift during this time period. However, it is important to note that the results of these initial heating tests may be, to some extent, affected by these changing thermodynamic conditions within the drift.

The size distributions of aerosols were measured with the downstream SMPS during the first 20 minutes of operation at I100 mode after installation of a fresh DFE-A (DFE-A-2) and fresh DFE-B (DFE-B-2). The results selected as examples are shown in Figure 7 and Figure 8, respectively. Those size distributions are contrasted to the corresponding one-hour average distributions measured at I100 for the DFE-A-1 after approximately 18 hours of operation, for the DFE-B-1 after approximately 15 hours of operation, and for the muffler. The same parameters were measured for the laundered version of DFE-A during the conditioning of the element at R50 conditions. Observed size distributions were compared to one-hour average distributions obtained for the same element after 25 hours of operation and for the muffler (Figure 9).

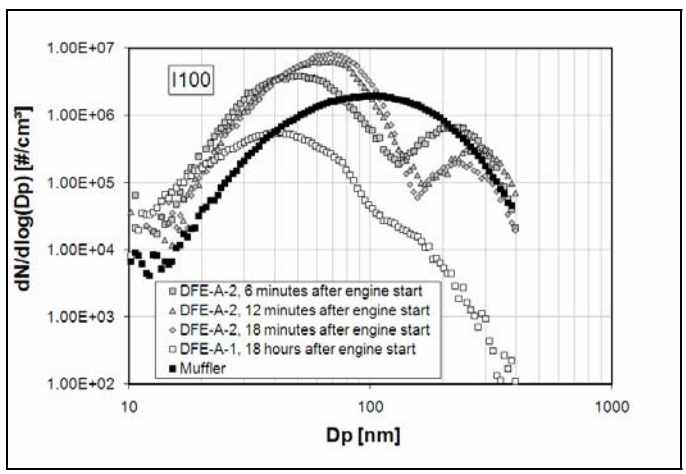


Figure 7. Effects of initial heating of DFE on size distributions of aerosols measured with SMPS for DFE-A.

The initial period of DFE-A-2 operation was characterized by emissions of visible white smoke and elevated concentrations of aerosols at the downstream station. The observed size distributions were found to be bi- or tri-modal with a characteristic secondary or tertiary peak, with $_{50}d_{em}$ ranging between 215 and 267 nm. The total number concentration of aerosols (2,516,000 #/cm^3), averaged between the sixth and eighteenth minute after engine start with fresh DFE-A-2, was more than double the average number concentration observed during the last hour of the muffler test (1,159,000 #/cm^3) and more than eight times higher than the average number concentration observed during the last hour of the test of DFE-A-1 (295,000 #/cm^3).

Peak concentrations were found to be higher than those observed for the muffler (Figure 7). According to the manufacturer (28) the source of the smoke during initial heat-up is the off-gassing of vegetable oils that are used as a filtration material binder.

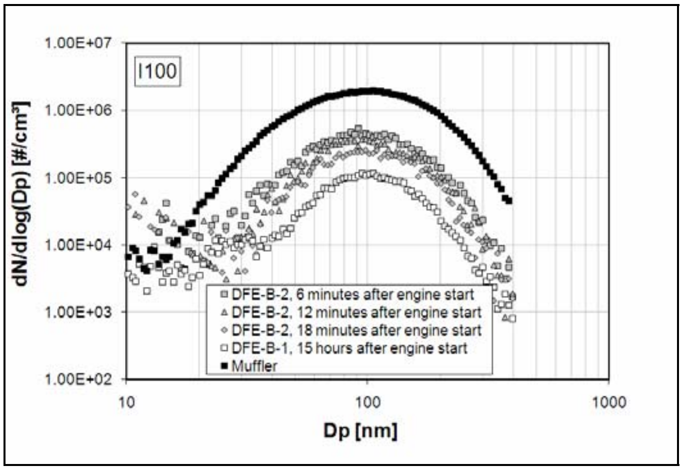


Figure 8. Effects of initial heating of the DFE on size distributions of aerosols measured with SMPS for DFE-B.

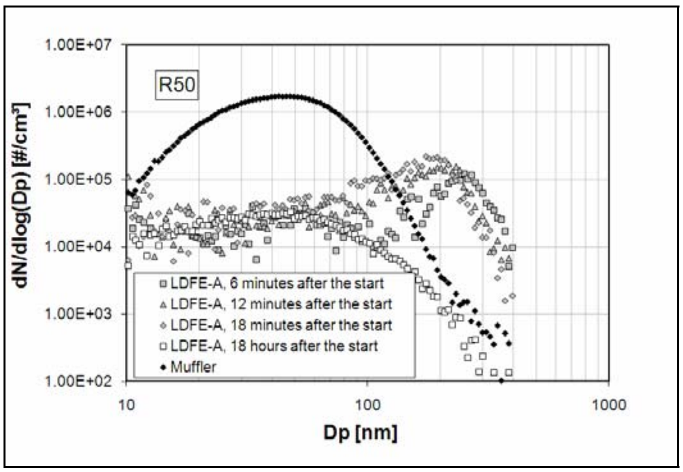


Figure 9. Effects of initial heating of the DFE on size distributions of aerosols measured with SMPS for LDFE-A.

For DFE-B-2, the size distributions exhibited a single mode with $_{50}d_{em}$ between 95 and 98 nm. The total number concentration (169,000 #/cm³), averaged between the sixth and eighteenth minute after engine start, was significantly lower than number concentration observed during the last hour of the muffler test (1,159 000 #/cm³) and two times higher than the average number concentration observed during the last hour of the test of aged DFE-B-1 (75,000 #/cm³).

The LDFE-A was operated at R50 and not I100 and cannot be compared directly to the other DFEs in this set of tests. The observed size distributions were found to be tri-modal with a tertiary peak (190 nm<$_{50}d_{em}$<241 nm) (Figure 9) similar to the secondary peak observed for new DFE-A-2 (Figure 7), but significantly less pronounced. The total number concentration (73,000 #/cm³), averaged between the sixth and eighteenth minute after engine start, was significantly lower than the number concentration observed during the last hour of the muffler test (870,000 cm³) and three times higher than the average number concentration observed during the last hour of the test of the aged LDFE-A (23,600 #/cm³). It is important to note that the intensity and duration of the off-gassing process depends on a number of factors, including exhaust temperatures and exhaust flow rate.

Effects of DFEs on Concentration of NO and NO2

The results of measurements of NO and NO_2 concentrations at the downstream station were used to calculate the average concentrations of total nitrogen oxides (NO_x = NO+NO_2) and percentage of NO_2 in the total NO_x over the last hour of each test. The measured NO_x concentrations are summarized in Figure 10, while the percentages of NO_2 in total NO_x are shown in Figure 11.

The effects of the DFEs on the average NO_x concentrations were found to be minor and within the accuracy of the instrument. The fraction of NO_2 in total NO_x was found to be generally lower for the DFEs than for the muffler. The fraction of NO_2 in NO_x in untreated exhaust was found to be strongly dependent on engine mode and exhaust temperature. NO_2 fraction was found to be substantially higher for the R50 and I50 modes than for the R100 and I100 modes. The exceptions were observed for DFE-A and DFE-B at I50 mode, where substantial increases in the NO_2 fraction compared to the muffler occurred.

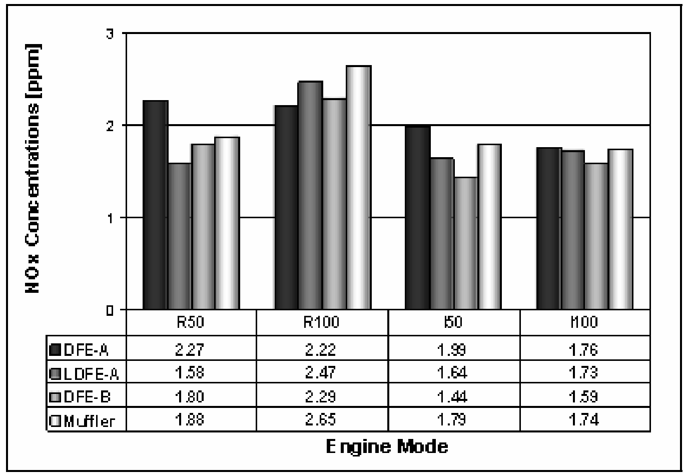


Figure 10. Effects of DFEs and muffler on NO_x concentrations for different engine modes [ppm].

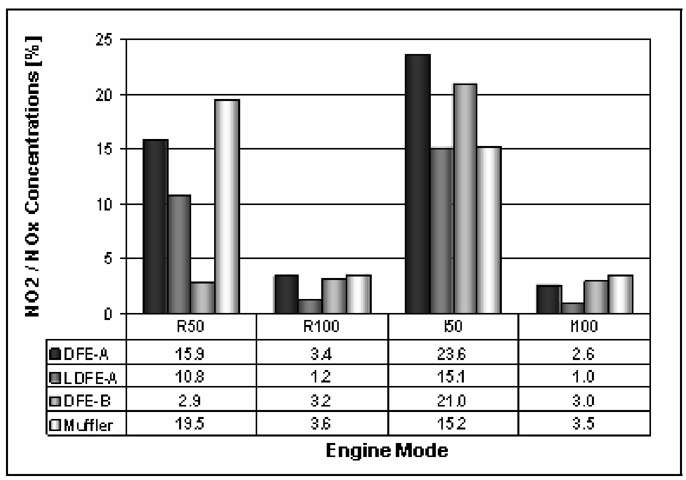


Figure 11. Effects of DFEs and muffler on percentages of NO_2 in NO_x for different engine modes.

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APPENDIX

Table 5. Total aerosol mass (TEOM) and total aerosol number (SMPS, ELPI) concentrations.

Exhaust configuration	Test mode	TEOM				SMPS				ELPI	
		Downstream		Upstream		Downstream		Upstream		Downstream	
		AVG	SDOM	AVG	SDOM	AVG	SDOM	AVG	SDOM	AVG	SDOM
		μg/cm³	μg/cm³	μg/cm³	μg/cm³	#/cm³	#/cm³	#/cm³	#/cm³	#/cm³	#/cm³
DFE-A-1	R50	25.1	1.7	11.0	2.2	1.78E+04	3.00E+03	1.44E+04	8.00E+02	1.80E+04	8.00E+02
	R100	9.4	3.6	7.1	4.2	2.01E+05	4.79E+04	1.40E+03	4.00E+02	2.02E+05	4.54E+04
	I50	-	-	-	-	6.25E+04	3.90E+03	2.63E+04	6.20E+03	6.97E+04	3.60E+03
	I100	15.8	7.7	7.2	2.1	2.95E+05	6.12E+04	2.51E+04	3.00E+03	2.59E+05	1.59E+04
LDFE-A	R50	5.4	1.1	4.7	1.5	2.36E+04	5.10E+03	4.10E+03	1.00E+02	3.10E+04	2.90E+03
	R100	14.5	0.6	7.5	2.1	2.83E+05	2.13E+04	8.40E+03	7.00E+02	2.92E+05	1.98E+04
	I50	13.3	1.3	10.9	2.8	1.74E+04	1.60E+03	8.30E+03	1.10E+03	1.92E+04	1.40E+03
	I100	20.8	1.9	9.1	2.1	5.99E+04	4.80E+03	1.48E+04	1.00E+03	5.90E+04	4.10E+03
DFE-B-1	R50	30.7	2.2	6.9	1.7	3.43E+04	1.80E+03	1.60E+03	1.00E+02	4.43E+04	2.00E+03
	R100	6.9	0.9	10.7	2.0	2.51E+05	1.95E+04	2.00E+03	2.00E+02	2.55E+05	1.64E+04
	I50	10.5	0.1	10.7	1.1	6.20E+03	8.00E+02	2.10E+03	2.00E+02	6.50E+03	5.00E+02
	I100	6.0	1.0	7.7	5.0	7.50E+04	1.22E+04	5.90E+03	1.30E+03	7.30E+04	8.90E+03
Muffler	R50	144.3	2.4	23.4	2.5	8.73E+05	2.82E+04	3.60E+03	2.00E+02	5.36E+05	1.95E+04
	R100	122.6	10.3	31.5	2.3	7.80E+05	1.71E+04	5.20E+03	5.00E+02	6.68E+05	3.58E+04
	I50	109.4	3.5	5.9	1.0	5.50E+05	2.08E+04	1.31E+04	6.00E+02	4.35E+05	2.10E+04
	I100	1058.8	27.5	13.4	3.8	1.16E+06	5.20E+04	2.80E+03	2.00E+02	1.39E+06	7.37E+04