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Effectiveness of Selected Diesel Particulate Matter Control Technologies for Underground Mining Applications: Isolated Zone Study, 2004

Department of Health and Human Services
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health

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By Aleksandar D. Bugarski, Ph.D., George H. Schnakenberg, Jr., Ph.D., Steven E. Mischler, James D. Noll, Ph.D., Larry D. Patts, and Jon A. Hummer

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ACRONYMS AND ABBREVIATIONS USED IN THIS REPORT

ACGIH	American Conference of Governmental Industrial Hygienists
AM	ArvinMeritor, Inc. (Columbus, IN)
ASTM	American Society for Testing and Materials
CAP	Clean Air Power, Ltd. (Houston, TX)
CFR	Code of Federal Regulations
CH_4	methane
C_i	net contribution of the tested vehicle to air concentrations of pollutant for control technology test
$C_{i\ BL}$	net contribution of the tested vehicle to air concentrations of pollutant for baseline test
c_i	measured concentration
$c_{i,VR}$	ventilation-adjusted concentrations
$c_{i,VR,,DOWN}$	ventilation-adjusted concentrations at the downstream sampling station
$c_{i,UP}$	measured concentration at the upstream sampling station
CO	carbon monoxide
CO_2	carbon dioxide
CPO	catalytic particulate oxidizer
CV	coefficient of variation
D_p	particle diameter
DFE	disposable filter element
dN/(d log D_p)	normalized particle number concentration
DOC	diesel oxidation catalyst
DPF	diesel particulate filter
DPM	diesel particulate matter
EC	elemental carbon
ETG	Emission Technology Group AB (Gothenburg, Sweden)
Fed. Reg.	Federal Register
FID	flame ionization detector
GMD	geometric mean diameter
GSD	geometric standard deviation
HV	high-volume
IC	ion chromatography
LHD	load-haul-dump
MARG	Methane Advisory Research Group
MSHA	Mine Safety and Health Administration
N/A	not available
NIOSH	National Institute for Occupational Safety and Health
NO	nitric oxide
NO_2	nitrogen dioxide
O_2	oxygen
OC	organic carbon
PAH	polycyclic aromatic hydrocarbon

PAS	Photoelectric Aerosol Sensor (EcoChem Analytics)
PC	personal computer
Pd	palladium
Pd DOC	diesel oxidation catalyst with palladium-based formulation
PRL	Pittsburgh Research Laboratory (NIOSH)
Pt	platinum
Pt DOC	diesel oxidation catalyst with platinum-based formulation
SMC	Stillwater Mining Co.
SMPS	scanning mobility particle sizer
SSM	standard sampling method
TEOM	tapered-element oscillating microbalance
TLV	threshold limit value (ACGIH)
TPM	total particulate matter
ULS	ultralow sulfur (diesel)
USBM	U.S. Bureau of Mines
VR	ventilation rate
$VR_{baseline\ \mathrm{LHD\ 1}}$	average ventilation rate for the LHD 1 baseline tests
$VR_{baseline\ \mathrm{LHD\ 2}}$	average ventilation rate for the LHD 2 baseline tests
YG	yellow grease (biodiesel)

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm^2	square centimeter
cm^3	cubic centimeter
ft	foot
ft^3/min	cubic foot per minute
g/m^3	gram per cubic meter
g/mL	gram per milliliter
hp	horsepower
hr	hour
Hz	hertz
in H_2O	inches of water
kJ/kg	kilojoule per kilogram
kPa	kilopascal
kW	kilowatt
L/min	liter per minute
m	meter
m^3/s	cubic meter per second
mbar	millibar
min	minute
mm	millimeter
mm^2/s	square millimeter per second
nm	nanometer
Pa	pascal
ppm	part per million
s	second
µg	microgram
$\mu g/cm^3$	microgram per cubic centimeter
$\mu g/m^3$	microgram per cubic meter
µm	micrometer
% vol	percent by volume
% wt	percent by weight
$\#/cm^3$	particle number per cubic centimeter
°C	degree Celsius
°F	degree Fahrenheit

EFFECTIVENESS OF SELECTED DIESEL PARTICULATE MATTER CONTROL TECHNOLOGIES FOR UNDERGROUND MINING APPLICATIONS: ISOLATED ZONE STUDY, 2004

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ABSTRACT

The National Institute for Occupational Safety and Health conducted a study to determine the effects of selected, state-of-the-art emission control technologies on the ambient concentrations of particulate matter and gases emitted by underground diesel-powered mining equipment. Tests were conducted in an isolated zone of an underground mine to evaluate the effectiveness of alternative fuel formulations, namely, water-fuel emulsions, blended biodiesel fuels, ultralow sulfur diesel fuel, and #1 diesel; and selected exhaust aftertreatment devices, namely, diesel oxidation catalysts (DOCs), diesel particulate filter (DPF) systems, and filtration systems designed around high-temperature disposable filter elements.

The results showed that using a cold-weather and warm-weather water-fuel emulsion formulation reduced mass concentrations of elemental carbon (EC) by about 70% and 85%, respectively. The 20% and 50% soy biodiesel blends reduced EC by 49% and 66%, respectively. The reductions were slightly less pronounced for the 20% and 50% yellow grease biodiesel blends—33% and 56%, respectively. EC concentrations were unaffected by using ultralow sulfur diesel in place of #1 diesel. Use of the reformulated fuels did not substantially alter the concentrations of nitric oxide and carbon monoxide. However, a measurable increase in the nitrogen dioxide (NO_2) peak concentration was observed during the biodiesel tests.

The ArvinMeritor (AM) fuel-burner DPF system with a palladium-catalyzed DOC reduced EC concentrations by 92%. The diesel filter elements from Donaldson Co., Inc., and Filter Service & Testing Corp. reduced the EC concentration of the mine air by 92% and 70%, respectively. When the palladium-based DOC was used with the AM DPF, it raised the average and peak downstream NO_2 concentrations by a factor of three. Tests of the AM DPF system with a platinum-catalyzed DOC and CAP/ETG catalytic particulate oxidizer system had to be terminated because the elevated NO_2 concentrations threatened to overexpose the operator. The tests with only a selected DOC also resulted in increased NO_2 concentrations in mine air.

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[1] Mechanical engineer.
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[3] Physical scientist.
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INTRODUCTION

In January 2001, the Mine Safety and Health Administration (MSHA) promulgated rule 30 CFR[6] 57.5060, which limits exposures of underground metal and nonmetal miners to diesel particulate matter (DPM). As a result of this rule, the underground mining community is currently working on identifying technically and economically feasible controls for curtailing DPM and gaseous emissions from existing and new diesel-powered vehicles in underground mines. To date, the replacement of older diesel engines with cleaner modern engines, improvements in mine ventilation, diesel engine maintenance, and the implementation of various diesel emission control technologies, including diesel particulate filters (DPFs) and reformulated fuels, are some of the tools showing potential to control DPM emissions.

Previous laboratory evaluations [Mayer et al. 1999; Larsen et al. 1999] and underground mine tests [Watts et al. 1995; McGinn et al. 2002; Bugarski and Schnakenberg 2001, 2002] have shown that current DPF technologies can be used to effectively control particulate matter emissions from diesel engines. This was further corroborated by the results of a series of tests conducted in an isolated zone at Stillwater Mining Co.'s (SMC) Nye Mine in southern Montana during the summer of 2003 [Bugarski et al. 2004]. The study showed that tested DPF systems caused an undesired increase in the ambient concentration of nitrogen dioxide (NO_2), potentially introducing a known health hazard. This increase in NO_2 emissions can be related to the processes promoted by a platinum-based catalyst used by these systems to promote the regeneration of the DPF at relatively low exhaust temperatures. This NO_2 increase is one of the major technical problems affecting implementation of DPFs in underground mines. In addition, the biodiesel results from the SMC study [Bugarski et al. 2004] corroborated results of others that neat (100% biodiesel) and biodiesel blends with regular diesel fuels were found to reduce the concentration of DPM [McDonald et al. 1997] and elemental carbon [Watts et al. 1998; 68 Fed. Reg.[7] 48667 (2003)] in underground mines.

New control technologies have emerged recently as a result of the high demand for aftertreatment systems to control diesel emissions from on-road and off-road vehicles. Some of these technologies are in wide use in on-road applications, but have not yet been tested for underground mining applications. Two relatively novel technologies, a DPF system with a diesel fuel burner developed by ArvinMeritor, Inc., and a flow-through catalytic particulate oxidizer (CPO) filtration system distributed in the United States by Clean Air Power Ltd., were found to be worth evaluating. In addition, filter systems using high-temperature disposable filter elements from Donaldson Co., Inc., and Filter Service & Testing Corp., both of which are currently used by the coal mining industry, were also selected for close examination in this study.

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[6] *Code of Federal Regulations.* See CFR in references.
[7] *Federal Register.* See Fed. Reg. in references.

Other DPM control strategies of interest are water-fuel emulsions, biodiesel blends, and ultralow sulfur diesel fuel. These alternative fuels are currently used by some metal and nonmetal underground mines, and there is evidence of their effectiveness from surveys conducted by MSHA, but their effectiveness must still be accurately quantified.

The study reported here was conducted to evaluate the effectiveness of the state-of-the-art technologies for controlling DPM and gaseous emissions from underground diesel-powered mining equipment using the isolated zone approach. The study was sponsored by the Metal/Nonmetal Diesel Partnership, an industry/labor/government partnership formed by the National Institute for Occupational Safety and Health (NIOSH), the National Mining Association, the National Stone, Sand and Gravel Association, the United Steelworkers of America, the MARG Diesel Coalition, and the Industrial Minerals Association–North America. The testing was conducted at the SMC Nye Mine in southern Montana from August 31, 2004, to September 9, 2004, by a team of researchers from NIOSH and SMC. The suppliers of the filtration systems and the reformulated fuels, and the instrumentation manufacturers contributed with technical support and in-kind contributions.

OBJECTIVE

The objective of this study was to determine the effects of selected state-of-the-art emission control technologies (see Table 1) on the ambient concentrations of diesel particulate matter (DPM) and gases emitted by underground diesel-powered mining equipment. The technologies were tested in an underground mine using mining vehicles that were operated under conditions that closely resembled actual production scenarios.

This short-term study addressed some limited issues related to the selection and implementation of the control technologies on the test vehicles used in the study. However, it was not designed to address other important issues related to the implementation and operation of diesel particulate filters (DPFs), including cost, the integration of various DPF system regeneration schemes into the production cycle, and their long-term reliability and durability. Addressing these issues will require long-term studies with continuous monitoring of performance of the DPF systems and periodic emissions testing.

The effects of the selected control technologies on concentrations of DPM and gases in the mine air were assessed by conducting two groups of tests in the isolated zone at the SMC Nye Mine in southern Montana (see Table 1). The first group of tests evaluated alternative fuel formulations, namely, water-fuel emulsions, blended biodiesel fuels, ultralow sulfur diesel fuel, and #1 diesel. Included in this group were two tests in which the muffler was replaced with a standard diesel oxidation catalyst (DOC). The second group of tests evaluated DPF systems, namely, the two systems supplied by ArvinMeritor and Clean Air Power/Emission Technology Group (CAP/ETG) and high-temperature disposable filter elements (DFEs) from Donaldson Co., Inc., and Filter Service & Testing Corp.

Table 1.—Control technologies evaluated in the study

Test Group (Test Vehicle)	Exhaust System	Fuel Formulation
Fuel Formulations (LHD 1 powered by Caterpillar 3126B DITA AA)	Muffler	#1 diesel
	Muffler	PuriNOx cold-weather water-fuel emulsion
	Muffler	PuriNOx warm-weather water-fuel emulsion
	Muffler	20% soy biodiesel and 80% #1 diesel blend
	Muffler	50% soy biodiesel and 50% #1 diesel blend
	DOC from DCL International	50% soy biodiesel and 50% #1 diesel blend
	Muffler	20% yellow grease biodiesel and 80% #1 diesel blend
	Muffler	50% yellow grease biodiesel and 50% #1 diesel blend
	Muffler	ULS (10-ppm sulfur) diesel
	DOC from DCL International	ULS (10-ppm sulfur) diesel
Filtration systems (LHD 2 powered by Deutz BF4M1013 FC/MVS)	Muffler	#1 diesel
	ArvinMeritor fuel-burner DPF system with platinum (Pt) DOC	#1 diesel
	ArvinMeritor fuel-burner DPF system with palladium (Pd) DOC	#1 diesel
	Donaldson disposable filtration element P604516	#1 diesel
	Filter Service disposable filtration element	#1 diesel
	Clean Air Power/ETG catalytic particulate oxidizer (CPO) DPF system	#1 diesel

METHODOLOGY

VEHICLES AND ENGINES

SMC selected two load-haul-dump (LHD) vehicles, designated as “LHD 1” and “LHD 2,” to serve as test platforms for the study. These Gs were selected because they are typical of the SMC Nye Mine production fleet and they were found to be suitable for the control technologies to be tested. These LHDs are classified as heavy-duty production machines, and their engines are routinely heavily loaded in the course of their normal duty cycle.

The basic specifications for the vehicles and engines are shown in Table 2.

Table 2.—Test vehicles and engines

Vehicle (Test Group)	Vehicle Type	Vehicle Make	Vehicle Model	Engine Make	Engine Model	Engine Displacement, L	Engine Rating, kW (hp)	Engine Type
LHD 1 (Fuels)	LHD	Wagner	ST–3.5	Caterpillar	3126B DITA AA	7.243	149 (200)	Fully Electronic Controlled, Turbocharged, Air to Air After Cooled
LHD 2 (Filters)	LHD	Wagner	ST–2D	Deutz	BF4M 1013 FC/ MVS	4.764	113 (151)	Fully Electronic Controlled, Turbocharged, Air to Air After Cooled

LHD 1, which was powered by a Caterpillar 3126B DITA engine, was selected as a test platform for conducting the fuel tests after Caterpillar representatives confirmed that engine performance would not be affected by the alternative fuels to be tested. In addition, the components of the fuel system on that engine were found to be compatible with all of the fuels targeted in this study. The vehicles powered by Deutz engines were ruled out as potential test vehicles because these engines were not compatible with water-fuel emulsions.

LHD 2, used during the study for testing filtration systems, was selected several months before the study by mine representatives as a test platform for evaluating the ArvinMeritor (AM) DPF system with a diesel fuel burner. The other tested filter systems were fitted to vehicle LHD 2, as temporary installations, only for the purpose of conducting specific tests. This approach allowed testing of the filtration systems on the same vehicle and direct comparison of their performance.

PREPARATION OF THE VEHICLE FOR THE STUDY

The Caterpillar 3126B DITA AA engine in LHD 1 was equipped with its original muffler for 8 of the 10 tests on fuel formulations. For two of the fuel tests, the engine was fitted with a DCL MINE–X catalytic converter, Model #3206–MD. The Caterpillar 3126B DITA AA engine has an open crankcase breather that was not filtered in this study. For the testing on fuels, the exhaust and oil fumes escaping from the breather are an insignificant fraction of total emissions. The different fuels would equally affect the exhaust blowby and the main engine exhaust.

The modifications to LHD 2 for the filter tests were related to the temporary installation of various exhaust system configurations. The ArvinMeritor (AM) DPF system had been installed on vehicle LHD 2 in January 2004. The other filter systems tested were fitted to vehicle LHD 2 as temporary replacements for the AM DPF system specifically for the purpose of conducting these tests. A muffler was fitted in place of the AM DPF for the test that was conducted to establish a baseline for DPM and gases against which the other systems would be compared. The Deutz BF4M1013 FC/MVS engine used in LHD 2 is designed with a closed-loop crankcase breather system, which eliminated spurious DPM emissions.

At SMC, skilled maintenance personnel, using an emissions-assisted maintenance program, service all vehicles and engines regularly. They made the necessary preparations for the tests, including changes on the exhaust systems, in the Nye Mine surface shop.

TESTED FUEL FORMULATIONS

The series of tests, which was conducted to evaluate eight different fuel formulations, is shown in Table 1. LHD 1 powered by a Caterpillar 3126B DITA AA engine was used for the tests. The effects of each fuel formulation were determined by comparing the airborne DPM and gas concentrations measured when LHD 1 was fueled with each fuel formulation to the concentrations measured when it was fueled with #1 diesel fuel.

The #1 diesel fuel used in these tests was supplied to the mine by a local refinery (Cenex, Columbus, MT). This particular fuel exceeds MSHA requirements (30 CFR 57.5065) for diesel fuels used in underground mines. In order to control experimental variation, all of the #1 diesel fuel used in this study was obtained from the same process batch.

Lubrizol Corp., Wickliffe, OH, supplied two formulations of water-in-diesel fuel emulsions with the trade name “PuriNOx.” The warm-weather formulation contains approximately 77% #2 diesel fuel, 20% water, and 3% proprietary PuriNOx emulsifying agent. This formulation is suitable for fueling vehicles when there is no risk of freezing. The cold-weather formulation contains approximately 86% #2 diesel fuel, 10% water, 2% methanol, and 2% of the proprietary emulsifying agent. It is formulated for colder climates. The emulsions are prepared in a specialized blending unit developed by

Lubrizol. It is important to note that, depending on operating conditions and engine settings, use of water emulsion can result in a reduction in peak horsepower and torque. The samples of cold- and warm-weather formulations were sent to Core Laboratories, Inc., Houston, TX, for analysis. The results of the analysis are summarized in Table 3.

Neat soy biodiesel, supplied by Sustainable Systems, LLC, Missoula, MT, was tested as a 20% and 50% blend with #1 diesel fuel. The neat biodiesel was blended in the desired volumetric fractions with #1 diesel at the site using an electronic volumetric flow meter from Great Plains Industries, Inc., Wichita, KS. Each fuel blend was stored in a designated tank. Samples of each soy fuel blend were collected from the designated fuel tank and sent to Core Laboratories, Houston, TX, for analysis. Results of the blends are presented in Table 3. West Central, Ralston, IA, the producer of the soy biodiesel, reported the following properties for the neat soy biodiesel fuel: free glycerin, 0.00135%; total glycerin, 0.1995%; flashpoint, 153 °C; sulfur (by ultraviolet fluorescence), 0.00014% by mass; kinematic viscosity, 4.20 mm^2/s; cetane number, 52.7.

Table 3.—Fuel formulation properties

Fuel Formulations			PuriNOx Cold-Weather	PuriNOx Warm-Weather	20% Soy Biodiesel	50% Soy Biodiesel	ULS Fuel
Properties	Method	Units					
Aromatics	ASTM D1319	% vol	22.4	23.7	—	—	26.4
Olefins	ASTM D1319	% vol	2.3	2.4	—	—	1.2
Saturates	ASTM D1319	% vol	75.3	73.9	—	—	72.4
Density at 16 °C	ASTM D4052	g/mL	0.853	0.866	0.836	0.854	0.850
Sulfur Content	ASTM D2622	ppm	300	279	205	129	4
Oxygen	By difference	% wt	7.8	15.3	4.4	7.4	1.3
Heat of Combustion	ASTM D240	kJ/kg	39,549	36,995	42,042	40,828	42,875
Flash Point	ASTM D93	°C	47	—	68	70	64

The neat yellow grease biodiesel (Biodiesel G–3000) used in this study was supplied by Griffin Industries, Inc., Cold Spring, KY. 20% and 50% blends were obtained by blending neat biodiesel with #1 diesel at the site using an electronic volumetric flow meter. Each fuel blend was stored in a designated tank. Griffin Industries provided a certificate of analysis for the neat Biodiesel G–3000. The properties of this fuel reported on the certificate are: free glycerin, 0.01%; total glycerin, 0.096%; flashpoint, >130 °C; sulfur, 0.004% by mass; kinematic viscosity, 4.81 mm^2/s at 40 °C; cetane number, 53.9. Blends made with yellow grease biodiesel supplied by Griffin Industries were previously evaluated as part of the 2003 isolated zone study at the SMC Nye Mine [Bugarski et al. 2004].

Federated Co-operatives Ltd., Saskatoon, Saskatchewan, Canada, supplied ultralow sulfur (ULS) diesel fuel. After the test, a sample of the ULS diesel was collected from the auxiliary fuel tank and sent to Core Laboratories for analysis. The results of the analysis are shown in Table 3.

TESTED AFTERTREATMENT SYSTEMS

The aftertreatment systems evaluated in this study are shown in Table 4. The mine vehicle used for these tests was LHD 2 powered by a Deutz BF4M1013 FC/MVS engine.

Table 4.—Aftertreatment systems

Filtration System	Media Type	Catalyst	DOC
ArvinMeritor (AM) with Pt DOC	Ceramic, Cordierite	N/A	Metal Substrate Platinum-Based Catalyst
ArvinMeritor (AM) with Pd DOC	Ceramic, Cordierite	N/A	Metal Substrate with Palladium-Based Catalyst
Donaldson P604516	High-Temperature Disposable Filter Element	N/A	N/A
Filter Service	High-Temperature Disposable Filter Element	N/A	N/A
Clean Air Power/ETG CPO	Deep-Bed Fiber, Quartz Silica Fiber	Precious Metal Catalyst-Coated Fibers	Ceramic Monolith Substrate with Precious Metal Catalyst

ArvinMeritor (AM) DPF System

The DPF system from ArvinMeritor, Inc. (AM), Columbus, IN, (Figure 1) uses an integrated fuel burner to perform automatic regeneration of the filter element. In January 2004, SMC installed this system on LHD 2 for use in production as part of a long-term evaluation. Prior to the isolated zone study, this system had accumulated approximately 470 hr in production. During that period, the fuel burner, acting automatically, successfully regenerated the filter element at regular intervals.

Figure 1.—ArvinMeritor DPF system.

DPM filtration by the AM DPF system occurs in an uncatalyzed ceramic wall-flow monolith filter element—the DuraTrap RC (Corning, Inc., Corning, NY). The computer-controlled diesel fuel burner is integrated on the inlet side of the DPF element. When activated, the burner ignites diesel fuel injected into the combustion chamber to heat the engine exhaust and filter element to about 650 °C, a temperature sufficient to consume all of the soot that has accumulated on the filter element. This process is called regeneration. The regeneration process can be initiated at predetermined time intervals, or it can be triggered by predetermined levels of engine back pressure. The former approach was adopted for the system installed on LHD 2. The operation of this system is completely automated and transparent to the operator.

The AM DPF system was tested twice in order to evaluate two different catalyst formulations for the DOC following the filter element. The original DOC, used with the system on LHD 2, had a platinum-based formulation washcoated onto a substrate. This DOC accumulated approximately the same number of hours as the other components of the AM DPF system. An earlier study at the Nye Mine [Bugarski et al., forthcoming] showed that platinum-based, catalyst-coated DPFs and DPFs in combination with platinum-based, catalyst-coated DOCs tend to increase the NO_2 concentration in diesel exhaust. An alternative DOC, using a palladium-based catalyst applied to a metal substrate, was designed to mitigate the NO_2 problem. After installing a new Pd DOC and prior to testing, LHD 2 was operated for approximately 1½ hr to condition the new catalyst.

Clean Air Power/ETG Catalytic Particulate Oxidizer (CPO) System

A Clean Air Power/ETG CPO system Model CPO180 was installed temporarily on LHD 2, as shown in Figure 2. The manufacturer, the Emission Technology Group (ETG) based in Gothenburg, Sweden, states that the catalytic particulate oxidizer (CPO) uses filter cartridges made of catalyzed silica fibers that are able to catalytically oxidize carbon particles at low temperatures without actually trapping them on a filter. The system consists of two units, a CPO followed by a DOC, and was installed under the guidance of the distributor.

After installing the system, the Clean Air Power/ETG CPO was conditioned by operating the vehicle for approximately 2 hr outside of the mine. After testing, the system was removed from the vehicle.

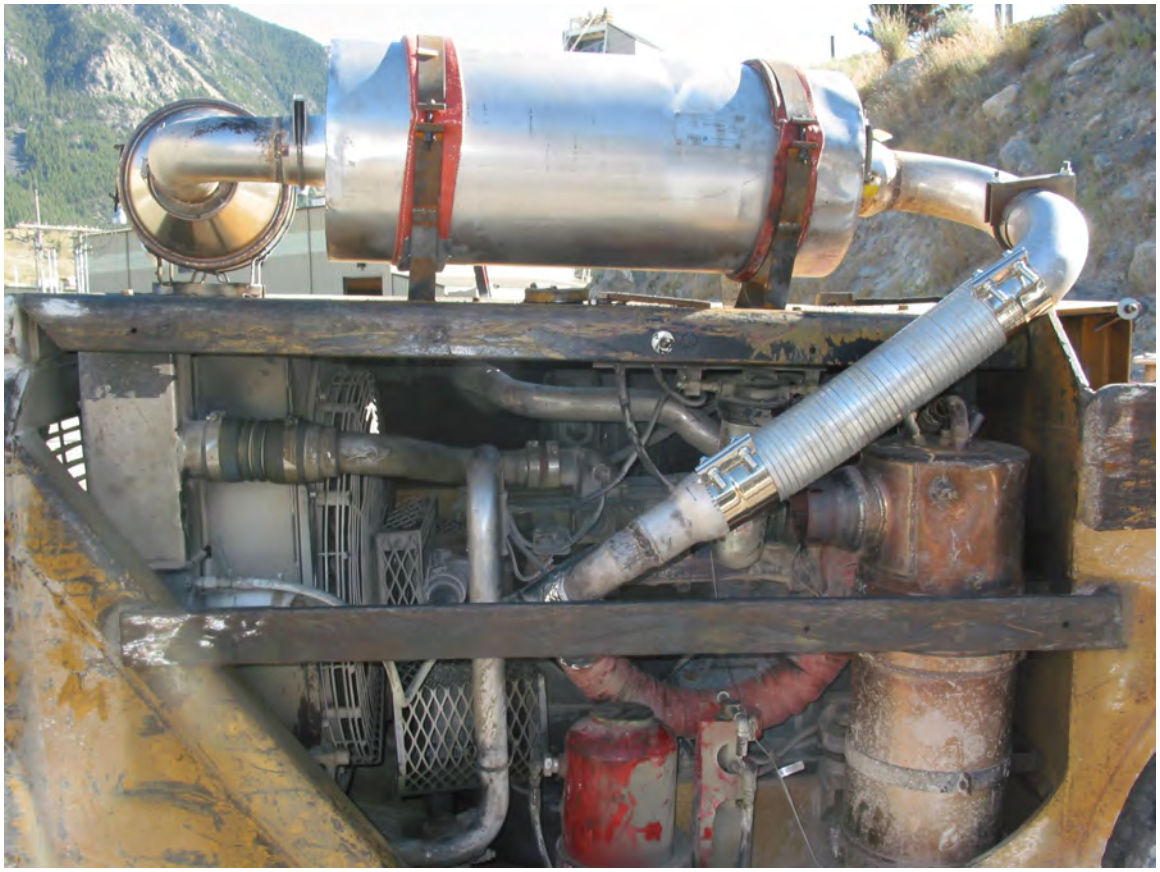


Figure 2.—Clean Air Power/ETG CPO system.

Filtration System With Disposable Filter Element From Donaldson (Model P604516)

In order to test the high-temperature disposable filter element (DFE) (part No. P604516 from Donaldson Co., Inc., Minneapolis, MN), it was installed temporarily on LHD 2, as shown in Figure 3. The DFE was contained within a stainless steel housing that was originally designed for filter elements from Filter Service & Testing Corp., Price, UT. The dimensions of the Filter Service DFE are almost identical to those of the Donaldson element. The housing was designed and built by Mac's Mining Repair of Huntington, UT, and was supplied for this study by SMC East Boulder Mine personnel, who were evaluating the disposable filter concept for reducing miners' exposures to DPM.

The pleated DFE is classified as a deep-bed filter consisting of a thin felt or woven mat of fibers. The fibers collect soot throughout their depth and as a rule become more efficient as the filter loading increases and the pathways through the filter become smaller and more restrictive. The filter medium is highly porous and creates relatively low exhaust back pressure when new. Because the filter material can withstand temperatures as high as 760 °C (1,400 °F), this DFE is finding use in some applications for filtering relatively hot exhaust that is not cooled by a water scrubber or other types of heat exchangers.

At the time of the test, this DFE was on the MSHA list of DPM control technologies, with a recommended temperature limit of less than 343 °C (650 °F) [MSHA 2005].

Prior to testing, the vehicle was operated for approximately 2 hr inside the mine to condition the new filter element.

Figure 3.—Filtration system used in testing high-temperature disposable elements from Donaldson and Filter Service.

Filtration System With Disposable Filter Element From Filter Service & Testing Corp.

A prototype of the high-temperature DFE from Filter Service was similar in dimensions, design, and physical properties to the Donaldson P604516 DFE. The filter material was constructed from high-temperature fiberglass medium. At the time of the isolated zone testing, the Filter Service DFE was not on the MSHA list of DPM control technologies [MSHA 2005].

For testing, the Filter Service DFE was placed in a housing temporarily installed on the LHD 2 test vehicle, the same installation used to test the Donaldson DFE (Figure 3). Prior to testing, the vehicle was operated for approximately 3 hr outside and inside the mine to condition the new DFE.

FUELING PROCEDURES

For the fuel tests, the LHD 1 tank was filled with test fuels at a fueling station (Figure 4) located in a crosscut in the isolated zone approximately midway between the upstream and downstream sampling stations. Having test fuels in the test zone eliminated the need for dismantling the upstream sampling station between consecutive reformulated fuel tests. For the filter tests, fueling of LHD 2 with #1 diesel was done from a temporary fueling station established outside the portal.

A hand pump, with an electronic fuel flow meter from Great Plains Industries, Inc., Wichita, KS, was used to transfer fuels from the drums to the auxiliary fuel tank on the test vehicle (Figure 5). The auxiliary tank was topped off after the warmup cycles were completed and just before the start of the test run. Fuel consumed during each test was roughly determined by subtracting, at the end of the test, the volume of fuel remaining in the auxiliary tank from the tank capacity. This method was not found to be sufficiently accurate to provide meaningful data on fuel consumption. Results are therefore not reported.

Figure 4.—Fueling station in the isolated zone.

Figure 5.—Auxiliary tank on LHD 1.

Precautions were taken to avoid cross-contamination of the fuels from consecutive fuel tests. Between tests, the auxiliary tank was drained and the fuel filter was replaced with a new one. After filling the emptied auxiliary tank with the desired test fuel, the vehicle fuel system was purged by operating the vehicle for two full cycles in the isolated zone prior to the start of the test. During this process, the excess fuel from the fuel system was diverted to the primary vehicle fuel tank. After completing two purge cycles, the auxiliary tank was refilled with test fuel, the return line was diverted back to the auxiliary tank, and the test run was started.

ISOLATED ZONE TESTING

The objective of this study was to evaluate the performance of selected control technologies using isolated zone testing. Isolated zone tests are designed to be a compromise between the genuineness of in situ measurements of concentrations and corresponding exposures, and the repeatability and accuracy of the emission measurements obtained under research laboratory conditions. When carefully designed, as were the tests at the SMC Nye Mine, isolated zone tests allow the operation of vehicles under conditions and over duty cycles that closely mimic actual production duty cycles. In addition, artifacts usually generated under laboratory conditions while attempting to simulate real-life conditions and processes do not compromise such tests in an isolated zone in a mine. Finally, isolated zone test measurements are not confounded by emissions from other vehicles and variability in ventilation as would occur in tests conducted in real production areas.

The effects of each of the selected control technologies on DPM and gas concentrations in the mine air were estimated from the measurements taken while each test vehicle was operated within the isolated zone with and without control technologies. In general, corrections for the background concentrations of the pollutants were made by subtracting the results of measurements performed at the upstream end of the zone from the corresponding results obtained at the downstream end of the isolated zone or on the vehicle. The efficiency of any technology tested was determined by comparing the pollutant concentrations determined when the technology was used to those concentrations resulting from operating the same vehicle over the same duty cycle with a standard muffler and fuel, i.e., the baseline configuration.

Test Site

The 530-m (1,739-ft) isolated zone was located in 52E ramp in the east section of the SMC Nye Mine. The upstream end of the zone was situated approximately 150 m (492 ft) from the portal and the entry point of fresh air. The elevation of the portal is approximately 1,525 m (5,000 ft) above sea level. The location of the isolated zone relative to the portal is shown in Figure 6. The average cross-sectional dimensions of the isolated zone drift were approximately 2.7 m (9 ft) wide by 3.6 m (12 ft) high. The ramp has a 9% rise toward the downstream end.

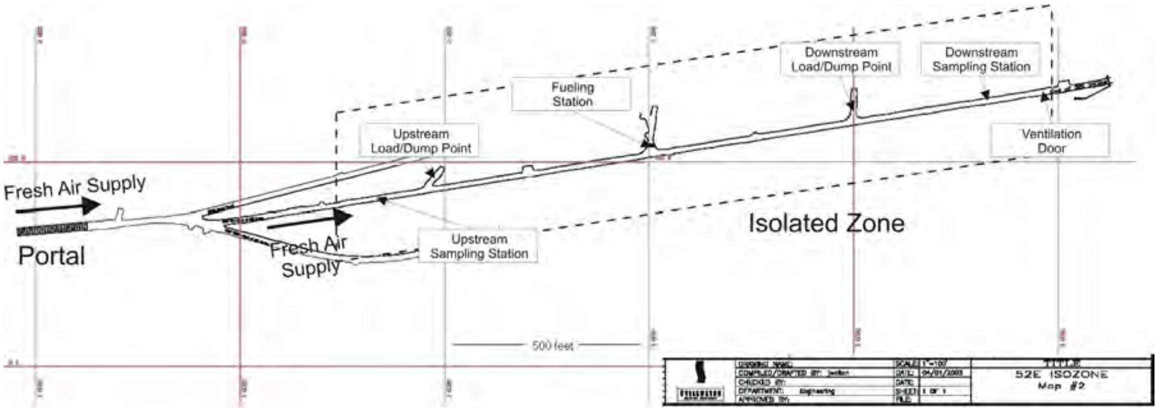


Figure 6.—Isolated zone, 52E entry, SMC Nye Mine.

The site selected for the isolated zone met the following requirements:

1. It is isolated from other parts of the mine where diesel-powered equipment is used.
2. It is ventilated with fresh air directly from the mine portal.
3. The quality and quantity of the air are not compromised by portal traffic.
4. The zone is sufficiently long and the opening is relatively small to ensure thorough air mixing at the planned ventilation rates and uniform contaminant distribution across the drift at the downstream sampling station.
5. The ventilation controls allow for adjustment and maintenance of relatively constant average air quantities during the tests.
6. Electric power to operate equipment and instrumentation is available at the downstream and upstream sampling stations.

A schematic of the isolated zone is shown in Figure 7. The two tested LHD vehicles were operated over a simulated duty cycle between two stopes, one at the upstream and one at the downstream load/dump points, which were approximately 300 m (984 ft) apart. The upstream sampling station was located approximately 90 m (295 ft) upstream of the upstream load/dump point. The downstream sampling station was located approximately 140 m (459 ft) downstream of downstream load/dump point. A third sampling point was located on the vehicle. The ventilation control doors were located approximately 60 m (197 ft) downstream of the downstream sampling station. The stopes at the upstream and downstream load/dump points were approximately 8 m (26.2 ft) deep. Sufficient quantities of waste rock were available in the stopes to support load and dump actions. The refueling station was located in one of the sealed stopes approximately halfway between the upstream and downstream load/dump points.

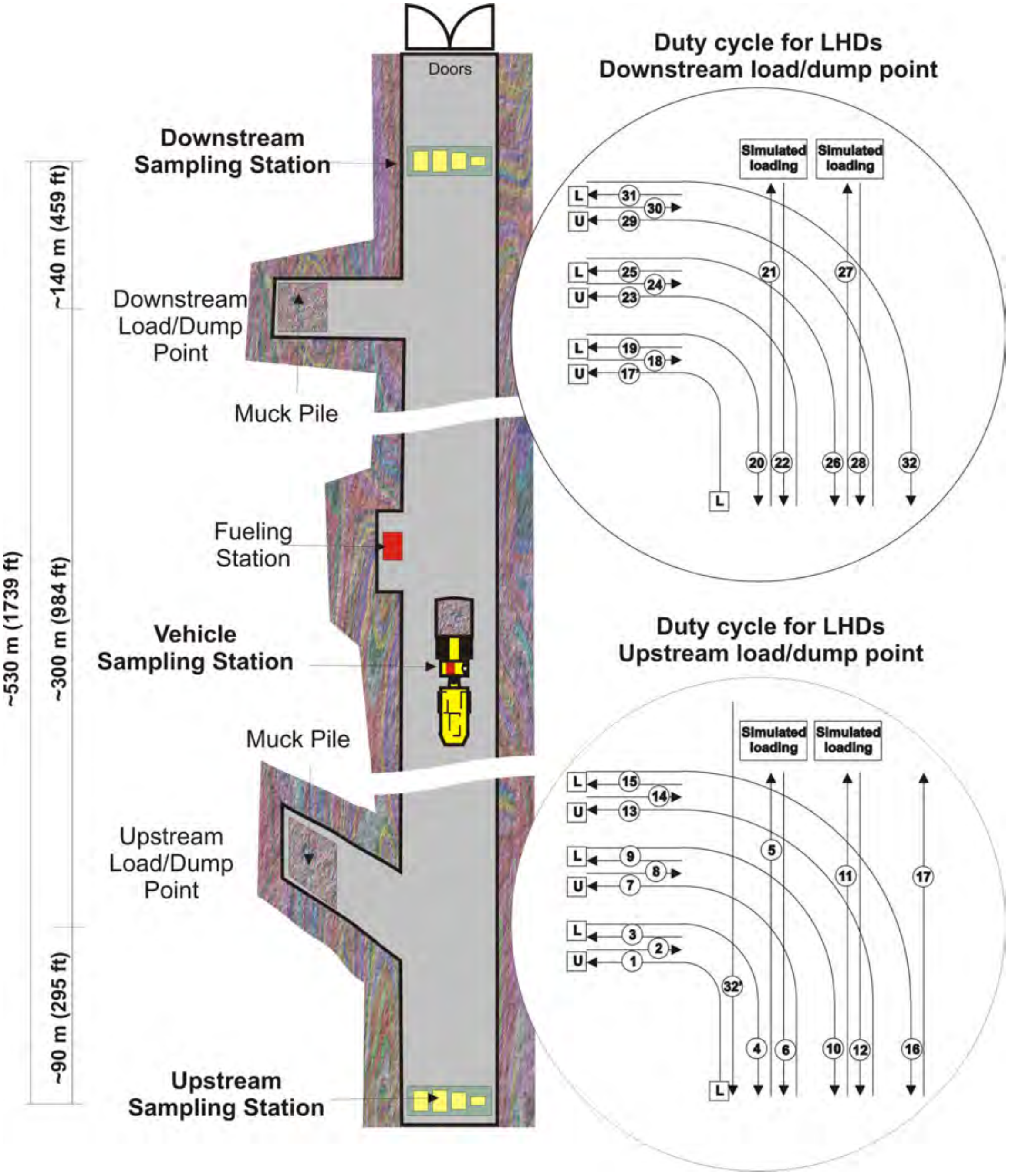


Figure 7.—LHDs in the isolated zone (not to scale).

Duty Cycles

A defined, conservative, simple, and repeatable duty cycle for the LHD vehicles, schematically represented in Figure 7, was developed by NIOSH personnel and experienced vehicle operators from the SMC Nye Mine. The test cycle simulated a production cycle typical for the LHD equipment.

The duty cycle consisted of two very similar load/dump tasks, one occurring at each of the load/dump points, and two tramming events, occurring between those points. The LHD started its cycle just upstream of the upstream load/dump point with the bucket, loaded with waste rock, facing downstream. The operator first turned the vehicle into the upstream stope, unloaded the bucket, retreated for the length of the vehicle, then advanced forward and loaded the bucket again. Next, the operator backed the vehicle out of the stope, retraced its path, and then advanced up the ramp (downstream) for two vehicle lengths beyond the stope just vacated, and then stopped. At this location, the operator raised the bucket (engaging the hydraulics) to simulate loading of an imaginary truck but without dumping the bucket, then lowered the bucket and backed the vehicle to the starting point of the cycle. This upstream loading operation was repeated three times. After the third execution, the loaded LHD vehicle trammed up the ramp to the downstream load/dump point. The LHD executed the same three load/dump tasks that had been performed at the upstream location. After the final load/dump task at the downstream point, the loaded vehicle trammed down the ramp to the upstream starting point, thus completing one test cycle. The next cycle was started immediately.

In each test, two full warmup cycles were executed prior to the start of sampling. The duration of a typical cycle for LHD 2 was 13–15 min depending on the operator; the duration for LHD 1 was 11–12 min. The duration of a test was dictated by the time required for collecting sufficient DPM samples. When it was determined that the test had run for a sufficient time, it was terminated after completion of the next full cycle.

The same operator operated LHD 1 throughout all fuel tests, including the baseline test. Two operators drove LHD 2. One miner operated the vehicle for both tests of the AM DPFs (with platinum and palladium DOCs). The other miner operated the vehicle for the baseline test, the tests of the disposable filter elements from Donaldson and Filter Service, and the Clean Air Power/ETG CPO system test.

Ventilation

The isolated zone was ventilated with fresh air from the portal. Since diesel-powered vehicles were not operated upstream of the test zone during the tests, the level of diesel contamination of the ventilation air upstream of the test zone was expected to be very low. The intent was to maintain the same ventilation rate of about 19 m^3/s (40,259 ft^3/min) for all tests. This amount of air was assumed to provide relatively stable airflow and good mixing of the pollutants. It is important to note that the ventilation rate maintained in the main drift during these tests was significantly higher than the ventilation rate supplied by the mine for similar vehicles/engines during production. Auxiliary ventilation was not supplied to the stopes at the upstream and downstream load/dump points.

SAMPLING AND MEASUREMENTS METHODOLOGY

Sampling Stations

For this study, three sampling stations were established in the isolated zone: the upstream station, the downstream station, and the vehicle station.

Upstream Sampling Station

The upstream sampling station was located approximately 90 m (295 ft) upstream of the upstream load/dump point. The following methods were used to determine concentrations of the particulate matter in the incoming fresh air at the upstream station:

1. A standard sampling method (SSM) was used to collect particulate samples for carbon analysis (NIOSH Analytical Method 5040) [Schlecht and O'Connor 2003a].
2. A high-volume (HV) sampling method was used to collect particulate samples for carbon analysis (NIOSH Analytical Method 5040).
3. A standard sampling method was used to collect filter samples for sulfate ion analysis (NIOSH Analytical Method 6004) [Schlecht and O'Connor 2003b].
4. A TEOM Series 1400a ambient particulate monitor from Rupprecht & Patashnick Co., Albany, NY, was used for real-time measurements of total particulate matter under 0.8 µm.
5. The scanning mobility particle sizer (SMPS) from TSI, Inc., St. Paul, MN, was used to measure size distribution and count concentrations of aerosols.

The following instrumentation was used to measure concentrations of the selected gases at the upstream station:

1. The ITX multigas monitor from Industrial Scientific, Oakdale, PA, was used for real-time measurements and recording of concentrations of carbon monoxide (CO), nitric oxide (NO), and nitrogen dioxide (NO_2).
2. The RKI Eagle monitor from RKI Instruments, Inc., Hayward, CA, was used for measuring concentrations of carbon dioxide (CO_2).

Downstream Sampling Station

The downstream sampling station (see Figure 8) was established approximately 140 m (459 ft) downstream of the downstream load/dump point and 60 m (197 ft) upstream of the ventilation doors. The following methods were used to determine concentrations of particulate matter in the contaminated air at the downstream station:

1. The SSM procedure was used to collect particulate samples for carbon analysis (NIOSH Analytical Method 5040).
2. The HV sampling procedure was used to collect particulate samples for carbon analysis (NIOSH Analytical Method 5040).
3. The HV sampling procedure was used to collect particulate samples for gravimetric analysis.
4. The SSM procedure was used to collect filter samples for sulfate ion analysis (NIOSH Analytical Method 6004).
5. The TEOM Series 1400a ambient particulate monitor was used for real-time measurements of total particulate matter under 0.8 µm.
6. The SMPS was used to measure size distribution and count concentrations of aerosols.
7. A Photoelectric Aerosol Sensor (PAS) 2000 real-time polycyclic aromatic hydrocarbon (PAH) monitor from EcoChem Analytics, West Hills, CA, was used for qualitative monitoring of elemental carbon (EC) concentrations in real time by virtue of PAHs attached to the carbon particles.

The following instrumentation was used to measure concentrations of the selected gases at the downstream station:

1. The iTX multigas monitor was used for real-time measurements and recording of concentrations of CO, NO, and NO_2.
2. The RKI Eagle monitor was used for real-time measurements and recording of CO_2 concentrations.

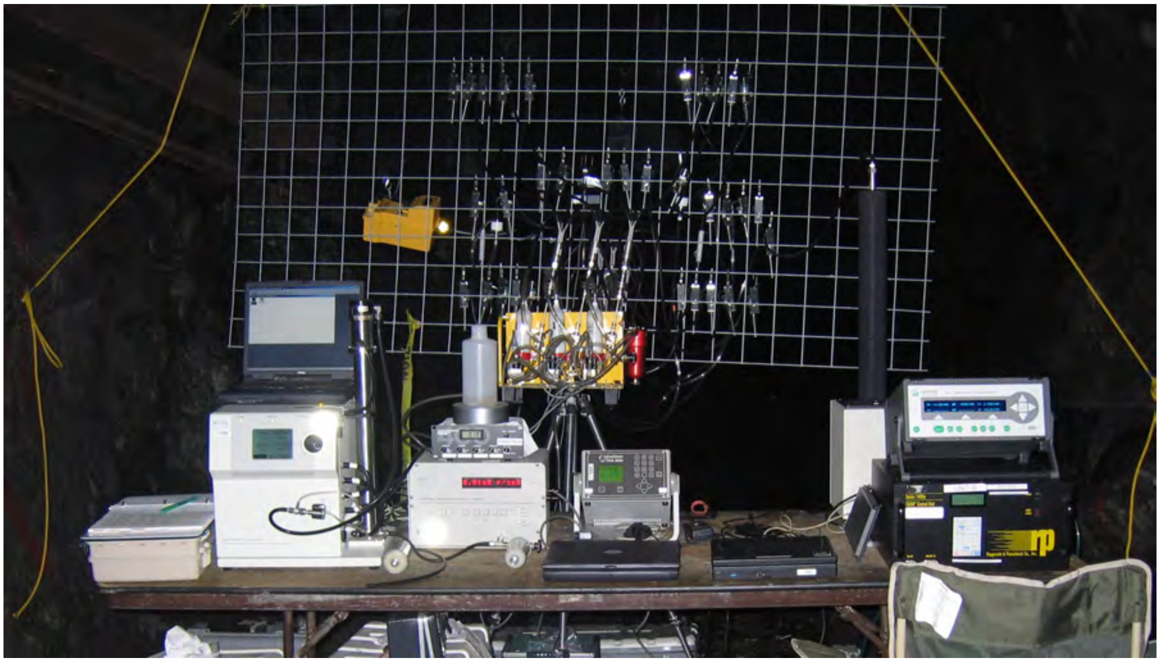


Figure 8.—Downstream sampling station showing instrumentation and wire grid supporting DPM samplers, anemometer, iTX gas monitor, and RKI Eagle CO_2 monitor.

Vehicle Sampling Stations

A vehicle sampling station was established on each test vehicle. The stations were located approximately 2 ft from the operator. At this sampling location, the standard sampling procedure was used to collect particulate samples for carbon analysis. The iTX multigas monitor and RKI Eagle CO_2 monitor were used to sample and record gas concentrations.

Sampling Strategy

The following procedure was established for sampling in the isolated zone:

1. The vehicle was driven to the fueling station prior to the test and the auxiliary tank topped off with fuel. While the vehicle was fueled, the operator was briefed on the details of the test protocol and instructed on the duty cycles.
2. After refueling was completed, the operator performed two warmup cycles.
3. As the vehicle passed the fueling station near the end of the second warmup cycle, the auxiliary tank was topped off and the vehicle proceeded to the upstream load/dump point, where it was stopped. The particulate matter samplers and all real-time sampling instrumentation on the vehicle were turned on. At this time, the test officially began.
4. At approximately the same time, the upstream sampling systems were turned on.
5. After a short delay, sampling at the downstream station was started. The real-time trace of the EC concentration measured by the PAS 2000 instrument was used to determine start time.
6. The objective was to collect at least 30 µg of elemental carbon on the HV sampling filters used at the downstream sampling station. The duration of a test was estimated from the real-time measurements of particulate concentrations at the downstream sampling station using the TEOM 1400a. The actual stop time was determined by using the real-time trace of EC concentrations from the PAS.
7. Shortly thereafter, when the vehicle reached the upstream load/dump point, the vehicle and the upstream sampling stations were stopped and the test was terminated.
8. The actual start and stop times and total sampling times were recorded.

Sampling Methodology and Instrumentation

Following is a description of the various equipment, instrumentation, and methods used in this study to collect particulate samples and directly measure concentrations of particulates and selected gases.

Standard Sampling of DPM for Carbon Analysis

A standard sampling method similar to the one used by MSHA for DPM compliance monitoring was used to collect DPM samples for carbon analysis at the downstream, upstream, and vehicle sampling stations during the fuel tests. The samples on the vehicle were collected in duplicate; the samples at the upstream and downstream stations were collected in triplicate. The 1.7 L/min sampling flow rate used by this method is inadequate for obtaining DPM samples in cases where the concentration of DPM is low and sampling times are short. Therefore, this method was not used to collect samples during the tests on the filtration systems.

The sampling train used at the vehicle sampling station consisted of a flow-controlled Escort ELF Sampling Pump from Mine Safety Appliances Co. (MSA), Pittsburgh, PA; and a 10-mm Dorr-Oliver Cyclone and SKC DPM Cassette, both from SKC, Inc., Eighty Four, PA. The SKC DPM Cassette contains a single-stage impactor and two stacked 37-mm-diam tissue quartz-fiber filters. The pumps were operated at 1.7 L/min. At this flow rate, only aerosols with an average aerodynamic diameter (D_{50}) smaller than 0.820 µm reached the collection filter [Olson 2001]. The pumps were calibrated at the mine at the beginning of the study. The flow rate for each of the sampling pumps was measured and recorded daily using a Gilibrator-2 bubble flow meter from Sensidyne, Clearwater, FL.

At the downstream and upstream sampling stations, a Model 0523–101Q high-volume rotary vane pump from Gast Manufacturing, Inc., Benton Harbor, MI, and a manifold with a bank of critical orifices with a nominal flow rate of 1.7 L/min were used instead of an MSA Escort ELF Sampling Pump to maintain and control the flow rate.

High-volume (HV) Method for Sampling DPM for Carbon Analysis

During all tests conducted in this study, an HV sampling method was used to collect three DPM samples at the downstream and two DPM samples at the upstream sampling stations. This high-volume sampling train, described in detail elsewhere [Bugarski et al. 2004], was used to enhance the collection of samples for carbon analysis by increasing the sampling flow rate and decreasing the collection area of the filter. The sampling flow rate was increased by merging into a single stream flows from five preclassifiers, each consisting of a 10-mm Dorr-Oliver Cyclone followed by a U.S. Bureau of Mines (USBM) single-stage diesel impactor. A flow rate of approximately 2.0 L/min was maintained through each cyclone and impactor pair. At this sampling flow rate, only particles with geometric mean smaller then 0.775 µm were deposited on the filters [Olson 2001]. All five preclassifiers were attached to a symmetrical plenum that distributed a total flow rate of approximately 10.0 L/min uniformly among the five streams. Each preclassifier assembly was connected to the plenum chamber by a 3-ft-long section of conductive tubing. The outlet of the plenum was directly connected to a stainless steel 25-mm-diam filter holder containing two stacked 25-mm tissue quartz-fiber filters (Tissuquartz 2500 QAT–UP, Pall Corp., Ann Arbor, MI).

The total sampling mass flow rates were maintained using a Model HFC 302 mass flow controller from Teledyne, Hampton, VA, in each of the three sampling lines from the 25-mm-diam filter holders. The total volumetric flow rates through each of the sampling streams were measured periodically by inserting a Gilibrator-2 bubble flow meter inline, between filter holders and mass flow controllers. The volumetric flow rates measured during this study were all corrected to ambient conditions. A Model 0523–101Q high-volume rotary vane pump from Gast Manufacturing was used to draw the sample through the filter.

Sampling DPM for Gravimetric Analysis

A similar high-volume sampling method was used to collect gravimetric samples. These were collected using a sampling train consisting of a 10-mm Dorr-Oliver Cyclone, a USBM single-stage impactor, and a cassette filter holder with a single 37-mm-diam Teflon filter (Teflo, 2.0 µm) from Pall Corp. A manifold with five critical orifices, each with a nominal flow rate of 1.7 L/min, was used to maintain a constant flow rate. The inlets of the five orifices were connected to a common sampling line to yield a total flow of 8.5 L/min through the 37-mm-diam filter. A Model 0523–101Q high-volume rotary vane pump from Gast Manufacturing provided suction to the manifold. The total particulate matter (TPM) collected on the filters had a D_{50} smaller than 0.820 µm. The total flow rate through the sampling train was determined at the NIOSH Pittsburgh Research Laboratory (PRL) and checked periodically during the study using a Gilibrator-2 bubble flow meter.

Sampling DPM for Sulfate Analysis

The sampling train for sulfate samples consisted of a 10-mm Dorr-Oliver Cyclone; a USBM single-stage impactor; a cassette filter holder with a single 37-mm-diam cellulose ester membrane filter Model AAWP03700, Millipore Corp., Bedford, MA; a critical orifice with a nominal flow rate of 1.7 L/min; and the Model 0523–101Q high-volume rotary vane pump from Gast Manufacturing. The DPM collected on the filters had a D_{50} smaller than 0.820 µm. The total flow rate through the sampling system was calibrated at NIOSH PRL and checked periodically during the study using a Gilibrator-2 bubble flow meter.

DPM Concentration Measurements With a TEOM Series 1400a Ambient Particulate Monitor

Two TEOM Series 1400a ambient particulate monitors from Rupprecht & Patashnick Co. were used to continuously measure concentrations of TPM with a D_{50} smaller than 0.820 µm. One TEOM was located at the upstream station, the other at the downstream sampling station.

The TEOM draws air through a filter at a constant flow rate while continuously measuring the mass accumulating on the filter and calculating near-real-time mass concentrations. The sample stream is drawn through the filter from a hollow tapered element that is connected to the suction side of the sampling system. The vibration frequency of the tapered element decreases as particulate mass collected on the filter increases. By frequently measuring the tapered-element frequency, the TEOM calculates the increase in mass of the sample that has accumulated on the filter. The concentration of TPM is calculated by dividing the accumulated mass by the volume of airflow across the filter during the period over which the frequency change is measured.

The flow through the instrument is maintained at a constant rate by a mass flow controller. The flow is corrected for temperature and barometric pressure. Internal instrument temperatures are controlled to minimize the effects of ambient temperature. To prevent condensation and ensure that the sample filter always collects particulates under similar conditions, the TEOM intake is heated to maintain the sampling stream at 50 °C.

During this study, the flow rates on both the upstream and downstream TEOM were set at 1.7 L/min. A cyclone and impactor were used as preclassifiers to the TEOM, allowing only particles with an average aerodynamic diameter (D_{50}) smaller than 0.820 µm to reach the collection filter. The average ambient concentrations of TPM were recorded and saved every 10 s. The reported average concentrations for a test were obtained from the difference in filter masses recorded at the same start and stop times used by the particulate samples for carbon analysis.

Measurement of Size Distribution and Particle Number Concentrations Using a Scanning Mobility Particle Sizer (SMPS)

Two SMPSs, one at the downstream sampling station and the other at the upstream sampling station, were used to periodically measure the size distribution and number of particles in the range of 10–392 nm. The SMPS at the upstream end of the isolated zone was built by TSI, Inc., and consisted of a Model 3080L electrostatic classifier and a Model 3010 condensation particle counter (CPC), both from TSI, Inc. The SMPS at the downstream sampling station consisted of a Model 3080L electrostatic classifier and a Model 3025A CPC, both from TSI, Inc.

The flows of monodispersed aerosol in both electrostatic classifiers were maintained at 0.6 L/min throughout the study. At the established polydispersed aerosol flow rate of 6 L/min, the inlet impactor had a cutoff point of 460 nm. The CPC was operated in high-flow mode to minimize diffusion losses. The sampling was performed using a 90-s up-scan and a 15-s down-scan. The instrument was operated using a dedicated laptop computer and Aerosol Instrument Manager Software from TSI, Inc.

Although the vehicle duty cycles for all tests were transient, the resulting aerosol distributions in the mine air were made quasisteady by relative movements of the vehicles and ventilation air. The effects of the tested control technologies on size distribution and count concentrations of aerosols in mine air were assessed based on the analysis performed on the measurements conducted while the test vehicle was performing the portion of the duty cycle at the downstream load/dump point—a point closest to the location of the SMPS.

The measurements performed during other portions of the duty cycle showed that the distributions and count concentrations of aerosols were extremely dependent on the position of the vehicles relative to the downstream instrument. This was a result of many time-dependent factors such as the engine emissions, the velocity of the air, the velocity of the vehicle, the ventilating of the upstream and downstream load/dump points, and the travel time of the plume.

Measurement of Concentration of O_2, CO, NO, and NO_2 Using an Industrial Scientific iTX Multigas Monitor

The ambient concentrations of oxygen (O_2), carbon monoxide (CO), nitric oxide (NO), and nitrogen dioxide (NO_2) were measured at all three sampling locations using Industrial Scientific iTX multigas monitors. One iTX multigas monitor was dedicated to each sampling location for the duration of the isolated zone testing. The iTX measured ambient concentrations every 10 s and stored them in its memory.

The iTX is a diffusion gas monitor based on electrochemical cell technology implemented in such a way as to measure concentrations independent of atmospheric pressure. The instrument continuously monitors and simultaneously displays all gases sampled. The concentration data were downloaded to a laptop PC at the end of each test day.

The iTX gas monitors were calibrated with certified concentrations of Industrial Scientific calibration gases prior to and upon completion of the isolated zone testing. Each iTX was checked daily using the iTX DS1000 Docking Station. The iTX DS1000 Docking Station is an automated instrument management system that consists of a master control and PC interface station. The Docking Station provides automatic calibration and instrument diagnostics and maintains instrument database records.

Measurement of CO_2 Concentration Using an RKI Eagle CO_2 Monitor

The ambient concentrations of carbon dioxide (CO_2) were measured at all three sampling stations using an RKI Eagle infrared CO_2 monitor. Ambient concentrations were measured every 60 s and recorded using data-logging capabilities of the instrument. The data were downloaded to a laptop PC at the end of each day.

Since the instrument uses the infrared method, it reports the CO_2 partial pressure at the prevailing barometric pressure (~84 kPa). In the postprocessing procedure, the results of the measurements were corrected to represent the equivalent CO_2 concentrations at the standard barometric pressure conditions (10^5 Pa). The correction was made using the results of calibration at NIOSH PRL and periodic checks in the isolated zone with 2,000 ppm CO_2 calibration gas supplied by RKI.

Measurement of Exhaust Temperatures and Engine Back Pressure

During tests, the exhaust temperatures upstream of the DPF systems were measured continuously using a Model KMQSS–125G–6, K-type thermocouple from Omega Engineering, Inc., Stamford, CT. The engine back pressure was measured using a Kavlico Model P356 differential pressure sensor from Kavlico Corp., Moorpark, CA. The output from the thermocouples and pressure sensors were logged at a rate of 0.2 Hz using a MiniLogger portable data-logging system from Logic Beach, Inc., La Mesa, CA. The logged data were retrieved using a laptop PC and the supplied HyperWare software.

Measurement of Ambient Temperature and Barometric Pressure

The ambient temperature and barometric pressure were measured and recorded by the TEOM 1400a.

Measurements of Ventilation Rate

Air velocities in the isolated zone were measured continuously during the tests in the approximate center of the drift at the downstream sampling station using an Anemosonic UA6 digital ultrasonic anemometer from Airflow Developments Ltd., High Wycombe, United Kingdom. The anemometer sensor was located in the center of the steel grid supporting the DPM samplers. Anemometer output was sampled every 2 s. A five-sample average was computed and stored into memory, creating a log of 10-s averages using a MiniLogger portable data-logging system from Logic Beach, Inc. The logged data were retrieved using a laptop PC and the supplied HyperWare software.

The logged air velocities were converted to air quantities by adding or subtracting the correction factor to the velocity obtained and then multiplying that velocity by the cross-sectional area of the entry at the point of measurement. The average air velocity for a test was determined by averaging all of the downstream air velocity readings over the period for downstream DPM sampling. All measured concentrations of particulate matter and gases for a control technology test were adjusted for differences between the prevailing test ventilation and that of the corresponding baseline test. This adjustment enabled the comparison of the results obtained from different tests.

The air velocities were periodically verified using a vane anemometer to conduct a moving traverse across the entry.

ANALYSIS OF SAMPLES

Analysis of DPM Samples Collected Using Standard and High-volume Sampling Methods for Elemental Carbon Content

The samples that were collected on quartz-fiber filters, using the standard and the high-volume sampling procedures, were analyzed by the NIOSH PRL analytical laboratory for elemental carbon content using the NIOSH Analytical Method 5040 [Schlecht and O’Connor 2003a; Birch and Cary 1996]. The analysis was performed following the carbon analyzer procedures from Sunset Laboratories, Forest Grove, OR. A blank (heat-treated quartz-fiber filter) and a sugar standard were run daily before analysis of the samples.

Calibrated punches were used to remove a section from the exposed area of each sample filter. A punch with a surface area of 0.72 cm^2 was used for heavily loaded samples, while a 1.5-cm^2 punch was used for all other samples. The resulting section was placed into the oven of the carbon analyzer and analyzed following the procedure described in the NIOSH *Manual of Analytical Methods* [Schlecht and O'Connor 2003a] and by Birch and Cary [1996].

The temperature steps for the organic carbon (OC) portion were set to 200, 450, 650, and 870 °C. The time spent at each temperature step was increased from that specified in the NIOSH method so that peaks for both the OC and elemental carbon (EC) could be fully resolved. This is a standard procedure at NIOSH PRL and has been determined to give results identical to the method specified in the NIOSH *Manual of Analytical Methods*.

NIOSH Analytical Method 5040 analyzes for OC and EC in two different stages. In the first stage, the OC evolves as the instrument ramps the oven temperature up over four progressively higher temperature steps in a pure helium (He) atmosphere. The EC does not evolve in the pure helium atmosphere. The evolved OC is oxidized to carbon dioxide (CO_2), reduced to methane (CH_4), and finally measured using a flame ionization detector (FID).

In the second stage, the oven temperature is reduced to approximately 600 °C. The EC is evolved as the instrument steps the oven temperature back up to approximately 900 °C in a He/O_2 atmosphere. Because of the O_2, EC is oxidized to CO_2, which is consequently reduced to CH_4 and measured with the FID. NIOSH Analytical Method 5040 also corrects for the pyrolysis of OC and carbonates.

Gravimetric Analysis of DPM Samples

The filters collected for gravimetric analysis were weighed in the NIOSH PRL weighing room. The cassettes with exposed filters were brought into the environmental chamber/ weighing room where they were unsealed, desiccated for at least 30 min, and then conditioned at 20 °C and 50% relative humidity for at least another 30 min. After the equilibration, the filters were removed from the cassettes and weighed. Each filter was placed on an NRD Model 2U500 antistatic strip for 30 s and finally onto a Mettler Model MT5 balance. The reading of the balance was recorded after a 60-s period.

Each of the filters was preweighed after conditioning prior to the tests, then reconditioned and weighed twice in a 2-week period after the tests.

Analysis of Filter Samples for Sulfate Ion Concentrations

Sulfate ion concentrations on filter samples were analyzed by DataChem Laboratories, Inc., Salt Lake City, UT, by ion chromatography (IC) according to NIOSH Analytical Method 6004. The samples were analyzed using a Dionex Model DX300 ion chromatograph equipped with a Hewlett-Packard 1050 autosampler and TotalChrom Client/Server chromatography software from PerkinElmer, Inc.

CALCULATION OF THE EFFECTS OF CONTROL TECHNOLOGIES

The effects of each of the tested control technologies were determined by comparing the results of tests with and without control technologies. Each of the comparisons contrasted tests using the same vehicle, with the same duty cycle and operator, if possible, and the same ventilation rate. The test of LHD 1 using #1 diesel and a standard muffler was used to establish a baseline for the fuel tests. The test with LHD 2 using #1 diesel with a muffler was used to establish a baseline for the filter tests. The effects of a specific control technology were quantified by comparing the contaminant concentrations observed for the test when the vehicle was operated with a control technology with those observed for the baseline test.

The concentrations of selected pollutants at the upstream, downstream, and vehicle sampling stations were determined using various sampling and measurement methods. Due to the nature of the test environment and methods, small variations in operating conditions were possible between tests, including variations in the ventilation rate, air temperature, etc. The data show that ventilation rate differences between tests could be the greatest source of uncertainty for the concentration measurements. However, this factor of uncertainty can be eliminated by correcting all measured concentrations for ventilation rate. The calculations for these corrections are presented below.

For the purpose of these analyses, the tests conducted in this study were divided into two groups, as shown in Table 1 and described earlier. In order to allow a direct comparison of the results between the tests within each test group, the measured concentrations (c_i) were corrected to the average ventilation rate (VR) for the baseline tests for each of the two groups ($VR_{baseline\ \mathrm{LHD\ 1}}$ and $VR_{baseline\ \mathrm{LHD\ 2}}$) using Equation 1:

$$c_{i,VR}\ [\frac{g}{m^3}] = c_i[\frac{g}{m^3}] \times \frac{VR_i[\frac{m^3}{s}]}{VR_{baseline}[\frac{m^3}{s}]} \qquad \text{Equation 1}$$

The net contribution of the tested vehicle/technology configuration to the air concentrations of pollutants (C_i) was calculated by subtracting the concentrations measured at the upstream sampling station ($c_{i,UP}$) from the ventilation-adjusted concentrations at the downstream sampling station ($c_{i,\ VR,,DOWN}$):

$$C_i[\frac{g}{m^3}] = c_{i,VR,DOWN}[\frac{g}{m^3}] - c_{i,UP}[\frac{g}{m^3}] \qquad \text{Equation 2}$$

Similarly, the net contribution of the tested configuration to the exposure of the operator was estimated by subtracting the upstream concentrations from the ventilation-adjusted concentrations measured at the vehicle.

In cases where the analysis of the upstream data showed that the upstream concentrations of the measured pollutant were below the detection limit of the method or instrumentation, the background concentrations were assumed to be negligible.

The net contributions were then used to calculate the relative effects of the tested control technologies on the concentrations of the monitored pollutants:

$$\text{Control Technology Effect for } \mathrm{C}_i \ [\%] = \left(1 - \frac{C_i}{C_{i\,BL}}\right) \times 100 \qquad \text{Equation 3}$$

where C_i is the net contribution of the vehicle to the air concentrations of pollutant for the control technology test and $C_{i\ BL}$ is the net contribution of the vehicle to the air concentrations of pollutant for the baseline test.

RESULTS AND DISCUSSION

An overview of the two groups of tests conducted during this study is presented in Table 5. Results of those tests are reported in two separate sections. The first section discusses results from the 10 tests designed to evaluate the effects of selected fuel formulations on concentrations and characteristics of particulate matter and selected gases. The second section discusses results of filter tests conducted to establish the effects of selected diesel particulate filter (DPF) systems and disposable filtration elements on concentrations and characteristics of the same pollutants.

Table 5.—Tests conducted during the study

Test Type	Exhaust System	Fuel Formulation	Comments
Fuel Tests (LHD 1)	Muffler	#1 diesel	Completed
	Muffler	PuriNOx cold-weather water emulsion	Completed
	Muffler	PuriNOx warm-weather water emulsion	Completed
	Muffler	20% soy biodiesel and 80% #1 diesel blend	Completed
	Muffler	50% soy biodiesel and 50% #1 diesel blend	Completed
	DOC (DCL International)	50% soy biodiesel and 50% #1 diesel blend	Completed
	Muffler	20% yellow grease biodiesel and 80% #1 diesel blend	Completed
	Muffler	50% yellow grease biodiesel and 50% #1 diesel blend	Completed
	Muffler	ULS (10 ppm sulfur) diesel	Completed
	DOC (DCL International)	ULS (10 ppm sulfur) diesel	Completed
Filter Tests (LHD 2)	Muffler	#1 diesel	Completed
	DPF system with Pt DOC (ArvinMeritor)	#1 diesel	Test prematurely terminated
	DPF system with Pd DOC (ArvinMeritor)	#1 diesel	Completed
	Disposable filtration element (Donaldson P604516)	#1 diesel	Completed
	Disposable filtration element (Filter Service)	#1 diesel	Completed
	DPF system (Clean Air Power/ ETG CPO)	#1 diesel	Test prematurely terminated

Two of the sixteen tests were not completed. The tests on the AM DPF system with a Pt DOC and the Clean Air Power/ETG catalytic particulate oxidizer (CPO) DPF system were terminated prematurely to prevent overexposure of the vehicle operator to nitrogen dioxide (NO_2). During the initial stages of these two tests, the gas monitor at the vehicle sampling station recorded concentrations of NO_2 that were close to, or exceeded, the 1973 American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit value (TLV) of 5 ppm. This limit is currently used by MSHA as a ceiling limit to regulate exposure of underground metal and nonmetal miners to NO_2 (30 CFR 57.5001). It is important to note that elevated concentrations were observed only when the test vehicle was performing the part of the duty cycle within and in front of the downstream stope. During the other parts of the duty cycle when the vehicle was in the main drift where the ventilation rate exceeded 19 m^3/s (40,258 ft^3/min), the NO_2 did not approach the ceiling limit. The Pt-based catalysts used in those systems most likely caused elevated NO_2 concentrations.

EFFECTS OF FUEL FORMULATIONS

Ten fuel tests, shown in Table 5, were conducted during this study. The objective of eight of the tests was to assess the effects of selected fuel formulations on the concentrations of DPM and selected gases in mine air. Test results with seven alternative fuel formulations were compared with those of #1 diesel, selected as baseline fuel. The objective of the two remaining tests was to evaluate the effects of a DOC when used with alternative fuels. The effects of the vehicle equipped with a DOC and fueled with 50% soy biodiesel blend or ULS diesel were compared with those of the same vehicle fitted with a muffler and fueled with #1 diesel.

LHD 1, powered by a Caterpillar 3126B DITA engine, was used as the test vehicle for the fuel tests. This engine was fitted with a regular muffler for eight tests and with a DOC for two of the tests. The same miner operated the test vehicle for each of the 10 tests.

The results of fuel tests are presented and discussed in three sections: ventilation rates, effects on particulate matter (aerosols), and effects on selected gases. The results presented in the particulate matter section are organized with respect to the results of EC analyses, gravimetric analyses, TEOM measurements, and aerosol size and number measurements.

Ventilation Airflow Rates for the Test on Fuel Formulations

Air velocities in the center of the drift were continuously measured at the downstream and upstream sampling stations during each of the tests. Ventilation rates (VRs) were calculated by multiplying corrected air velocities by the corresponding cross-sectional area of the drift. The VRs were strongly influenced by the movement of the vehicle inside the isolated zone during the tests as illustrated in Figure 9, which presents an example of the baseline fuel test. However, the average VRs among the tests were nonetheless very consistent, as indicated in Table 6.

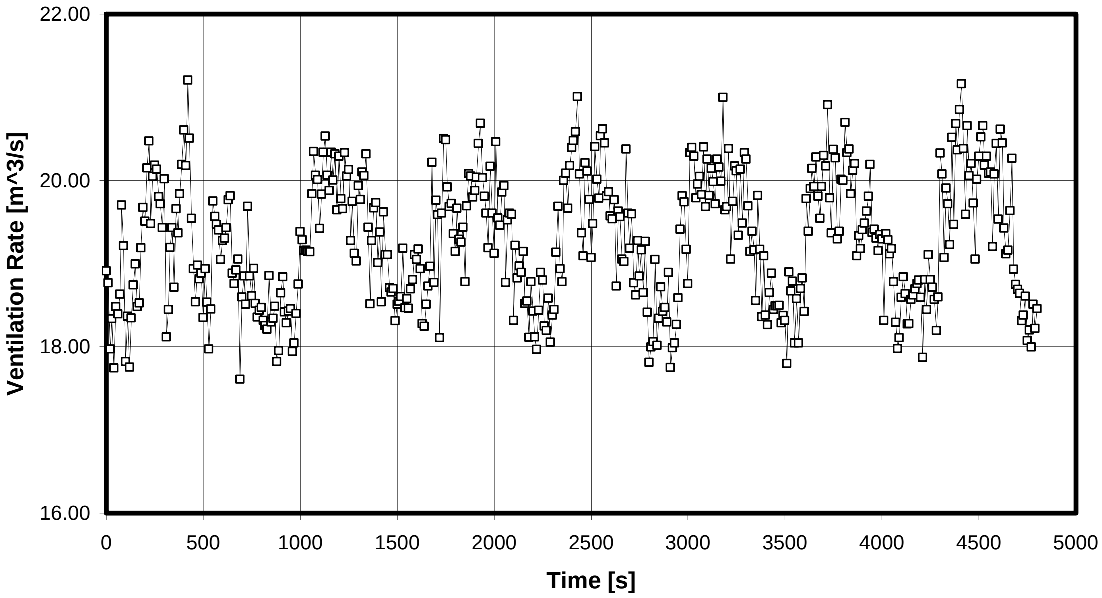


Figure 9.—Ventilation rates measured at the downstream sampling station during the baseline fuel test.

Table 6.—Average VRs at the downstream sampling station for the fuel tests

Fuel Tests (LHD 1)	Average Ventilation Rates	
	m^3/sec	ft^3/min
#1 Diesel/Muffler	19.28	40,851
PuriNOx Cold-Weather/Muffler	19.39	41,077
PuriNOx Warm-Weather/Muffler	19.59	41,498
20% Soy Biodiesel Blend/Muffler	19.25	40,782
50% Soy Biodiesel Blend/Muffler	19.16	40,601
50% Soy Biodiesel Blend/DOC	19.84	42,040
20% Yellow Grease Biodiesel Blend/Muffler	19.60	41,531
50% Yellow Grease Biodiesel Blend/Muffler	18.99	40,230
ULS Diesel/Muffler	19.19	40,671
ULS Diesel/DOC	19.44	41,181

The average VRs presented in Table 6 were used to adjust all measured concentrations of particulate matter and gases to those that would prevail if the average VRs for those tests were equal to the average baseline fuel test VR of 19.28 m^3/s (40,851 ft^3/min). The adjustment of measured concentrations to a common VR allowed a direct comparison of the results obtained from different tests.

Effects of Fuel Formulations on Aerosols

Table 7 summarizes the results of the analyses on the effects of each of the eight fuel formulations on concentrations of EC, TPM, and sulfate. The results are presented as the ventilation rate-adjusted average net contributions of the test vehicle to the downstream mass concentrations. The results of EC, gravimetric, and TEOM analyses are graphically presented in Figure 10. Two sets of results are shown for EC analyses. One set of results is from analyses performed on samples collected using an HV sampling method. Another set is from analyses performed on the samples collected by the SSM. Results on aerosol concentrations, measured by an SMPS, are presented at the end of this section.

Table 7.—Effects of fuel formulations on EC, gravimetrically and TEOM-determined TPM, and sulfate (SO_4) concentrations (common ventilation rate = 19.28 m^3/s)

Fuel Tests (LHD 1)	VR-Adjusted Average Net Contributions to Concentrations				
	EC NIOSH 5040 HV, µg/m^3	EC NIOSH 5040 SSM, µg/m^3	TPM Gravimetric Analysis, µg/m^3	TPM TEOM, µg/m^3	SO_4 IC Analysis, µg/m^3
#1 Diesel/Muffler	275	262	361	388	5.5
PuriNOx Cold-Weather/ Muffler	90	99	200	207	5.4
PuriNOx Warm-Weather/ Muffler	40	40	157	129	5.8
20% Soy Biodiesel/ Muffler	141	166	243	244	3.2
50% Soy Biodiesel/ Muffler	93	108	183	192	2.6
50% Soy Biodiesel/DOC	87	103	155	—	6.6
20% YG Biodiesel/ Muffler	184	177	262	278	4.6
50% YG Biodiesel/ Muffler	120	121	196	212	2.4
ULS Diesel/Muffler	250	243	341	405	0.3
ULS Diesel/DOC	188	187	249	278	0.8

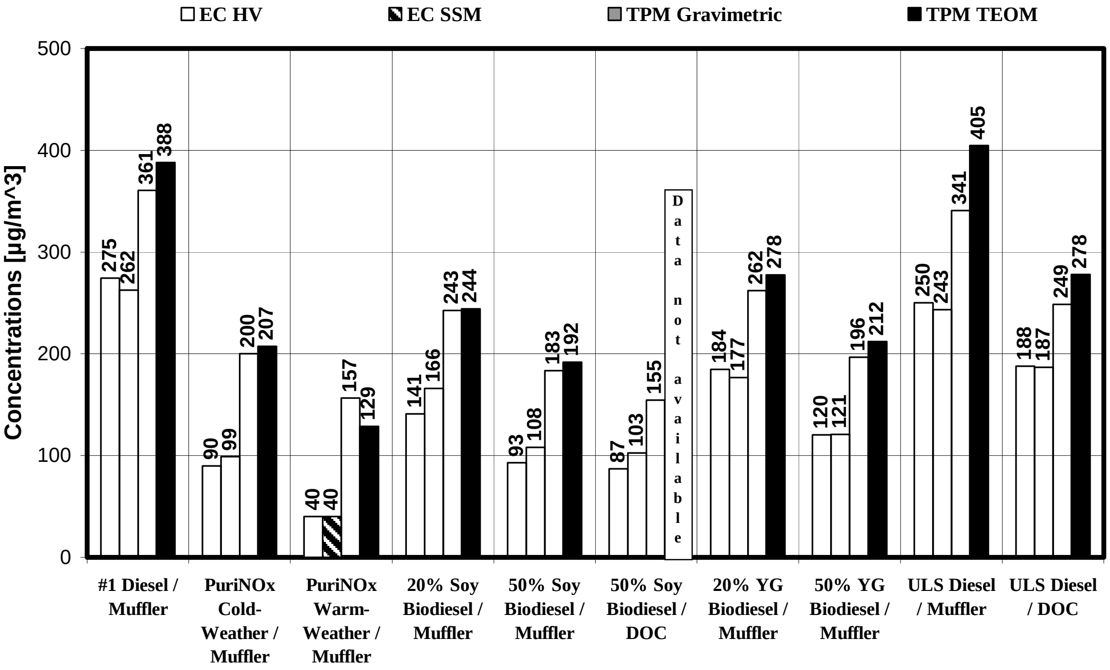
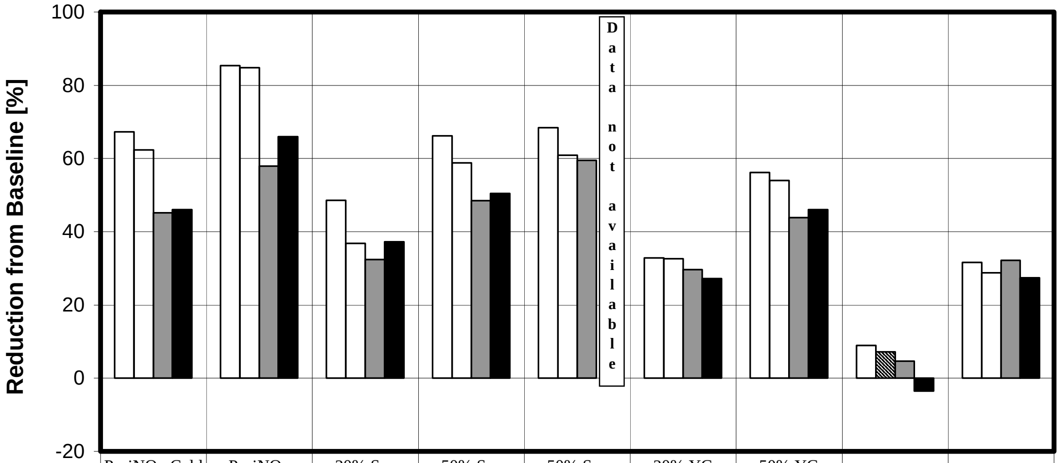


Figure 10.—Contributions of fuel formulation to concentrations of EC and gravimetrically and TEOM-determined TPM (common ventilation rate = 19.28 m^3/s).

Effects of Fuels on the Mass Concentration of EC

The average net contributions of a tested configuration to the mass concentration of EC at the downstream station during fuel formulation tests are shown in the first two data columns of Table 7. EC concentrations measured at the upstream sampling station were below the limits of detection (0.9 µg/sample for HV and 1.6 µg/sample for SKC) and thus were considered to be zero for each of the fuel tests.

Results shown in Table 7 and Figure 10 were used to calculate the relative effects of alternative fuel formulations and a DOC on EC and TPM concentrations shown in Figure 11. Relative effects were calculated by comparing the net contributions from each of the fuel tests with those from the baseline test (a muffler with #1 diesel fuel). Positive values indicate reductions in concentrations.



	PuriNOx Cold-Weather / Muffler	PuriNOx Warm-Weather /	20% Soy Biodiesel / Muffler	50% Soy Biodiesel / Muffler	50% Soy Biodiesel / DOC	20% YG Biodiesel / Muffler	50% YG Biodiesel / Muffler	ULS Diesel / Muffler	ULS Diesel / DOC
□ EC HV	67	85	49	66	68	33	56	9	32
▨ EC SSM	62	85	37	59	61	33	54	7	29
▩ TPM GRAV	45	58	32	48	60	30	44	5	32
■ TPM TEOM	46	66	37	50		27	46	-3	27

Figure 11.—Changes in average concentrations of EC and TPM for tested fuel formulations. Positive values indicate reductions in concentrations.

Results of the EC analysis on the HV samples show that the cold- and warm-weather water-fuel emulsions reduced concentrations of EC by 67% and 85%, respectively. The EC analysis performed on SSM samples showed fairly comparable results with a 62% and 85% reduction in net EC contribution for those two water-fuel blends, respectively.

The 20% soy biodiesel blend reduced EC concentrations by 49% (HV) and 37% (SSM). An increase in the soy biodiesel fraction to 50% resulted in further reductions in the concentrations of EC (66% for HV and 59% for SSM). The results for the yellow grease (YG) biodiesel blends indicated that EC reductions were slightly less pronounced than those for the corresponding soy biodiesel blends.

Results indicated very little difference in the effects of ULS diesel fuel and baseline #1 fuel on EC concentrations. However, when ULS fuel was used with a DOC in the exhaust system, there was about a 30% reduction in EC concentrations. It is important to note that the sulfur content of #1 diesel fuel was approximately 255 ppm, and the sulfur content of ULS diesel was 10 ppm.

The contributions of tested configurations to the concentrations of EC at the vehicle sampling station are summarized in Table 8. These contributions were found to be generally higher than those for the downstream sampling station. This can be attributed to the fact that during parts of the duty cycle, the vehicle sampling station was in a poorly diluted exhaust plume. Nonetheless, the relative changes in EC concentrations are comparable to those found for the downstream location.

Table 8.—Effects of fuel formulations on ventilation-adjusted average net vehicle contributions to concentrations of EC at the vehicle sampling station (common ventilation rate = 19.28 m^3/s)

Fuel Tests (LHD 1)	Adjusted Average EC Concentrations, NIOSH 5040 SSM, µg/m^3	Reductions in Adjusted Average Contribution to EC Concentration, %
#1 Diesel/Muffler	362	—
PuriNOx Cold-Weather/Muffler	137	62
PuriNOx Warm-Weather/Muffler	84	77
20% Soy Biodiesel Blend/Muffler	179	51
50% Soy Biodiesel Blend/Muffler	123	66
50% Soy Biodiesel Blend/DOC	111	69
20% Yellow Grease Biodiesel Blend/Muffler	257	29
50% Yellow Grease Biodiesel Blend/Muffler	162	55
ULS Diesel/Muffler	365	–1
ULS Diesel/DOC	213	41

Effects of Fuels on the Mass Concentration of TPM Determined by Gravimetric Analysis

The average net contributions of tested configurations to the mass concentration of TPM, determined by gravimetric analysis, are shown in the third data column of Table 7. The observed reductions in net contributions relative to the baseline case are presented in the third row of the Figure 11 data table (labeled "TPM GRAV").

The TPM mass on most downstream samples was found to be above a quantification limit of 85 µg/sample for gravimetric analysis. The results presented in Table 7 show that the TPM concentrations determined by gravimetric analysis agree reasonably well with those measured by the TEOM.

Gravimetric analysis showed that the cold-weather emulsion reduced TPM concentrations by 45%. The warm-weather emulsion contributed to a 58% reduction. Fueling the test vehicle with a 20% blend of soy and a 20% blend of yellow grease biodiesel reduced TPM concentrations by 32% and 30%, respectively. When the vehicle was fueled with 50% blends of soy and yellow grease biodiesel, the reductions were 48% and 44%, respectively.

When the muffler was replaced by a DOC, the gravimetric analysis also showed reductions in TPM concentrations. For example, using a DOC with a 50% blend of soy biodiesel increased the reduction of TPM from 48% to 60%. In the case of ULS diesel, the DOC increased the reduction in TPM from 5% to 32%.

Effects of Fuels on the Mass Concentration of TPM Measured Using the TEOM 1400a

Results of continuous TPM mass concentration measurements with the TEOM 1400a instruments at the downstream sampling stations during the fuel tests are shown in Figures 12–14.

TPM concentrations at the upstream sampling station were found to be very low. In several instances, due to external vibration and shocks imposed on the instrument, the readings were found to be negative. Therefore, upstream concentrations were assumed to be negligible and the net vehicle contributions to TPM concentrations were assumed to be equal to downstream concentrations.

The graphs presented in Figures 12–14 illustrate the transient nature of the TPM concentrations at the downstream sampling station. The primary cause of this phenomenon is the cyclic nature of the vehicle duty cycle and ventilation flow.

The average concentrations of TPM were calculated as differences between the reported TEOM filter masses at the start and end of the sampling period. The ventilation-adjusted average concentrations of TPM are presented in the fourth data column of Table 7. The calculated reductions relative to the baseline case are presented in the fourth row of the data table in Figure 11 (labeled “TPM TEOM”).

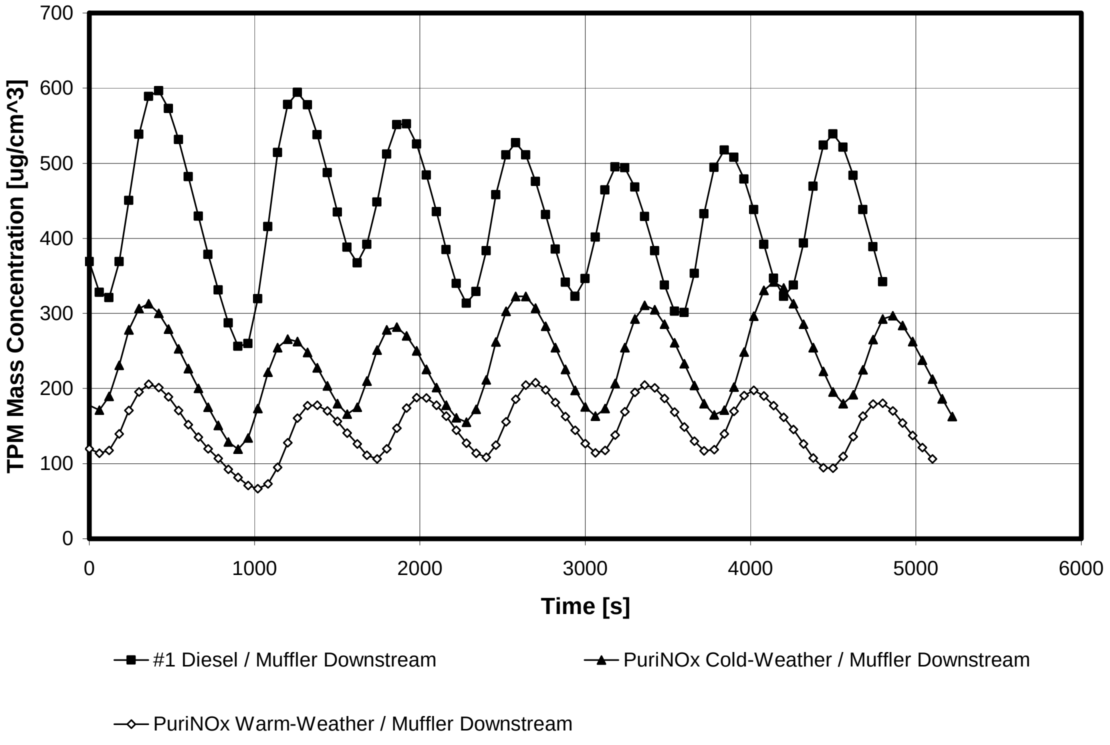


Figure 12.—Effects of water emulsions on mass concentrations of TPM at downstream sampling station measured by TEOM.

Mass concentrations of TPM observed at the downstream sampling station during the baseline test as well as tests with cold- and warm-weather water emulsions are shown in Figure 12. The peak concentrations and cumulative net contributions to TPM concentrations, measured by the TEOM, were substantially lower in the cases where water emulsions were used. The relative reductions in net TPM concentrations were calculated to be 46% and 66% for cold- and warm-weather water emulsions, respectively (see Figure 11).

Real-time TPM measurements of biodiesel blend tests taken at the downstream sampling stations are plotted along with baseline results in Figure 13. Due to problems with the instrument at the downstream sampling station, results are not available for the test during which the vehicle was equipped with a DOC and operated with a 50% soy biodiesel blend. The net contributions of the TPM concentrations, measured by the TEOM, were found to be substantially reduced when #1 diesel was substituted with soy and yellow grease biodiesel blends. The reductions were found to be slightly higher for soy than for yellow grease blends.

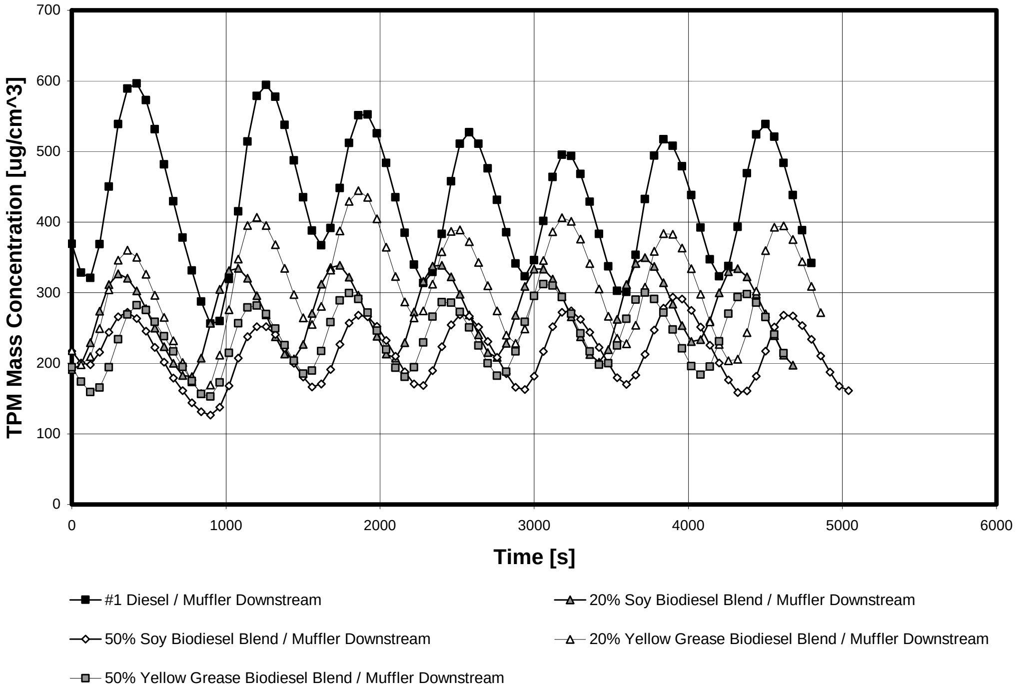


Figure 13.—Effects of biodiesel blends on mass concentrations of TPM at downstream sampling station measured by TEOM.

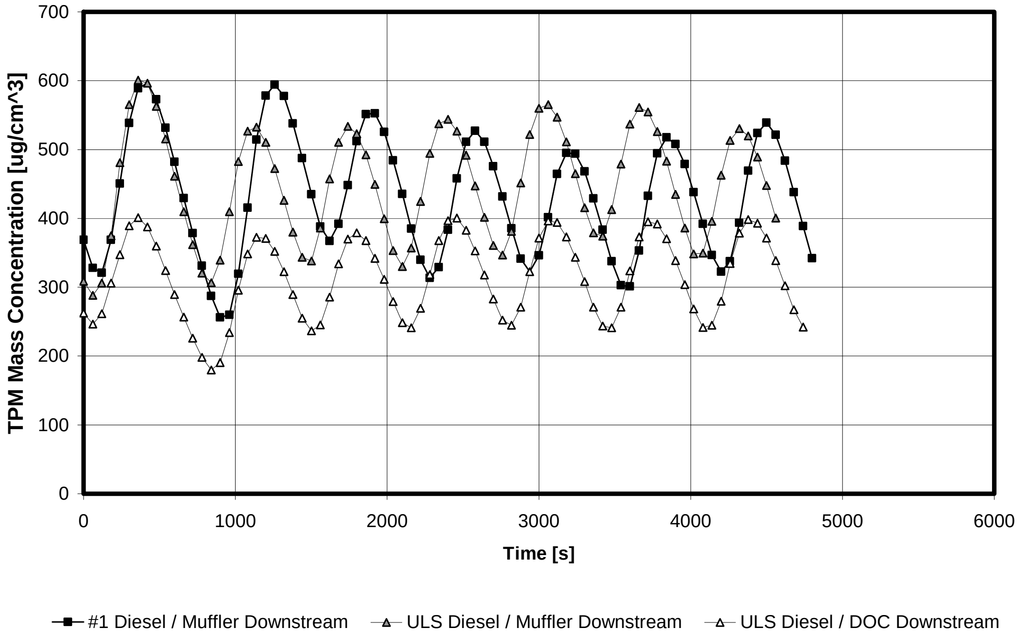


Figure 14.—Effects of ULS fuel on mass concentrations of TPM at downstream sampling station measured by TEOM.

Effects of Fuels on the Mass Concentrations of Sulfates

Net contributions to the sulfate mass concentrations at the downstream sampling station during the fuel tests are summarized in the fifth column of Table 7. The concentrations reported for the samples collected at the upstream sampling station were found to be slightly above the 0.3-µg/sample limit of detection for the applied method. Therefore, those concentrations were used in the calculation of net contributions to the downstream SO_4 concentration. Several of the concentrations reported for the samples collected at the downstream sampling station were found to be between the limit of detection and the 1.0-µg/sample limit of quantification, but most were found to be above the limit of quantification.

Results show that cold-weather (300 ppm sulfur) and warm-weather (279 ppm sulfur) water emulsions had minor effects on the net contributions of sulfate concentrations. These data also show quantifiable reduction in the concentrations of sulfates in mine air in the case of soy biodiesel blends (200 ppm sulfur for the 20% blend and 129 ppm sulfur for the 50% blend) and yellow grease biodiesel (approximately 40 ppm sulfur neat YG blended with 255 ppm sulfur #1 diesel) that were roughly proportional to the sulfur content in the blends. The same analysis revealed that ULS diesel fuel (4 ppm sulfur) reduced the vehicle's contribution to the sulfate concentrations from 5.5 µg/m^3, observed for the test with #1 diesel, to 0.3 µg/m^3. When the muffler was replaced with a DOC, the net contributions of the vehicle to the concentrations of sulfates increased from 2.6 to 6.6 µg/m^3 in the case of 50% soy biodiesel, and from 0.3 to 0.8 µg/m^3 in the case of

ULS diesel. This increase was most likely due to the creation of sulfates by catalytic processes in the DOC.

Effects of Fuel Formulations on Size Distribution and Number Concentration of Aerosols

The size-selective measurements performed at the downstream and upstream sampling stations during the tests with 10 different fuel formulations were used to assess the effects of those formulations on the physical characteristics of diesel aerosols in mine air. These characteristics included the average geometric mean diameter (GMD), geometric standard deviation (GSD), peak concentration, and total concentration of the aerosols. The concentration distributions were adjusted for differences in the VR between the tests by adjusting them to the common VR of 19.28 m^3/s, the average VR maintained during the baseline test.

The results of the statistical analyses performed on the data, including GMDs, GSDs, and ventilation-adjusted total aerosol number concentration, are summarized in Table 9. Each aerosol number concentration presented is the ventilation rate-adjusted average of several measurements performed during a test. The net contributions of the vehicle emissions to the aerosol concentration values are obtained by subtracting concentrations measured at the upstream sampling station from those measured at the downstream station. The relative changes in the net contributions were calculated using the baseline case as the reference.

The results of measurements at the upstream sampling station, presented in the seventh data column in Table 9, showed that the background number concentrations of aerosols entering the isolated zone during the tests were relatively low. The peak aerosol concentrations at the upstream end of the isolated zone were found to be approximately three orders of magnitude lower then those at the downstream end. Those differences in downstream and upstream concentrations are illustrated in Figure 15, which shows the size distributions measured during water emulsion tests. Despite their almost negligible effects on the results, the upstream concentrations were included in the calculations of the net contribution of the tested configurations to the aerosol concentrations at the downstream station. However, when aerosol size distributions were analyzed, the size distributions of the upstream aerosols were neglected because of their small effects on the results.

Table 9.—Effects of fuel formulations on size distribution and concentrations of aerosols in mine air (common ventilation rate = 19.28 m^3/s)

Fuel Tests (LHD 1)	Downstream			Upstream			Net Contribution	
	Average GMD, nm	Average GSD	Adjusted Average Total Number, $\times 10^7$ #/cm^3	Average GMD, nm	Average GSD	Adjusted Average Total Number, $\times 10^7$ #/cm^3	Adjusted Average Total Number, $\times 10^7$ #/cm^3	Change (increase is positive), %
#1 Diesel/ Muffler	95.1	1.76	4.2930	—	—	0.0264	4.2667	
PuriNOx Cold-Weather/ Muffler	68.4	1.69	4.8899	—	—	0.0173	4.8726	14.2
PuriNOx Warm-Weather/ Muffler	54.9	1.72	4.9816	—	—	0.0145	4.9671	16.4
20% Soy Biodiesel Blend/ Muffler	80.6	1.67	3.7668	—	—	0.0100	3.7567	–12.0
50% Soy Biodiesel Blend/ Muffler	70.3	1.68	3.3994	—	—	0.0090	3.3904	–20.5
50% Soy Biodiesel Blend/ DOC	67.0	1.73	3.1971	—	—	0.0082	3.1889	–25.3
20% Yellow Grease Biodiesel Blend/ Muffler	81.0	1.63	4.7291	—	—	0.0249	4.7042	10.3
50% Yellow Grease Biodiesel Blend/ Muffler	61.4	1.67	3.1690	—	—	0.0366	3.1324	–26.6
ULS Diesel/ Muffler	93.0	1.73	3.7749	—	—	0.0558	3.7191	–12.8
ULS Diesel/ DOC	89.3	1.71	3.4450	—	—	0.0065	3.4385	–19.4

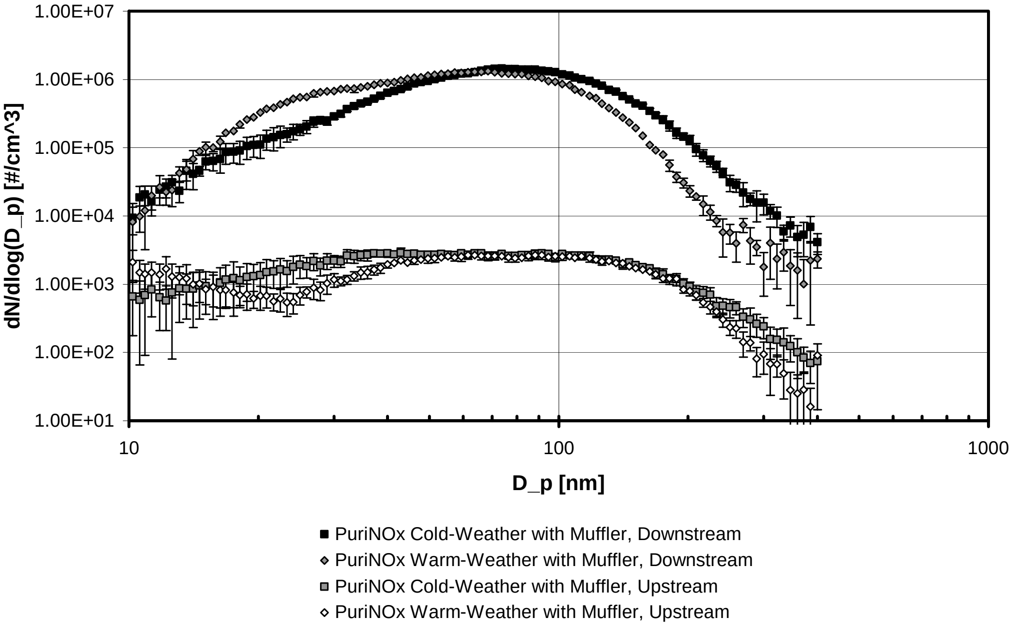


Figure 15.—Aerosol size distributions at downstream and upstream stations observed during water emulsion tests (common ventilation rate = 19.28 m^3/s).

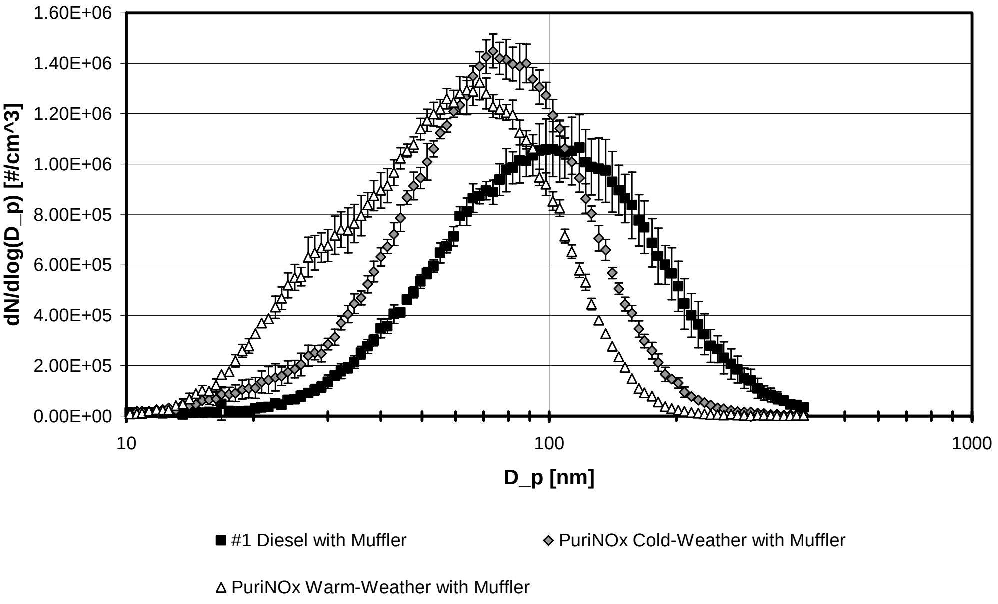


Figure 16.—Effects of water emulsions on the size distributions of aerosols (common ventilation rate = 19.28 m^3/s).

Figure 16 shows the effects of the two water emulsions on the aerosol size distributions downstream of the test zone. The size distributions of the particles observed during the tests with water emulsions are characterized by lower GMDs and higher peak concentrations than the size distributions observed during the baseline test with #1 diesel (see Table 9 and Figure 16). The GMD of the baseline particles was 95 nm, while the GMDs for the cold- and warm-weather water-fuel emulsions were 68 and 55 nm, respectively. The peak particle number concentration for the baseline test with #1 diesel was 1,065,000/cm^3 and was lower than those observed for cold-weather (1,449,000/cm^3) and warm-weather (1,324,000/cm^3) emulsions. The relative increases in total aerosol number concentrations were 14% and 16% for the cold- and warm-weather water-fuel emulsions, respectively.

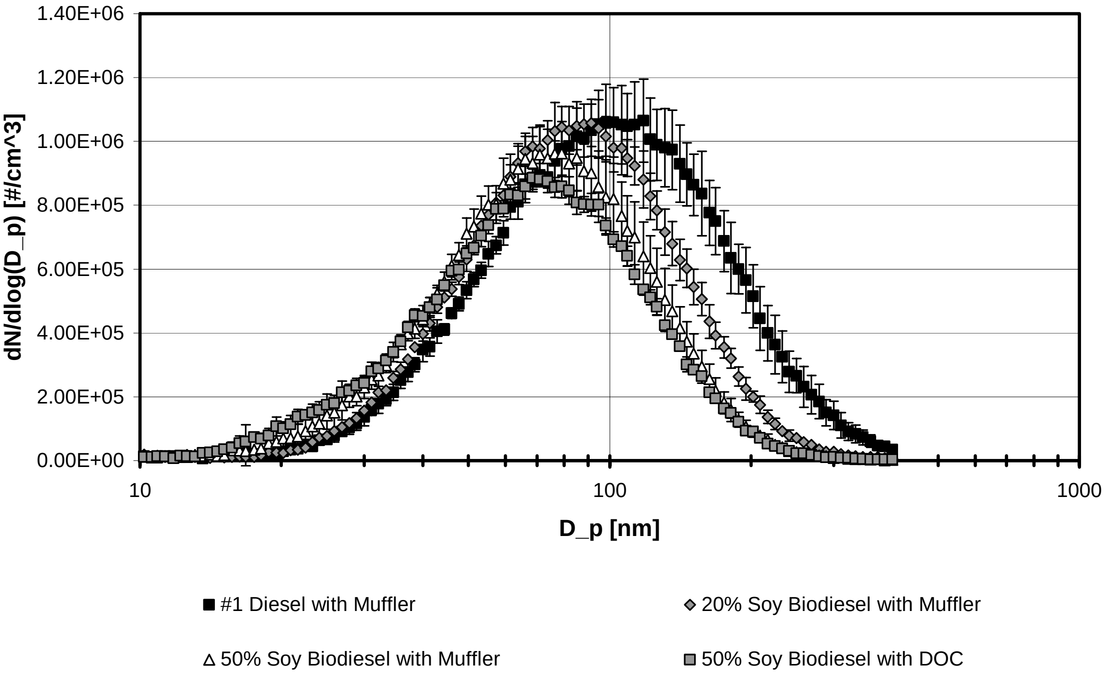


Figure 17.—Effects of soy biodiesel blends on the size distributions of aerosols (common ventilation rate = 19.28 m^3/s).

Figure 17 shows the downstream particle size distributions for the baseline test and tests using soy-based biodiesel blends. The number concentration and GMD for each test are shown in Table 9. Figure 17 shows that the particles from the biodiesel blends have lower GMDs and somewhat lower peak concentrations than those for the baseline fuel. The GMD distributions of particles for the tests with 20% and 50% soy biodiesel blends were 81 and 70 nm, respectively, whereas the baseline particle GMD was 95 nm. The peak particle number concentration was 1,058,000/cm^3 for the 20% soy blend and 962,000/cm^3 for the 50% soy blend versus the baseline particle number concentration of 1,065,000/cm^3. The total aerosol concentrations were found to be reduced by 12% and

21% when 20% and 50% soy biodiesel blends, respectively, were used. The DOC, when used with the 50% soy biodiesel blend, caused a further decrease in the GMD (67 nm vs. 70 nm), the peak concentrations, and the total concentration of aerosols (by 25%) (see Table 9 and Figure 17).

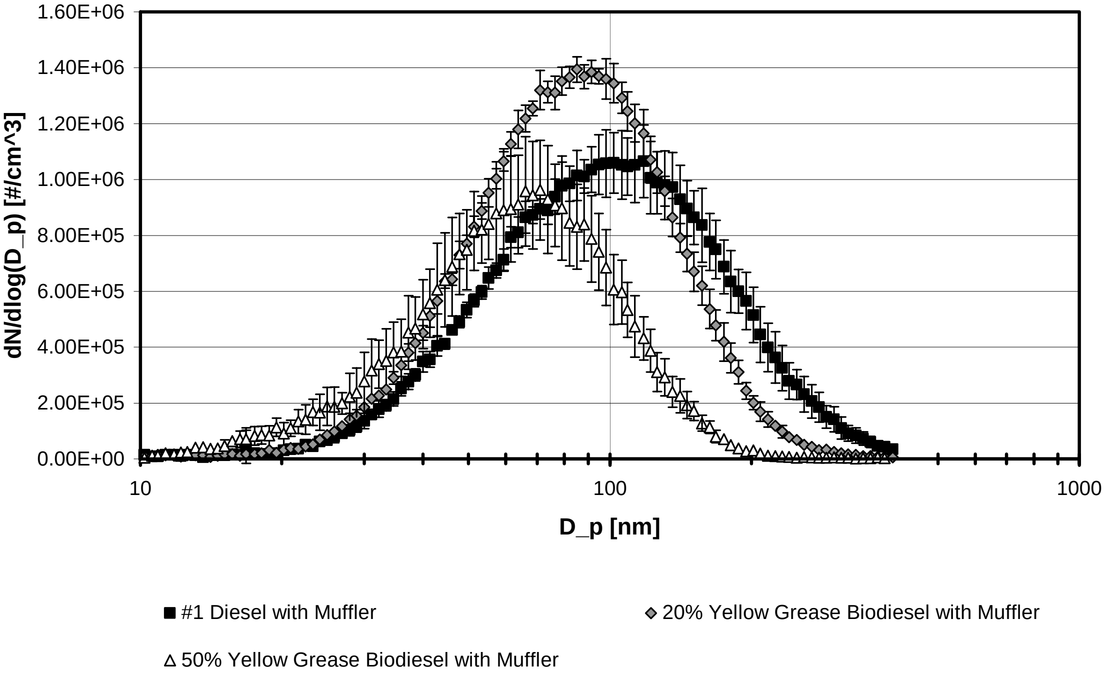


Figure 18.—Effects of yellow grease biodiesel blends on the size distributions of aerosols (common ventilation rate = 19.28 m^3/s).

The aerosol size distributions for the baseline test and tests using yellow grease biodiesel blends are shown in Figure 18. Corresponding data are shown in Table 9. The data revealed that the distributions observed during tests with yellow grease biodiesel blends exhibited lower GMDs than those observed during the baseline fuel test. GMDs for the tests with 20% and 50% yellow grease biodiesel blends were 81 and 61 nm, respectively, whereas the baseline particle GMD was 95 nm. The peak particle number concentration for 20% yellow grease blend was 1,394,000/cm^3 and, unlike that observed for the soy-based blend, was higher than that for the 50% yellow grease blend (962,000/cm^3) and the baseline fuel (1,065,000/cm^3). The total aerosol number concentration relative to the baseline fuel increased by 10% when the 20% yellow grease fuel blend was used, but showed a decrease of 27% when the 50% yellow grease fuel blend was used.

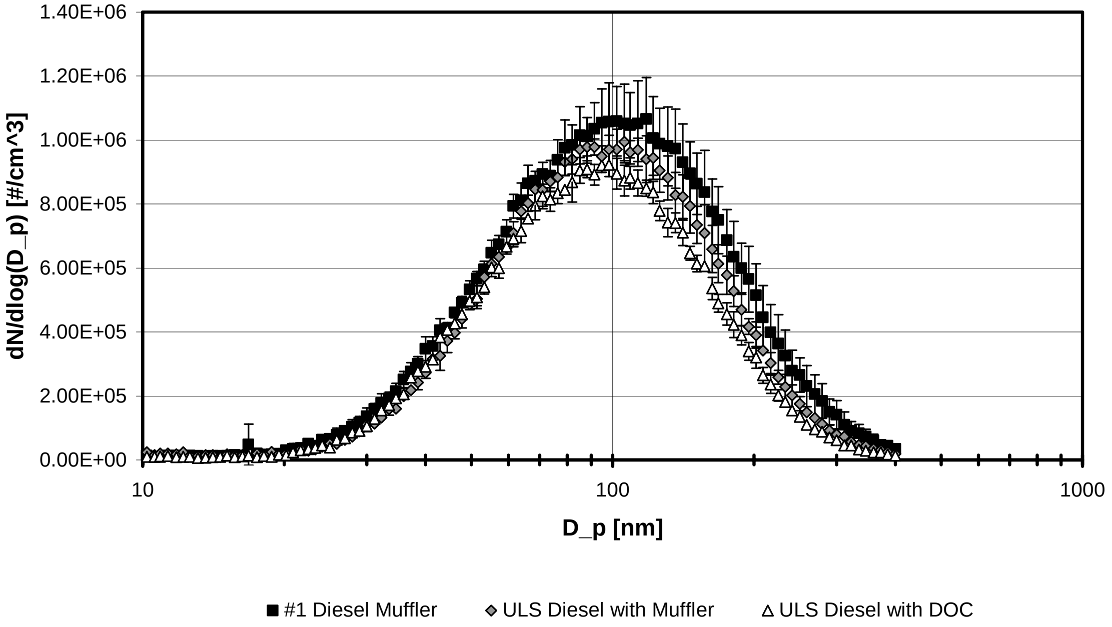


Figure 19.—Effects of ULS diesel on the size distributions of aerosols (common ventilation rate = 19.28 m^3/s).

When the vehicle was fueled with ULS diesel, the particle size distributions were characterized by slightly lower GMDs and higher peak concentrations than those observed during the baseline test with #1 diesel (see Table 9 and Figure 19). While the particle distributions generated by vehicles fueled with #1 diesel fuel were characterized by a GMD of 95 nm, the GMD for the particle distributions from ULS fuel was 93 nm. The peak concentration of 1,065,000/cm^3 and total net contribution to aerosol concentrations of 42,667,000/cm^3 for the test with #1 diesel were found to be slightly higher than those observed for ULS diesel (994,000/cm^3 and 37,191,000/cm^3, respectively). The GMD, peak concentration, and total concentration of aerosols were found to be further reduced when a ULS diesel was used in the vehicle that was fitted with a selected DOC (Table 9 and Figure 19).

Effects of Fuel Formulations on Concentrations of NO, NO_2, CO, and CO_2

During fuel tests, NO, NO_2, CO, and CO_2 concentrations were measured continuously at the upstream, downstream, and vehicle sampling stations. During these tests, the concentrations of NO, NO_2, and CO at the upstream sampling station were found to be under the detection limit of the iTX multigas instrument. Therefore, the net contributions of the vehicles to those gases were assumed to be equal to their concentrations at the downstream and vehicle locations. Continuous measurements with the RKI Eagle CO_2 monitor at the upstream sampling station showed that the background concentration of CO_2 remained relatively constant throughout the tests, averaging 321 ppm when corrected for local atmospheric pressure. This value was used during the analysis as the average background concentration of CO_2 for all tests.

Gas data were adjusted to the common average ventilation rate of the baseline fuel test. The ventilation-adjusted net contributions of fuel formulations and diesel oxidation catalyst to average and maximum peak concentrations of NO, NO_2, CO, and CO_2 are summarized for the downstream and vehicle sampling stations in Tables 10 and 11, respectively.

Table 10.—Net contributions of fuel formulations to average and peak NO, NO_2, CO, and CO_2 concentrations at the downstream sampling station (common ventilation rate = 19.28 m^3/s)

Fuel Tests (LHD 1)	NO, ppm		NO_2, ppm		CO, ppm		CO_2, ppm	
	Avg.	Max.	Avg.	Max.	Avg.	Max.	Avg.	Max.
#1 Diesel/Muffler	3.7	13.0	0.1	0.4	2.2	10.0	808	2,258
PuriNOx Cold-Weather/Muffler	N/A	N/A	N/A	N/A	N/A	N/A	816	2,270
PuriNOx Warm-Weather/Muffler	N/A	N/A	N/A	N/A	N/A	N/A	778	2,320
20% Soy Biodiesel Blend/Muffler	4.2	13.0	0.1	0.6	1.8	7.0	844	2,307
50% Soy Biodiesel Blend/Muffler	4.1	12.9	0.1	0.6	1.6	7.0	852	2,349
50% Soy Biodiesel Blend/DOC	4.4	13.4	0.3	1.1	0.0	0.0	859	2,269
20% YG Biodiesel Blend/Muffler	N/A	N/A	N/A	N/A	N/A	N/A	843	2,269
50% YG Biodiesel Blend/Muffler	N/A	N/A	N/A	N/A	N/A	N/A	861	2,301
ULS Diesel/ Muffler	N/A	N/A	N/A	N/A	N/A	N/A	877	2,300
ULS Diesel/DOC	3.5	11.1	0.2	0.9	0.0	0.0	855	2,303

NO, NO_2, and CO results collected at the downstream sampling station during the tests on PuriNOx water emulsions, yellow grease biodiesel blends, and ULS diesel are not available due to problems in data acquisition. The results of measurements conducted at the vehicle sampling station with the PuriNOx warm-weather water emulsion and 20%

yellow grease biodiesel blends are also not available due to problems encountered during the data-recording process.

Table 11.—Net contributions of fuel formulations to average and peak of NO, NO_2, CO, and CO_2 concentrations at the vehicle sampling station (common ventilation rate = 19.28 m^3/s)

Fuel tests (LHD 1)	NO, ppm		NO_2, ppm		CO, ppm		CO_2, ppm	
	Avg.	Max.	Avg.	Max.	Avg.	Max.	Avg.	Max.
#1 Diesel/Muffler	5.2	14.0	0.4	1.4	2.8	11.0	804	2,413
PuriNOx Cold-Weather/Muffler	5.1	15.1	0.4	1.3	1.9	8.0	807	1,892
PuriNOx Warm-Weather/Muffler	N/A	N/A	N/A	N/A	N/A	N/A	886	1,963
20% Soy Biodiesel Blend/Muffler	5.2	16.0	0.5	1.9	1.7	9.0	844	2,030
50% Soy Biodiesel Blend/Muffler	6.1	16.9	0.5	1.4	1.6	8.0	853	2,021
50% Soy Biodiesel Blend/DOC	6.4	18.5	0.7	2.7	0.0	0.0	916	2,197
20% YG Biodiesel Blend/Muffler	N/A	N/A	N/A	N/A	N/A	N/A	999	2,145
50% YG Biodiesel Blend/Muffler	6.5	16.7	0.4	1.7	1.7	10.8	874	2,027
ULS Diesel/Muffler	6.6	16.9	0.5	1.8	2.8	11.9	950	2,705
ULS Diesel/DOC	5.2	16.1	0.6	2.8	0.0	0.0	924	3,020

Effects of Fuels on the Concentrations of NO, NO_2, and CO

An examination of the results obtained for the downstream location (Table 10) and on the vehicle (Table 11) showed little difference in the NO, NO_2, and CO concentrations between the baseline and the fuel formulation cases for which data are available.

Carbon Dioxide (CO_2)

According to the results presented in Table 10, differences in downstream average and peak concentrations of CO_2 between the tests were relatively minor. The computed coefficient of variation (CV) was 4% for the average and 1% for the peak CO_2 concentrations. The small differences signify the ability of the vehicle operator to replicate the fuel consumption and load on the engine during the duty cycle throughout all of the fuel tests. The results of measurements at the vehicle sampling station show much less agreement in average (CV = 7%) and peak CO_2 concentrations (CV = 16%). This could have been caused by high variability in the dilution rate at the vehicle sampling station, particularly during the parts of the duty cycle performed in the stope.

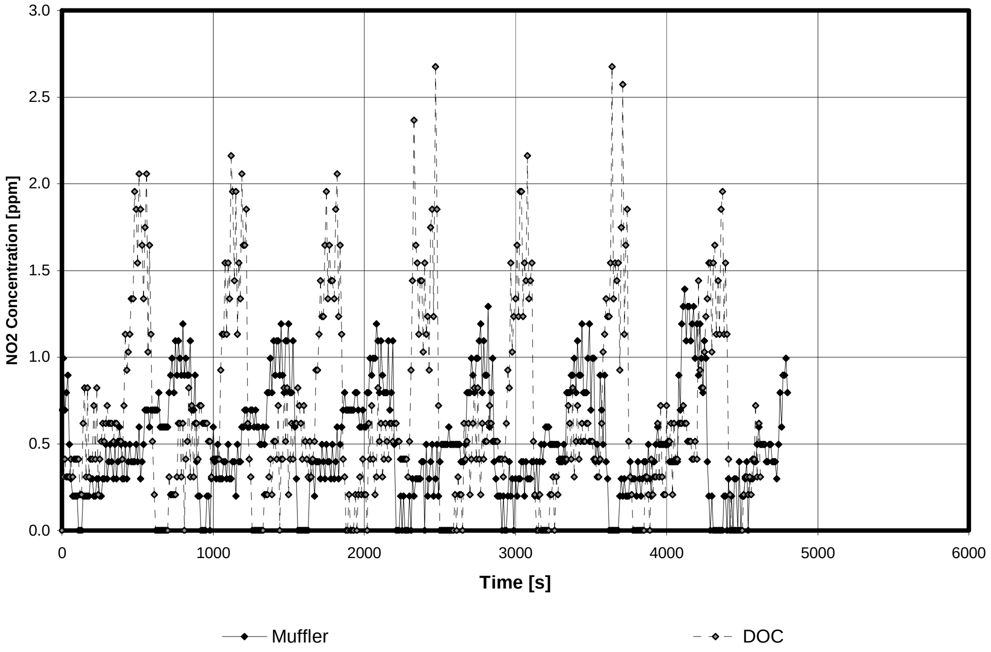


Figure 20.—Effects of tested DOC on concentrations of NO_2 at vehicle sampling station observed from the test with 50% soy biodiesel (common ventilation rate = 19.28 m^3/s).

Effects of a Diesel Oxidation Catalyst (DOC)

To assess the effects of a DOC on vehicle emissions, the tests using the 50% soy biodiesel blend and ULS diesel were conducted twice, once when the vehicle was equipped with a muffler and once when the vehicle was equipped with a DOC. As Tables 10–11 and Figure 20 illustrate, during the tests with a DOC the average and peak NO_2 concentrations at the downstream and vehicle sampling stations were found to be higher than in those cases when the vehicle was equipped with a muffler. The tests with 50% soy biodiesel showed that use of the DOC increased the net ventilation-adjusted average and peak NO_2 at the vehicle by 31% and 92%, respectively. Similarly, the tests with ULS diesel showed that use of the DOC increased the equivalent NO_2 concentrations by 24% and 58%, respectively. During both DOC tests, peak concentrations of NO_2 at the vehicle sampling station approached 3 ppm. Use of the DOC rendered downstream and on-vehicle CO concentrations undetectable.

EFFECTS OF FILTRATION SYSTEMS

This section presents the results of the tests on selected filtration systems (see Table 5). Six tests, of which four were successfully completed, were conducted in the isolated zone with the objective of assessing the effects of selected diesel particulate filter (DPF) systems and disposable filter elements (DFEs) on concentrations of DPM and gases in mine air. Two of the tests were on the ArvinMeritor (AM) DPF system with a fuel burner, followed by a DOC catalyzed, in one case, with a proprietary platinum (Pt) based formulation and, in the other case, with a proprietary palladium (Pd) based formulation. Two tests were conducted to evaluate DFEs from Donaldson and Filter Service. One test was conducted to evaluate a Clean Air Power/ETG flow-through catalytic particulate oxidizer (CPO). The baseline was established using data generated during the test with the vehicle equipped with a regular muffler.

The tests with the AM with the Pt-based DOC and the Clean Air Power/ETG CPO system were terminated in the early phase of the tests, and only gas data gathered in that period were available for the analysis. The test on the AM system with the Pd-catalyzed DOC was extended for an additional three full cycles to assess the effects of the diesel fuel burner supported regeneration process. The results of the measurements obtained during these three additional cycles are reported separately from those of the filter test.

The vehicle used for these tests was LHD 2 powered by a Deutz BF41013FC/MVS engine. It was not possible to use the same operator for all of the tests.

Ventilation Airflow Rates for Filtration Systems Tests

The ventilation rates (VRs) were obtained from air velocity measurements performed at the downstream station. During the filter tests, VRs were also found to be strongly influenced by vehicle movement inside the isolated zone, as illustrated by the example of the VR recorded during the baseline filter test (see Figure 21). The VRs averaged over the length of the individual filter tests are summarized in Table 12. The average VRs among the tests were found to be very consistent, as indicated in Table 12.

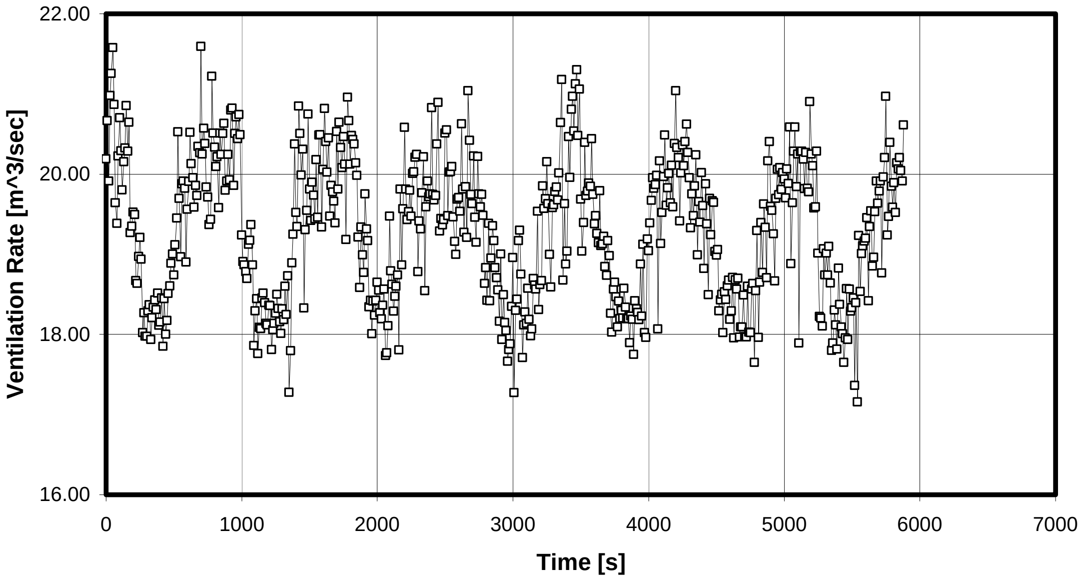


Figure 21.—Ventilation rates measured at the downstream sampling station during the baseline filter test.

Table 12.—Average VRs at the downstream sampling station for the filter tests

Filter Tests (LHD 2)	Average Ventilation Rates	
	m^3/sec	ft^3/min
Muffler	19.29	40,874
AM Pd DOC	19.27	40,827
Donaldson	19.36	41,016
Filter Service	19.57	41,467

The average VRs presented in Table 12 were used to adjust all measured concentrations of particulate matter and gases to the average VR of the baseline fuel test, 19.29 m^3/s (40,874 ft^3/min). Adjustment of the measured concentrations to a common VR is required to make a direct comparison of the results between the tests.

Effects of Filtration Systems on Aerosols

The VR-adjusted average net contributions of the vehicle tested during the filter tests to the downstream mass concentrations of EC, TPM, and SO_4 are summarized in Table 13. The EC and TPM concentrations for each test are graphically presented in Figure 22.

Table 13.—Effects of filtration system on average EC, gravimetrically and TEOM-determined TPM, and sulfate (SO_4) concentrations (common ventilation rate = 19.29 m^3/s)

Filter Tests (LHD 2)	VR-Adjusted Average Contributions to Concentrations			
	EC NIOSH 5040, µg/m^3	TPM Gravimetric Analysis, µg/m^3	TPM TEOM, µg/m^3	SO_4 IC Analysis, µg/m^3
Muffler	105	172	180	3.4
AM Pd DOC	8	54	51	15.3
Donaldson	9	27	43	1.4
Filter Service	31	65	62	0.5
AM Pd DOC Regeneration	N/A	N/A	183	N/A

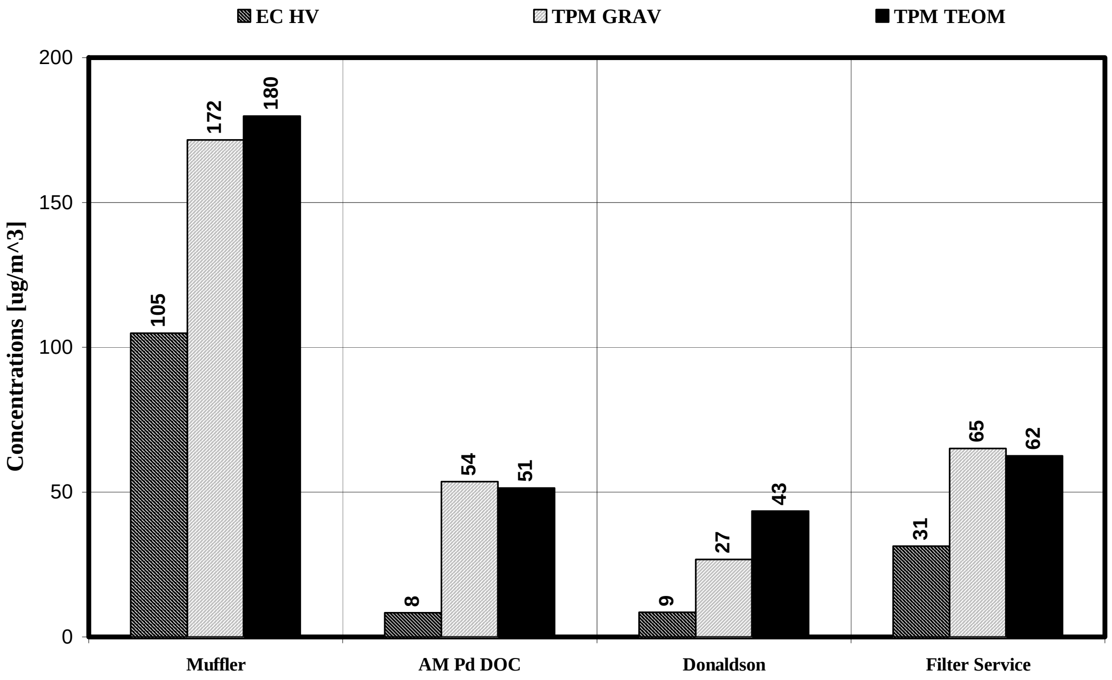
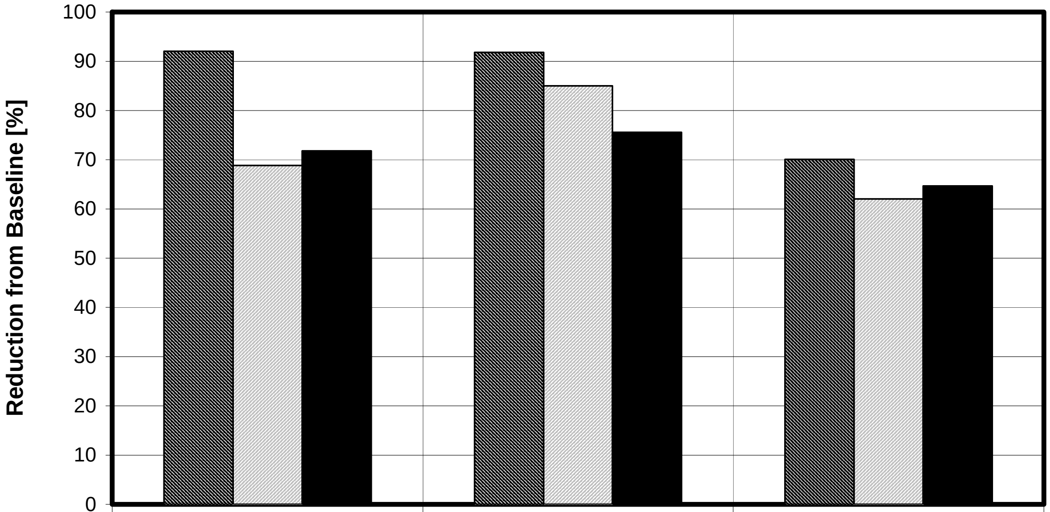


Figure 22.—VR-adjusted average concentrations of EC and gravimetrically and TEOM-determined TPM (common ventilation rate = 19.29 m^3/s).

Figure 23 shows the relative effects of the filtration systems on the aerosol concentrations expressed as percentages of reduction relative to the baseline case.



	AM Pd DOC	Donaldson	Filter Service
▧ EC HV	92	92	70
▨ TPM GRAV	69	85	62
■ TPM TEOM	72	76	65

Figure 23.—Changes in average concentrations of EC and TPM with implementation of filtration systems. Values indicate reductions in concentrations.

Effects of Filtration Systems on Mass Concentration of EC

The results presented in Figure 23 show that two systems, the AM DPF system with a palladium (Pd) catalyzed DOC and the Donaldson DFE, reduced the net contribution of vehicle to mass concentrations of EC by 92%. The disposable filter element from Filter Service reduced the contribution by 70%.

Effects of Filtration Systems on Mass Concentration of TPM Determined by Gravimetric Analysis

The ventilation rate-adjusted results of the gravimetric analyses performed on the samples collected at the downstream sampling station during the filter tests are presented in Table 13. The mass of the samples collected during these tests was found to be above the 25-µg/sample detection limit, but below the 85-µg/sample quantification limit.

The results presented in the Figure 23 data table show that the AM DPF system with a Pd-catalyzed DOC reduced downstream TPM concentrations by 69%. The disposable elements from Donaldson and Filter Service reduced downstream TPM concentrations by 85% and 62%, respectively.

All three filter systems more efficiently reduced EC concentrations than TPM concentrations in the mine air. The most pronounced difference between EC and TPM efficiencies was observed with the AM DPF system. This difference can be partially attributed to an increase in sulfate formation due to catalytic processes in the DOC.

Effects of Filtration Systems on the Mass Concentration of TPM Measured With the TEOM 1400a

During filter tests, continuous measurements of mass concentrations of TPM from the TEOM 1400a instruments at the downstream and upstream sampling stations are shown in Figure 24. TPM concentrations at the upstream sampling station were much lower than the downstream concentrations and thus were not used in the calculations. The average concentrations of TPM were calculated using the differences between the reported TEOM filter masses at the start and end of the sampling period. The ventilation-adjusted averages are presented in Table 13 and Figures 22–23.

Generally, results obtained from TEOM measurements are in agreement with the gravimetric results. TEOM results show that downstream TPM concentrations were reduced from those observed during the baseline test by 72% in the case of the AM DPF system with the Pd-catalyzed DOC, by 76% in the case of the Donaldson DFE, and by 65% in the case of the Filter Service DFE.

Throughout the tests, continuous monitoring with the TEOM instrument revealed differences in the effects of the tested filtration systems on TPM concentrations at the downstream sampling station, as shown in Figure 24. Although the concentrations of TPM during the test with the Donaldson DFE steadily declined throughout the duration of the test, the TPM concentrations during the test with the Filter Service DFE generally increased throughout the test. It can be hypothesized that the relatively clean filtration element from Donaldson, which had operated for only a couple of hours prior to the test, gained efficiency while accumulating DPM throughout test. The available data were insufficient to draw any conclusion as to the reasons for the loss in efficiency observed with the Filter Service DFE.

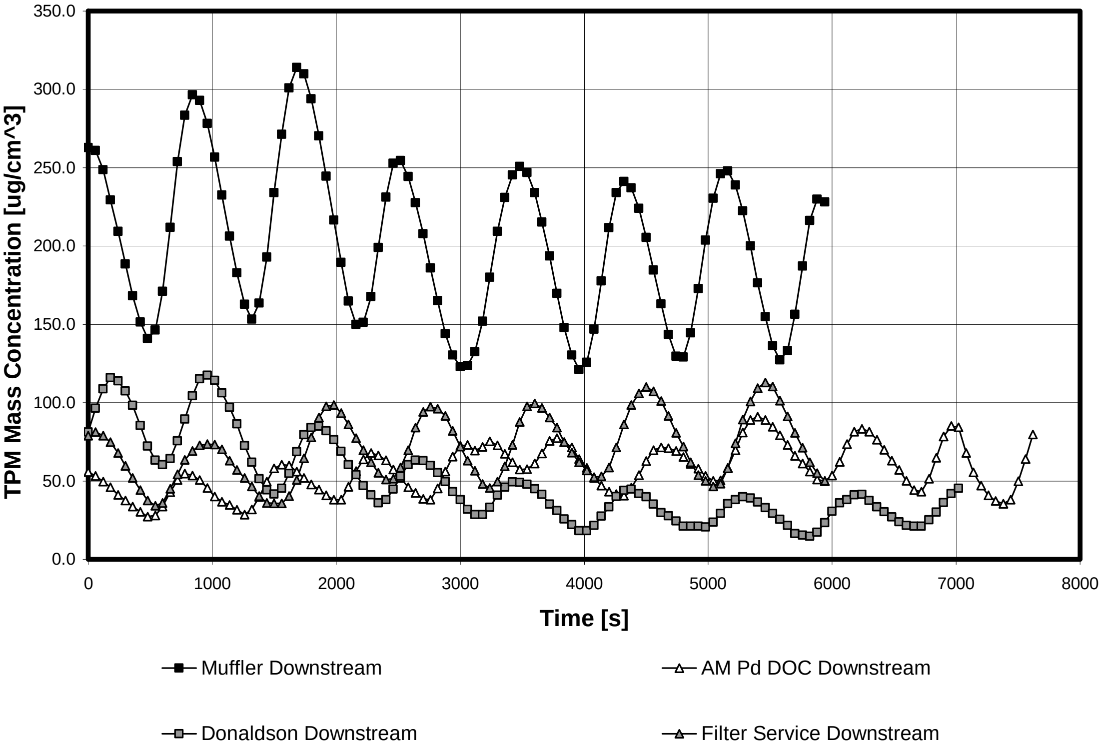


Figure 24.—Effects of filtration systems on mass concentrations of TPM measured throughout the tests by TEOM (common ventilation rate = 19.29 m^3/s).

Effects of Filtration Systems on Mass Concentration of Sulfates

The results of the sulfate analysis performed on the filter samples collected at the downstream and upstream sampling stations during the filter tests are summarized in Table 13. The concentrations of sulfates at the upstream sampling station were found to be between the 0.3-µg/sample limit of detection and the 1.0-µg/sample limit of quantification for the applied method. The downstream sulfate concentrations were found to be above the 1.0-µg/sample limit of quantification during all tests except the Filter Service DFE test, where sulfate concentrations were between the limit of detection and limit of quantification.

Results indicate that when the muffler was replaced with the AM DPF system having the Pd DOC, the net vehicle contributions to sulfate concentrations increased from 3.4 to 15.3 µg/m^3. It seems that catalytic processes in the DOC enhanced the oxidation of sulfur dioxide, resulting in sulfate production. On the other hand, the sulfate results show reductions in sulfate concentration relative to the baseline when the Donaldson and Filter Service DFEs were used.

Effects of Filtration Systems on Size Distribution and Number Concentration of Aerosols

The results of size-selective measurements performed at the downstream and upstream sampling stations during the filter tests are shown in Figure 25. The upstream measurements showed that the background number concentrations of aerosols entering the isolated zone during these tests were relatively low when compared to contribution from the tested vehicles (see Figure 25). Despite their almost negligible effects on the results, the upstream concentrations were included in the calculations of the net contribution of the tested configurations to the aerosol concentrations at the downstream station. However, when aerosol size distributions were analyzed, the size distributions of the upstream aerosols were neglected because of their small effects on the results.

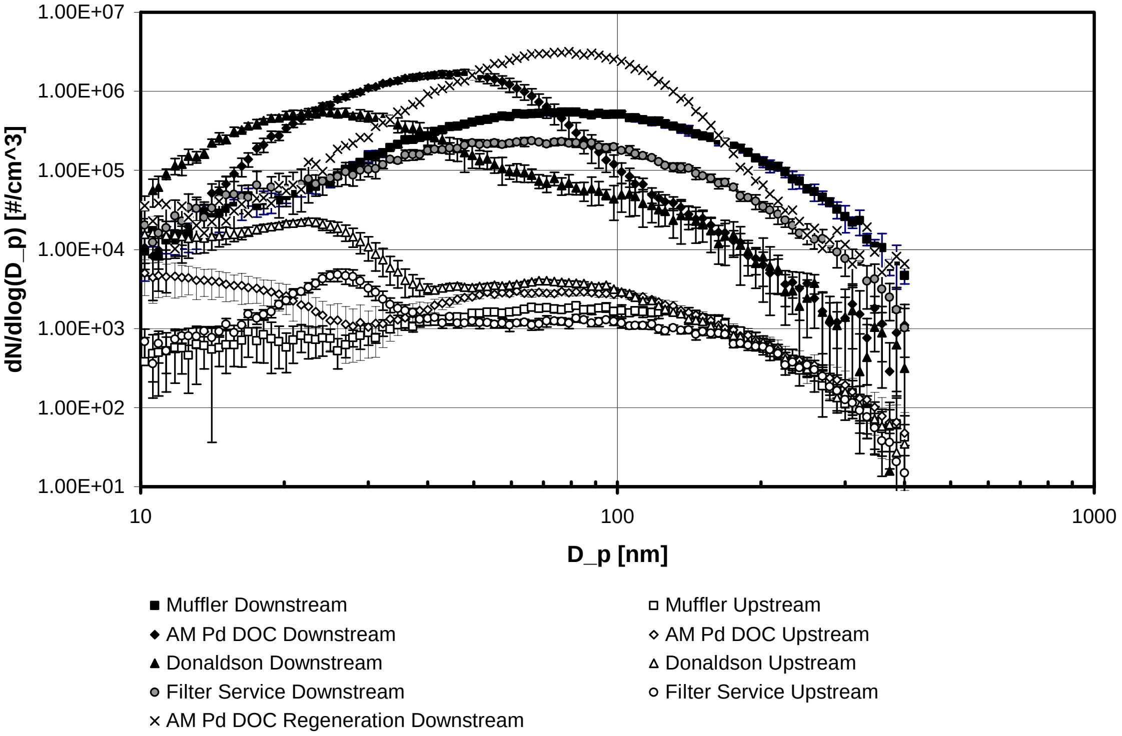


Figure 25.–Effects of filtration systems on aerosol size distribution (common ventilation rate = 19.29 m^3/s).

A summary of the statistical analysis results performed on measured size distributions is given in Table 14. This table provides the average geometric mean diameters (GMDs), average geometric standard deviations (GSDs), and ventilation-adjusted average total number concentrations of aerosols for observed size distributions. Two GMDs and GSDs are shown for the bimodal distributions.

Table 14.—Effects of diesel particulate matter filtration systems on size distribution and concentrations of aerosols in mine air (common ventilation rate = 19.29 m^3/s)

Filter Tests (LHD 2)	Downstream					Upstream			Net Contribution	
	Avg. GMD, nm		Avg. GSD		Adjusted Avg. Total Number, $\times 10^{7-+}$ #/cm^3	Avg. GMD	Avg. GSD	Adjusted Avg. Total Number, $\times 10^7$ #/cm^3	Adjusted Avg. Total Number, $\times 10^7$ #/cm^3	Change, %
	Mode 1	Mode 2	Mode 1	Mode 2						
Muffler	34.2	86.0	1.52	1.69	2.2098	—	—	0.0101	2.1997	0.0
AM DPF with Pd DOC	42.5		1.49		4.5337	—	—	0.0208	4.5128	–105.2
Donaldson	24.2	68.3	1.48	1.70	1.6952	—	—	0.0692	1.6260	26.1
Filter Service	35.8	73.6	2.14	1.70	1.0360	—	—	0.0131	1.0229	53.5
AM DPF with Pd DOC, Regeneration	72.2		1.52		8.3654	—	—	0.0208	8.3446	–279.3

The size distributions measured during the AM DPF with Pd DOC test were found to be single-modal distributions with substantially smaller geometric mean and higher peak concentrations than that observed for the baseline case (see Figure 25 and Table 14). The net contribution of the system to the total particle number was also found to be 105% higher (see Table 14) than that of the muffler. During the regeneration of the DPF system, the peak aerosol number concentration increased from about 1,666,000/cm^3, observed during normal operation, to approximately 3,177,000/cm^3. During the regeneration process, the aerosol number concentrations were found to be approximately 280% higher than those found when the vehicle equipped with a muffler was tested.

Results of measurements obtained with the Donaldson DFE are summarized in Table 14 and Figure 25. The bimodal size distributions observed during this test were characterized by a pronounced nucleation mode peak that was not observed during the baseline test. The Donaldson DFE reduced total aerosol number concentrations by approximately 26% relative to the baseline case.

Particles measured during the Filter Service DFE test were also found to have a bimodal distribution with a small nucleation mode peak. The Filter Service DFE reduced the vehicle’s contribution to total particulate number by approximately 54% relative to the baseline.

The effects of the Donaldson and the Filter Service DFEs on size distribution and aerosol concentration were found to be quite different. The size distribution of the particles measured during the test with the Donaldson DFE was characterized by much lower concentrations in the larger particle size range. By contrast, the size distributions during the Filter Service DFE test were characterized by significantly fewer nucleation-mode particles (see Figure 25). This is in agreement with the results of the EC, gravimetric, and TEOM measurements, which showed higher EC and TPM reductions for the Donaldson versus the Filter Service DFE.

A substantial increase in the number of particles in the nanoparticle range was observed for the Donaldson DFE, but not for the Filter Service DFE. Since carbon analysis shows very low EC mass concentrations for the Donaldson element, one can hypothesize that these nanoparticles contain primarily other known constituents of DPM emitted in ambient air such as organic carbons, sulfates, and water. All of these constituents would likely nucleate and/or condense near the tailpipe after passing through the DFE.

Effects of Filtration Systems on Concentrations of NO, NO_2, CO, and CO_2

During the filter tests, concentrations of NO, NO_2, CO, and CO_2 were measured continuously at the upstream, downstream, and vehicle sampling stations. As with the fuel tests, concentrations of NO, NO_2, and CO at the upstream sampling station were found to be below the detection limit of the iTX multigas instrument used in this study. Therefore, the net vehicle contributions to gas concentrations were assumed to be equal to their concentrations measured at both the downstream and vehicle sampling stations. Continuous measurements with the RKI Eagle CO_2 monitor at the upstream sampling station showed that the CO_2 concentration remained relatively constant throughout the tests, averaging 321 ppm. This was used as the average background CO_2 concentration for all tests.

The net contributions of vehicles equipped with the tested filtration systems to the NO, NO_2, CO, and CO_2 concentrations at the downstream and vehicle sampling stations are summarized in Tables 15 and 16, respectively. The average and peak concentrations are reported for all successfully completed tests. In addition, peak concentrations recorded prior to the premature termination of tests with the AM DPF with a Pt DOC and the CAP/ETG CPO system, as well as peak concentrations recorded during the regeneration process of the AM DPF system with a Pd DOC, are reported in Tables 15–16. The durations of these shortened tests preclude calculating meaningful averages.

As noted earlier, the peak gaseous concentrations at both the downstream and vehicle sampling stations were recorded while the vehicle was performing the part of the duty cycle inside and in front of the stope at the downstream load/dump point.

Table 15.—Net contributions of filtration system to average and peak NO, NO_2, CO, and CO_2 concentrations at the downstream sampling station (common ventilation rate = 19.29 m^3/s)

Filter Tests (LHD 2)	NO, ppm		NO_2, ppm		CO, ppm		CO_2, ppm	
	Avg.	Max.	Avg.	Max.	Avg.	Max.	Avg.	Max.
Muffler	3.5	12.0	0.1	0.6	0.6	4.0	572	1,574
AM Pt DOC	N/A	8.0	N/A	1.9	N/A	0.0	N/A	N/A
AM Pd DOC	3.1	11.0	0.2	0.8	0.0	0.0	487	1,335
AM Pd DOC Regeneration	N/A	11.0	N/A	1.1	N/A	0.0	N/A	N/A
Donaldson	3.6	13.0	0.0	0.2	0.7	4.0	551	1,658
Filter Service	4.1	13.2	0.0	0.2	0.7	4.1	590	1,783
CAP/ETG CPO	N/A	9.0	N/A	2.9	N/A	N/A	N/A	N/A

Table 16.—Net contributions of filtration system to average and peak NO, NO_2, CO, and CO_2 concentrations at the vehicle sampling station (common ventilation rate = 19.29 m^3/s)

Filter Tests (LHD 2)	NO, ppm		NO_2, ppm		CO, ppm		CO_2, ppm	
	Avg.	Max.	Avg.	Max.	Avg.	Max.	Avg.	Max.
Muffler	5.4	26.0	0.2	1.6	1.2	9.0	774	3,552
AM Pt DOC	N/A	18.0	N/A	5.7	N/A	0.0	N/A	N/A
AM Pd DOC	3.9	17.0	0.2	1.9	0.0	0.0	554	2,031
AM Pd DOC Regeneration	N/A	13.0	N/A	1.6	N/A	0.0	N/A	N/A
Donaldson	6.3	21.1	0.1	0.9	2.2	10.0	747	3,057
Filter Service	6.3	21.3	0.0	0.5	1.4	9.1	897	2,911
CAP/ETG CPO	N/A	10	N/A	4.1	N/A	N/A	N/A	N/A

Nitric Oxide (NO)

NO concentrations at the downstream and vehicle sampling locations were found to be generally lower during tests with the AM DPF having Pt and Pd DOCs and the CAP/ETG CPO system than those during the baseline case. The slight reduction in NO is partially attributable to the conversion of NO to NO_2 by the DOC. Increases in NO were observed during tests using the Donaldson and the Filter Service DFEs.

Nitrogen Dioxide (NO_2)

NO_2 results, presented in Tables 15–16, show that the test vehicle equipped with the AM DPF and a Pt DOC increased peak NO_2 concentrations at the downstream and vehicle sampling stations approximately three times from the baseline concentrations. A substantially smaller increase in NO_2 concentration was observed when the vehicle was fitted with the AM DPF and a Pd DOC.

It is important to note that the 19.29 m^3/s (40,874 ft^3/min) average ventilation rate maintained in the main drift during these tests was significantly higher than the MSHA-established 5.3 m^3/s (12,000 ft^3/min) ventilation rate for the Deutz BF4M1013FC engine. However, despite this relatively high air quantity supplied to the main drift, the peak NO_2 concentration at the vehicle sampling location exceeded 5 ppm when the LHD with the AM DPF and Pt DOC was operated within and in front of the downstream stope. In addition, it is then reasonable to assume that if the vehicle with the AM DPF and Pd DOC was operated at the MSHA ventilation rate, the peak NO_2 concentrations at the vehicle sampling location would be approximately 2.5 ppm.

Figures 26–27 illustrate similar elevated NO_2 concentrations recorded during the initial test stages on the CAP/ETG CPO system. These situations resulted in a premature termination of tests on the AM DPF with Pt DOC and CAP/ETG CPO systems to prevent overexposure of the vehicle operator.

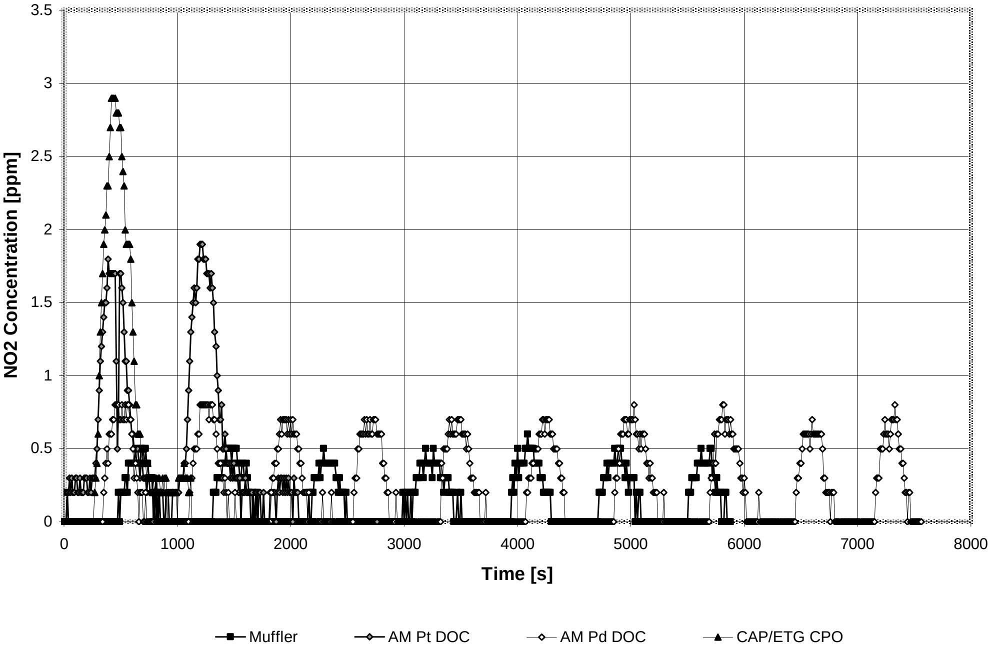


Figure 26.—Effects of filtration systems on NO_2 concentrations at downstream sampling station (common ventilation rate = 19.29 m^3/s).

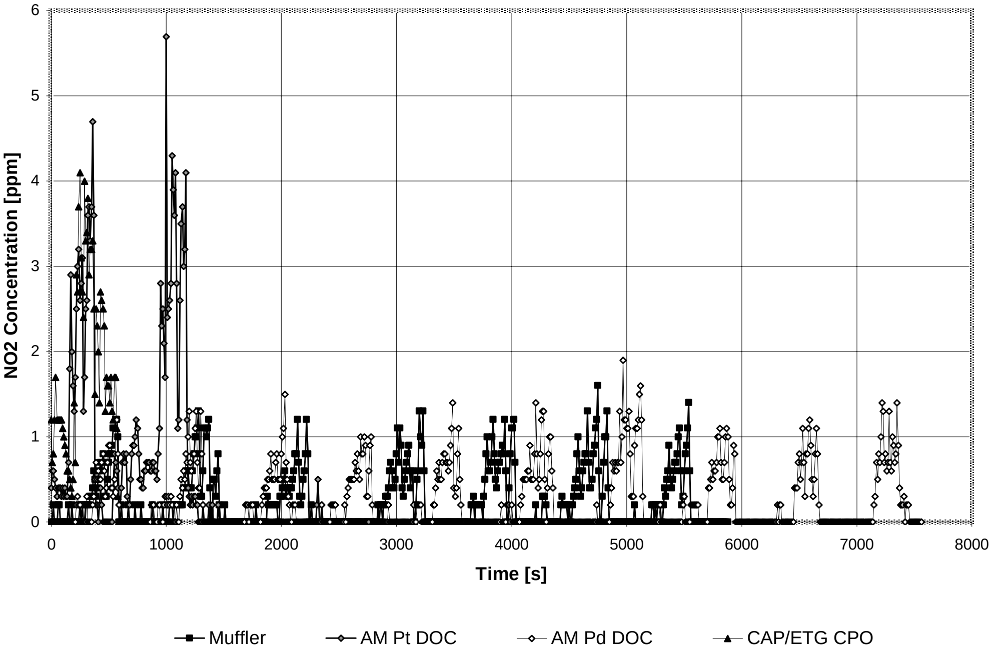


Figure 27.—Effects of filtration systems on NO_2 concentrations at vehicle sampling station (common ventilation rate = 19.29 m^3/s).

Carbon Monoxide (CO)

The net contribution of the vehicle equipped with either an AM DPF and a Pt or Pd DOC or the CAP/ETG CPO system to the concentration of CO at the downstream and vehicle sampling stations was found to be negligible. CO reductions can be attributed to the DOC's catalytic processes. The DFEs from Donaldson and Filter Service had no measurable effect on CO concentration.

Carbon Dioxide (CO_2)

According to the results of measurements performed at the downstream and vehicle sampling stations, the differences in the average and maximum peak concentrations of CO_2 were much more pronounced between the filter tests than between the fuel tests. This can be explained by the fact that the same miner operated the LHD 1 vehicle during all of the fuel tests, whereas two different operators operated the LHD 2 vehicle during the filter tests. One miner operated the vehicle during the tests on the AM DPF system with a Pt or Pd DOC. However, a different miner operated the vehicle during the baseline test and the tests on the Donaldson and the Filter Service DFEs. Operator driving styles can affect fuel consumption and thus CO_2 emissions.

Effects of Filtration Systems on Exhaust Temperature and Engine Back Pressure

Results of continuous exhaust temperature and engine back pressure measurements are presented in Figures 28–30. Due to equipment problems, results are not available for the Donaldson or the Filter Service DFE tests.

During the test on the AM DPF with a Pd DOC, the exhaust temperatures and engine back pressure were recorded during the filter test and during the fuel burner-controlled regeneration process. The results are shown in Figure 29.

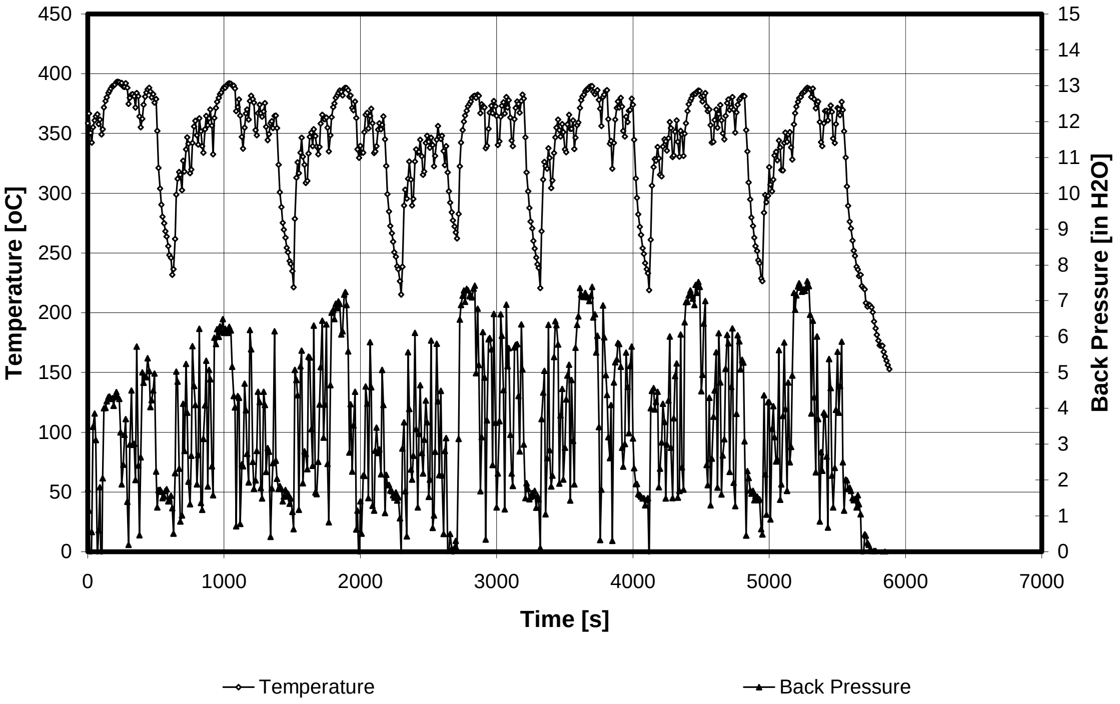


Figure 28.—LHD 2 exhaust temperature and engine back pressure during muffler test.

Peak exhaust temperatures at the filter inlet and outlet and peak engine back pressure measured during the filter tests are summarized in Table 17.

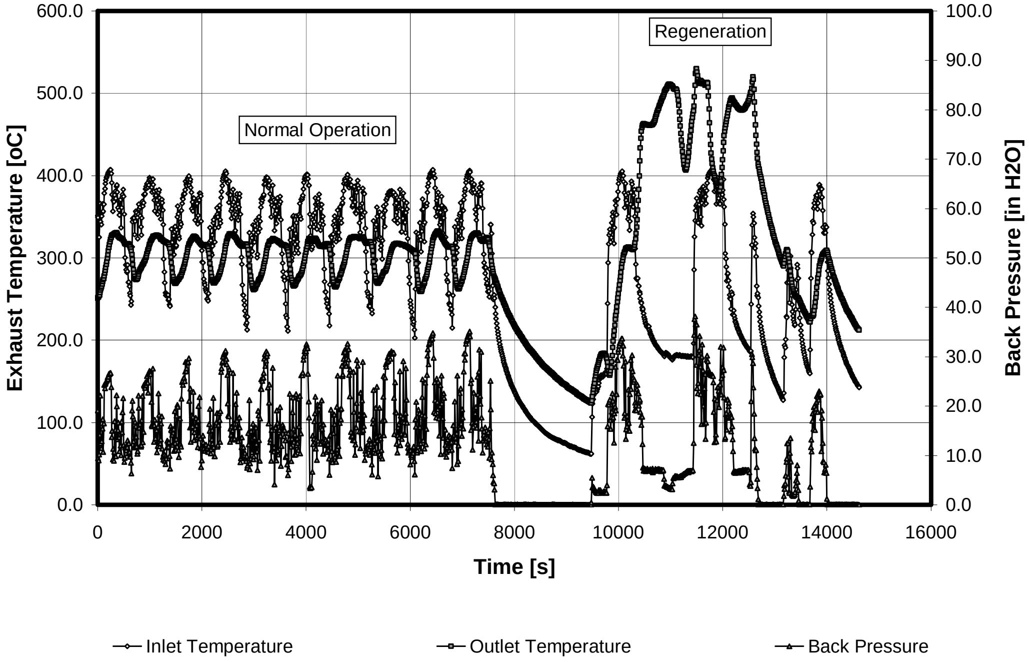


Figure 29.—LHD 2 exhaust temperatures and engine back pressure during testing with an AM DPF and Pd DOC.

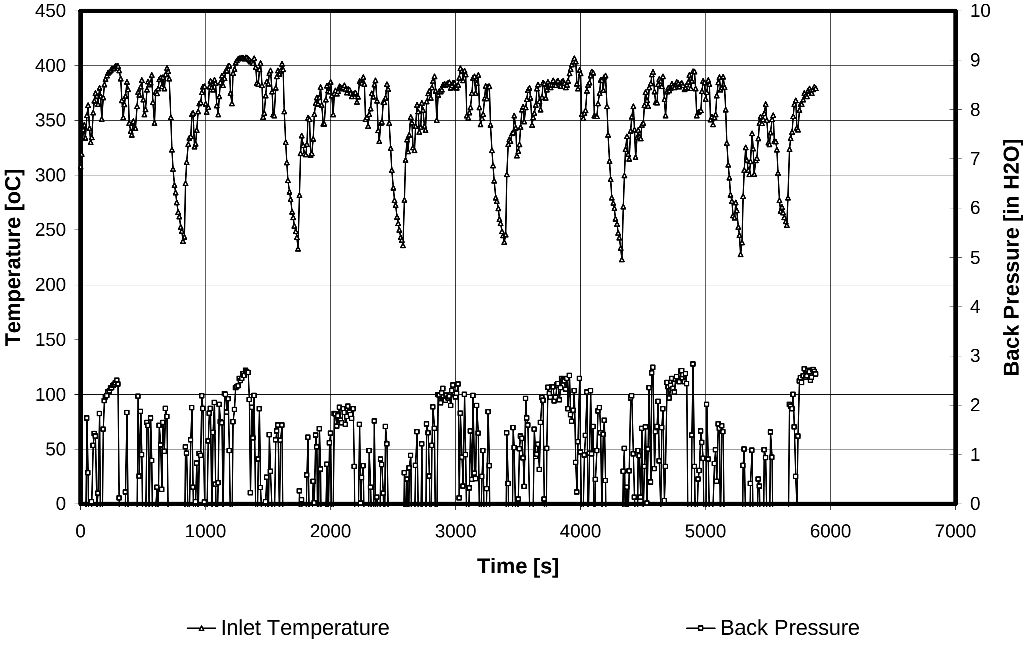


Figure 30.—LHD 2 exhaust temperature and engine back pressure during testing with Filter Service DFE.

Table 17.—Peak exhaust temperatures and engine back pressures measured during the filter tests

Filter Tests (LHD 2)	Peak Exhaust Temperature				Peak Engine Back Pressure			
	Inlet to Filter		Outlet From Filter		Start of Test, mbar	Start of Test, in H_2O	End of Test, mbar	End of Test, in H_2O
	°C	°F	°C	°F				
Muffler	393	740	N/A	N/A	16.2	6.5	18.7	7.5
AM Pd DOC	407	765	332	630	56.2	22.6	87.3	35.1
Donaldson	N/A	N/A	N/A	N/A	10.0	4.0	15.4	6.2
Filter Service	407	765	N/A	N/A	6.2	2.5	6.7	2.7
AM Pd DOC Regeneration	408	766	530	985	83.6	33.6	57.2	23.0

The inlet exhaust temperatures were found to be slightly higher when the vehicle was operated with the filter systems instead of a muffler (see Figures 28–30 and Table 17). It is important to note that the exhaust temperatures at the inlet filter face of the DFEs often exceeded 260 °C (500 °F), the maximum temperature recommended by the manufacturers for these elements.

During the regeneration process, the exhaust temperature at the outlet of the AM DPF system with a Pd DOC peaked at 530 °C (985 °F), exceeding the peak exhaust temperature of 332 °C (630 °F) observed during normal operation. During regeneration, the maximum engine back pressure was reduced to the values measured at the beginning of the test.

Relatively clean DFEs from Donaldson and Filter Service caused less engine back pressure than the ceramic filter element used in the AM DPF. Engine back pressure imposed by the disposable elements was found to be even lower than that caused by the restriction in the muffler. The increase in engine back pressure during the tests with DFEs was also less than the increase measured during the test with the AM DPF system.

SUMMARY

Seven alternative fuel formulations and four filtration systems were tested in the isolated zone at the SMC Nye Mine to evaluate the effectiveness of these technologies in controlling DPM and gaseous emissions from underground diesel-powered mining equipment. The results showed that using the cold-weather water-fuel emulsion formulation reduced mass concentrations of EC by about 70%, TPM determined by gravimetric analysis by 45%, and TPM determined by the TEOM by 46%. Size distribution measurements performed by an SMPS showed a 14% increase in total aerosol number concentration. The warm-weather water-fuel emulsion formulation reduced EC by about 85%, gravimetric TPM by 58%, and TEOM TPM by 66%. SMPS measurements showed about a 16% increase in aerosol number concentration. The sulfate results show that both formulations produced similar concentrations as #1 diesel.

The four tested biodiesel fuel blends, 20% and 50% blends of neat soy biodiesel and 20% and 50% blends of neat yellow grease (YG) biodiesel with #1 diesel fuel were found to reduce EC and TPM concentrations in mine air. The results showed EC reductions of 49% and 66% for 20% and 50% soy biodiesel blends, respectively. The reductions were slightly less pronounced for the 20% and 50% YG blends (33% and 56%, respectively). The 20% YG blend reduced gravimetric TPM concentration by 32%, whereas the 50% YG blend reduced TPM concentration by 48%. Replacing the muffler with a DOC further reduced the TPM concentration of the 50% YG blend to 60%. The results of TEOM analysis showed similar reductions in TPM. Sulfate concentrations for all four blends tested were reduced roughly in proportion to the lower sulfur content of the blended fuel (biodiesel fuel is free of sulfur). The DOC used with the 50% YG blend increased the sulfate concentration from 2.6 to 6.6 µg/m^3. The SMPS results indicated that the total aerosol number concentrations for the 20% and 50% soy blend were reduced by 12% and 21%, respectively; however, the 20% YG blend increased the concentration by 10% versus a 27% reduction for the 50% YG blend. Use of the DOC with the 50% soy blend reduced the number concentration by 25% compared to the baseline.

EC and TPM concentrations were unaffected by using ULS diesel in place of #1 diesel, whereas the sulfate concentrations decreased from 5.5 to 0.3 µg/m^3. Using a DOC with ULS diesel increased the sulfate concentration to 0.8 µg/m^3. SMPS results showed a 12.8% lower net total aerosol number concentration for the ULS diesel, and using a DOC led to further reduction in the number concentration.

Use of the reformulated fuels and the baseline #1 diesel fuel exhibited similar downstream and on-vehicle concentrations of NO and CO. However, a measurable increase in the NO_2 peak concentration was observed during the biodiesel tests. The DOC increased both the average and peak NO_2 concentrations at the downstream and on-vehicle locations. The tests with 50% soy biodiesel showed that use of the DOC increased the net ventilation-adjusted average and peak NO_2 at the vehicle by 31% and 92%, respectively. Similarly, the tests with ULS diesel showed that use of the DOC increased the equivalent NO_2 concentrations by 24% and 58%, respectively. The

peak concentrations that had been approaching 3 ppm occurred while the vehicle was in a short stope off the main drift during the loading/dumping simulation. When those peaks occurred, the ventilation rate in main drift was over 19 m^3/s (40,258 ft^3/min), a quantity that is more than double the accepted minimum for this engine. Use of the DOC rendered downstream and on-vehicle CO concentrations undetectable.

The ArvinMeritor (AM) fuel-burner DPF system with a palladium (Pd) catalyzed DOC reduced EC concentrations by 92%. The same system reduced downstream concentrations of TPM by 69% (gravimetric) and by 72% (TEOM). The Pd-catalyzed DOC increased the sulfate concentration from 3.4 to 15.3 $\mu g/m^3$. SMPS results indicated a 105% increase in the total particle number, possibly corroborating the hypothesis of increased concentrations of sulfate aerosols. During the regeneration of the AM DPF system, the peak aerosol number concentration increased from about 1,666,000/cm^3, observed during the normal operation, to approximately 3,177,000/cm^3.

The DFEs from Donaldson and Filter Service reduced the vehicle EC contribution by 92% and 70%, respectively. The same DFEs reduced downstream TPM concentrations determined by gravimetric analysis by 84% and 58%, respectively. TEOM-determined TPM concentrations were reduced by 76% and 65%, respectively. Sulfate concentrations were reduced by both DFE systems. SMPS results for the Donaldson DFE showed a bimodal distribution characterized by significantly smaller particles compared to the baseline and reduced the total number of particles by 26%. The Filter Service DFE reduced the total particle number by 54%.

The AM DPF with the Pd DOC system reduced the NO concentrations at the downstream and vehicle stations. The DFEs, on the other hand, increased the NO concentrations.

When the Pt-based DOC was used with the AM DPF, it raised the peak downstream NO_2 concentrations by a factor of three (from 0.6 to 1.9 ppm). The prevailing ventilation rate in the main drift during that test was about 3.3 times the MSHA rate (5.3 m^3/s (12,000 ft^3/min)) for the test engine. Nevertheless, the on-vehicle peak NO_2 for the AM DPF Pt DOC system exceeded the 5-ppm MSHA ceiling limit (30 CFR 57.5001). When the Pd-based DOC was used with the AM DPF, however, the average downstream NO_2 only increased from 0.6 to 0.8 ppm. Tests of the AM DPF system with Pt DOC and CAP/ETG CPO system had to be terminated because the elevated NO_2 concentrations threatened to overexpose the operator.

The AM DPF with either DOC as well as the CAP/ETG CPO system rendered the downstream and on-vehicle CO concentrations undetectable. The DFEs from Donaldson and Filter Service were found to have no measurable effect on CO concentration.

Finally, our study also revealed a number of potential challenges related to economic and technical aspects of implementing the studied control technologies into underground mines. The successful implementation of control technologies was found to be predicated on addressing a number of issues that are relatively unique to each mine and even to individual applications within a given mine. Those issues need to be further researched.

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