The Effectiveness of Selected Technologies in Controlling Diesel Emissions in an Underground Mine - Isolated Zone Study at Stillwater Mining Company's Nye Mine

Final Report to Metal/Nonmetal Diesel Partnership
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Introduction

This study is organized under the auspices of the Metal/Nonmetal Diesel Partnership formed by the National Institute of Occupational Safety and Health (NIOSH), the National Mining Association (NMA), the National Stone Sand and Gravel Association (NSSGA), the United Steel Workers of America (USWA) and the MARG Diesel Coalition. The ultimate objective of the study is to reduce the exposure of underground miners to diesel particulate matter (DPM) and gases, and to help in fulfilling the partnership's goal of identifying technically and economically feasible controls to curtail particulate matter emissions from existing and new diesel powered vehicles in underground metal and nonmetal mines.

The majority of current knowledge on the performance of the diesel particulate filter (DPF) systems and other control technologies is based on studies done under laboratory conditions, the results then being applied the results to on-highway vehicles. According to the best knowledge of the authors, only two comprehensive studies that were conducted recently at Noranda's Bathurst Mining and Smelting Mine and International Nickel Company's Stobie Mine under the sponsorship of the Diesel Emissions Evaluation Program [McGinn 2001, Bugarski and Schnakenberg 2001, Bugarski and Schnakenberg 2002] offered some insight into the problems associated with the deployment of modern DPFs to underground mining vehicles. The U.S. mining industry has expressed concern that this rather limited knowledge base is not sufficient to help them comply with the rule limiting DPM exposure of underground metal and nonmetal miners [30 CFR 57.5060 2001].

The partnership agreed that a series of comprehensive field evaluations of DPFs in several underground mines was needed to determine their viability of DPF systems and establish confidence in their performance. The first in this series of studies was the one conducted in Stillwater Mining Company's Nye Mine, Nye, Montana. This study was conducted in two phases. The objective of the first phase was to establish the effectiveness of the selected technologies in reducing diesel emissions by using an isolated zone methodology. The objective of the second phase was to assess the effectiveness of diesel particulate filters in controlling the exposure of underground miners in actual production scenarios. As part of the first phase of the study a series of tests were conducted at Nye Mine from May 19, 2003 until May 30, 2003. The results of Phase I of the study are presented in this report.

Objectives

The objective of the study was to determine the in-situ effectiveness of the selected technologies available to the underground mining industry for reducing particulate matter and gaseous emissions from diesel-powered equipment. The protocol was established to determine the effectiveness of those technologies in an underground environment under operating conditions that closely resemble actual production scenarios.

This study was designed to provide Stillwater, and the general mining community, with better insights into the performance of control technologies and enable them to identify the appropriate devices for reducing diesel emissions. The focus of the Stillwater research was on technologies that offer solutions for reducing DPM emissions. This report provides the results and assessment of the following control technologies: diesel particulate filters, disposable paper filters, diesel oxidation catalytic converter, and reformulated fuels.

This short-term study addressed some issues related to the selection and installation of filtration systems, but was not able to address other important issues related to the implementation and operation of DPFs, namely regeneration of DPF systems during the production cycle, their 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 primary technical objective of the study was to assess the effects of selected control technologies on concentrations of DPM and gases in the mine air. The majority of this effort was dedicated to evaluating the performance of state-of-the art DPF systems that were designed and supplied by several major manufacturers. Additional efforts were made to assess the effect of blended biodiesel, # 1 and #2 diesel fuels, and of selected diesel oxidation catalysts (DOC) on air quality and emissions.

The primary thrust of this study was the series of the measurements of ambient concentrations of DPM and gases in an isolated zone in the mine while each of the tested vehicles was performing a structured, repeatable duty cycles within that isolated zone. This part of the study was executed in the isolated zone of the 52E drift of Stillwater Nye mine.

The ambient measurements were complemented with measurements of DPM and gas concentrations in the exhaust system of the tested vehicles while the vehicles were parked and their engines were loaded under stationary conditions. This part of the study was conducted in the surface equipment repair shop at the Nye mine.

The study was conducted by researchers from NIOSH and Stillwater Mining Company with representatives of the partnership and MSHA present during some portions of the 2-week effort.

Methodology

Tested vehicles and emissions control technologies

Vehicles and engines

Stillwater Mining selected the diesel equipment to represent typical vehicles and power packages from the Stillwater Nye mine production fleet. The selected vehicles, two trucks and three load-haul-dump vehicles are classified as heavy-duty production machines. These vehicles were selected to be representative of 1) the mine fleet, 2) the duty cycle for that type of vehicle and 3) their effect on mine air quality. The engines powering these vehicles are also representative of the fleet. Some of the selected vehicles represent those of the fleet that routinely heavily load their engines, while others are assumed to represent those that perform tasks that produce less of a load on the engines.

The short description of the vehicles used in this study follows.

MTI DT-1604 trucks #92128 and #92133

MTI DT-1604 (Mining Technologies International, Sudbury, Ontario) is a truck with rated load of 14545 kg (32000 lb) and box capacity of 8.2 m^3 (10.8 yd^3). Truck #92128 is powered by a Deutz BF6M 1013FC and truck #92133 is powered by BF6M 1013ECP.

MTI LT-350 load-haul-dump #92506

MTI LT 350 (Mining Technologies International, Sudbury, Ontario) is a load-haul-dump with rated load of 3409 kg (7500 lb) and bucket capacity of 1.9 m^3 (2.5 yd^3). This model is powered by a Deutz BF4M 1013C.

Caterpillar Elphinstone R1300 load-haul-dump #92526

Caterpillar Elphinstone R 1300 (Caterpillar Elphinstone PTY LTD, Burnie, Tasmania, Australia) is a load-haul dump vehicle with rated load of 6500 kg (14333 lb) and bucket capacity of 2.8 m^3 (3.7 yd^3). This particular vehicle is powered by a Caterpillar CAT 3306 DITA engine derated to 123 KW (165 HP). In Stillwater Nye mine the #92526 and similar vehicles are typically used at a draw point for loading MTI DT 1604 trucks.

Caterpillar Elphinstone R1500 load-haul-dump #99942

Caterpillar Elphinstone R 1500 (Caterpillar Elphinstone PTY. LTD, Burnie, Tasmania, Australia) is a load-haul dump vehicle with a rated load of 10200 kg (22491 lb) and bucket capacity of 4.8 m^3 (6.3 yd^3). This model is powered by a Caterpillar CAT 3306 DITA engine rated at @ 164 KW (220 HP). In Stillwater Nye mine the #99942 and similar vehicles are typically used at a draw point for loading MTI DT 1604 trucks.

Preparation of the vehicle for the study

The major modifications on the vehicles/engines were those related to removal of oxidation catalytic converters for the purpose of establishing engine baseline emissions and the modifications required to install the DPF systems. The catalytic converters were temporarily removed from the vehicles and replaced with an adequate muffler. The other modification was to install a system to capture crankcase breather effluent on those engines that need it to eliminate that source of emission during control system evaluations. The Deutz BF4M1013 and BF6M1013 engines, which powered three of the tested vehicles (#92128, #92133, and #92506), are designed with a closed loop crankcase breather systems. The Caterpillar 3306 DITA engines release unfiltered crankcase emissions (primarily oil mist and exhaust blowby) to the atmosphere. For this study, Stillwater fitted the Caterpillar engine being tested with a system to filter and routed the crankcase blowby to the engine air intake.

Prior to the study all vehicles and engines had been serviced by the mine personnel using an emissions assisted maintenance program. The necessary preparations for the tests, including changes on exhaust systems, were usually made in the surface shop at Nye mine, the day before the vehicle was to be tested.

Control technologies

As previously stated, the primary objective of this study was to evaluate the effectiveness of six diesel particulate filtration systems on reducing the concentration of DPM in the underground mine environment. Additionally, the effects of replacing the currently used #1 diesel fuel with the blends of #1 diesel and “yellow grease” biodiesel (B20 and B50) and with #2 diesel were investigated. The effects of catalytic converters on diesel emissions were also examined.

Diesel particulate filter systems

Several state-of-the-art diesel particulate filter (DPF) systems were evaluated during this study. Two of the DPF systems, Engelhard DPX installed on #92128 and DCL MineX installed on #99942, were selected from a list of equipment already being used at Stillwater mine (Table 1). In addition, the other four DPF systems, CleanAir Systems DPF installed on #92133, DCL Blue Sky installed on #92506, Mac's Mining Repair/Donaldson installed on #92506, and ECS Cattrap installed on #92526 were selected, retrofitted to the selected vehicle, and evaluated in this study (see Table 2).

Table 1. The vehicles and DPF systems from Stillwater inventory equipped with DPF systems prior to the study

Vehicle #	Vehicle Type	Engine Manufact.	Engine Model	Vent Rate [cfm]	DPF Manufact.	DPF Model	DPF Brand Name	DPF Media Type	DPF Media Size [in X in]	DPF Regen- eration
91580	Locomotive	Deutz	BF6M 1013FC	12,000	Engelhard	9308	DPX	Cordierite	10.5X12	platinum washcoat
91582	Locomotive	Deutz	BF6M 1013ECP	12,000	Engelhard	9308	DPX	Cordierite	10.5X12	platinum washcoat
92054	WAGNER ST-2D LHD	Deutz	BF4M 1013 FC	8,000	DCL	5C57 11	MINE-X	Cordierite	9X12	platinum washcoat
92122	MTI DT-1604 haul truck	Deutz	BF4M 1013FC	N/A	Engelhard	9308	DPX	Cordierite	10.5X12	platinum washcoat
92128	MTI DT-1604 haul truck	Deutz	BF6M 1013FC	12,000	Engelhard	9308	DPX	Cordierite	10.5X12	platinum washcoat
92130	MTI DT-1604 haul truck	Deutz	BF6M 1013ECP	12,000	Engelhard	9308	DPX	Cordierite	10.5X12	platinum washcoat
92131	MTI DT-1604 haul truck	Deutz	BF6M 1013ECP	12,000	Engelhard	9308	DPX	Cordierite	10.5X12	platinum washcoat
92135	MTI DT-1604 haul truck	Deutz	BF6M 1013ECP	12,000	Engelhard	9308	DPX	Cordierite	10.5X12	platinum washcoat
92140	EJC 515 haul truck	Deutz	BF6M 1013ECP	12,000	Engelhard	9308	DPX	Cordierite	10.5X12	platinum washcoat
92535	ELPHINSTONE R-1300 LHD	CAT	3306 DITA	10,000	DCL	5C57 11	MINE X	Cordierite	9X11	platinum washcoat
92608	MTI LT-270 LHD	Deutz	BF4M 1012C	6,500	DCL	5C57 11	MINE X	Cordierite	9X12	platinum washcoat

Table 2. The vehicles from Stillwater Nye mine inventory that were retrofitted with DPF systems as part of the study

Vehicle #	Vehicle Type	Engine Manufact.	Engine Model	Vent. Rate [cfm]	DPF Manufact.	DPF Model	DPF Type	DPF Media	DPF Media Size [in x in]	DPF Regeneration Concept
92128	MTI DT-1604 haul truck	Deutz	BF6M 1013FC	12,000	Engelhard		DPX	Cordierite	10.5 X 10	platinum washcoat
92133	MTI DT-1604 haul truck	Deutz	BF6M 1013ECP	12,000	Clean Air Systems	FPA 158W	-	Cordierite	11.25X 14	platinum washcoat + Ce-Pt fuel borne catalyst
92506	MTI LT-350 LHD	Deutz	BF4M 1013C	11,500	DCL	3211-SA-6CG1-21	BlueSky	Silicon carbide	10.5" X 10"	catalyzed + on-board electrical regeneration
92506	MTI LT-350 LHD	Deutz	BF4M 1013C	11,500	Donaldson	P604516	-	High temp. disposable		disposable washable
92526	Elphinstone R-1300 LHD	CAT	3306 DITA (165 hp)	10,000	ECS	CT28	Cattrap	Cordierite		base metal washcoat + off-board electrical regeneration
99942	Elphinstone R-1500 LHD	CAT	3306 DITA (220 hp)	15,000	DCL	5C5711	MineX	Cordierite	9X11	platinum washcoat

Engelhard DPX DPF System

The Engelhard DPX® DPF (Engelhard Corporation, Iselin, New Jersey) (Figure 1) uses a Corning cordierite wall-flow monolith filter element which has been "washcoated" with a proprietary platinum-based catalyst. Theoretically, the DPF should passively regenerate during an engine's duty cycle if the exhaust temperature is over 350 °C for an extended period (at least 30 % of the engine's operating time) of the cycle. Although the system is designed primarily for control of diesel particulate matter emissions, significant reductions in emissions of carbon monoxide and unburned hydrocarbons are expected due to a significant presence of the platinum-based catalyst. As some recent studies suggested [Schnakenberg and Bugarski, 2001], platinum washcoated filters are found to promote the (undesired) oxidation of nitric oxide to nitrogen dioxide. Such DPFs should be carefully considered prior to their use in underground mining applications. Although several similar systems were used on the production vehicles at Nye mine for extended periods of time, NO_2 emissions have not been quantified by mine personnel and had not been found to be a serious problem in the prevailing ventilation.

Figure 1. Engelhard DPX DPF system on the truck #92128

CleanAir Systems DPF System

The CleanAir Systems DPF system (CleanAir Systems, Santa Fe, New Mexico) (Figure 2) uses a Corning cordierite wall-flow monolith filter element which has been “washcoated” with a proprietary platinum-based catalyst. The system is used in conjunction with a fuel additive (Clean Diesel Technology, Stamford, Connecticut, Platinum Plus DFX-DPF) a bimetallic catalyst that contains both platinum and cerium which allows it to be used effectively at a dosage level substantially lower than other fuel borne catalysts. Theoretically the system, with this fuel-borne catalyst, should passively regenerate during the engine’s duty cycle if the exhaust temperature is over 330 °C for extended periods (at least 30 % of the operating time) of the cycle. The system was designed to provide DPF regeneration for duty cycles having relatively low exhaust temperatures. According to the manufacturer this system should not significantly increase nitrogen dioxide emissions.

The fuel additive was mixed into the fuel tank of the #92133 during the fueling. The recommended dosage of 30 ounces for 125 gallons of fuel was used.

The system was delivered several weeks prior to the study and had accumulated approximate 200 hours of run time prior to the testing.

Figure 2. CleanAir Systems DPF System on the truck #92133

DCL BlueSky™ DPF System

The DCL BlueSky™ (DCL International, Concord, Ontario) system (Figure 3) is designed as an active system that does not completely regenerate during the duty cycle and therefore requires periodic removal of soot using integral electrical heaters and an off-board regeneration station to provide controlled heater power and compressed air for soot combustion. During the regeneration process the vehicle needs to be parked next to the regeneration station that is connected to power and compressed air supplies. The system uses a silicon carbide wall-flow monolith filter element that allows relatively short 2-hour regenerations. The frequency and length of regeneration sessions is dependant on engine DPM emissions which depend upon engine design, condition, and nature of the duty cycle.

This particular system was made available for this study by the Stillwater East Boulder mine. The system was decommissioned from the original application prior to this study because of the inability of operators to regenerate the DPF due to failed heating elements. The heating elements were replaced, and the system was installed on LHD #92506 (see Figure 3). Owing to the limited space available on the vehicle, this system was installed with a temporary arrangement and used only during the evaluation in the isolated zone and shop. The system was removed immediately after the tests, and it was not evaluated in the production because, in part, the mine was unable to provide the necessary infrastructure in production zones to support electrically regenerated systems.

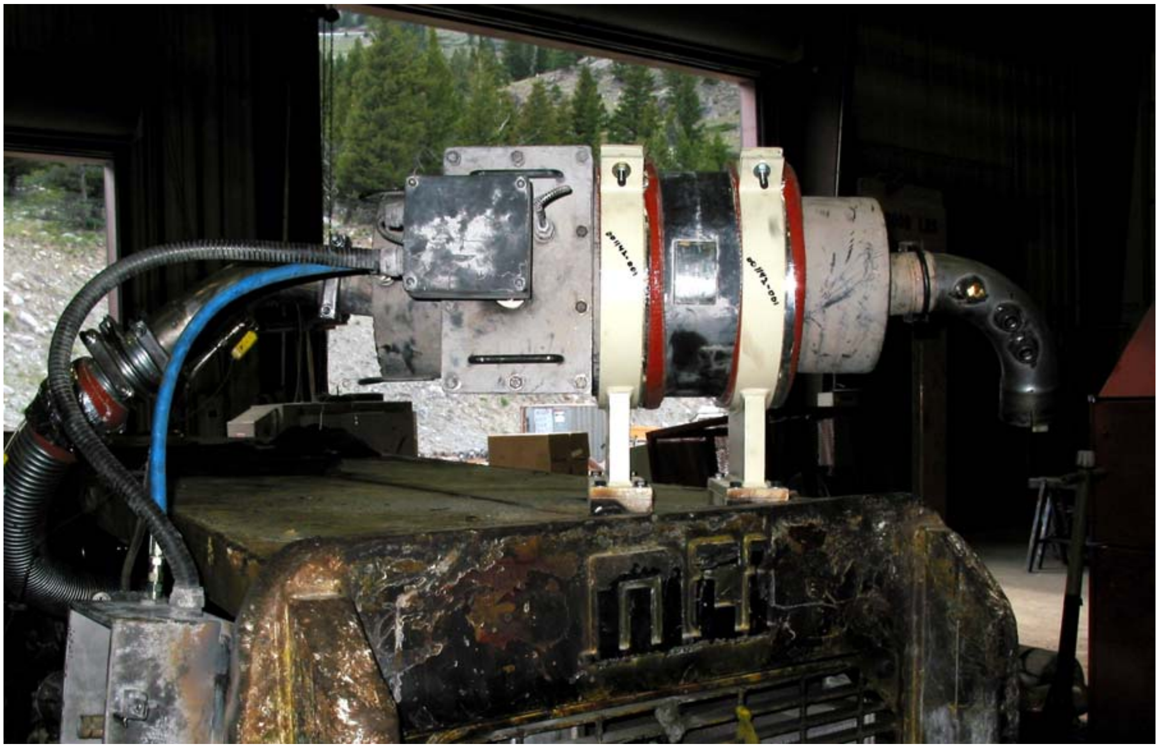

Figure 3. DCL BlueSky DPF System on the LHD #92506

Mac's Mining Repair/Donaldson P604516 Filtration System

This filtration system is in the developmental stages and uses two Donaldson P604516 (Donaldson Company Inc, Minneapolis, Minnesota) high temperature disposable filter elements. Two filter elements were evaluated as part of a temporary setup that was custom fitted to the Deutz BF4L1013 engine that powered the LHD #92506 (Figure 4). Since these filter elements were designed to handle between 300 and 400 scfm of exhaust it was necessary to fit two filter elements in parallel to handle the engine exhaust flow rate. The elements were fitted into dual stainless steel canisters designed and built by Mac's Mining Repair, Huntington, Utah.

Figure 4 . Mac's Mining Repair/Donaldson P604516 filtration system on the LHD #92506

The filter element is a deep bed filter that collects particulate matter throughout its entire depth. The filter medium has a high porosity or permeability and generates relatively low exhaust backpressure when new. The medium is resistant to heat, water, and/or other combustion by-products. Specifications of the filter sub-components provide for appropriate levels of product durability at varying time and temperature levels. Though not specifically endorsed by the manufacturer, the filter may be cleaned allowing for limited re-use. At the time of the study, the filter elements and medium were at development stage and they were not available on the market. The filtration system was removed from #92506 shortly after the trial. The filter was not run prior to the test (degreened) and one could expect it to show lower filtration efficiencies in the first hour than for the remaining hours of its life.

ECS Cattrap™ DPF System

ECS (Engine Control Systems, Newmarket, Ontario) designed the Cattrap™ system (Figure 5) as a retrofit to the load-haul-dump #92526. It is a passive system that uses a base metal catalyst coated cordierite monolith which would partially regenerate during engine operation but might also require periodic cleaning, using the ECS CombiClean ™ regeneration station. Theoretically the system should passively regenerate during the duty cycle if the exhaust temperatures are over 390 °C for a significant portion (at least 30 %)

of the engine operating time. The frequency of the periodic cleaning is dependant on the ability of this system to regenerate during the cycle. The exhaust temperature traces generated during the pre-selection period indicated that exhaust temperatures were sufficient over the duty cycle of #92526 to support almost complete regeneration. The manufacturer predicted that cleaning would be necessary approximately every 250 hours, the same period as scheduled preventive maintenance sessions, but the actual frequency of the regeneration sessions was supposed to be established empirically after the filter was installed and the vehicle was operated over an extended period of time.

The ECS CombiClean™ cleaning station consists of a vacuum that effectively removes soot and ash from filters without allowing any contaminants to escape into the air followed by a controlled thermal regeneration using electric heaters. The filter needs to be removed from the vehicle and placed on the cleaning station. The complete cleaning process takes approximately eight hours because of the thermal sensitivity of the cordierite DPF element.

The DPF system tested at #92526 included a diesel oxidation catalyst (DOC) mounted downstream of the DPF. The DOC is designed to reduce emissions of carbon monoxide and unburned hydrocarbons.

The system was delivered and installed during the first week of testing. Therefore, the system had only approximately two days in the service prior to testing. The system was decommissioned shortly after the trial.

Figure 5. ECS Cattrap DPF system on the LHD #92526

DCL MineX SOOTFILTER® DPF System

DCL MINE-X SOOTFILTER® DPF system (DCL International, Concord, Ontario) (Figure 6) that was tested on LHD #99942 uses a platinum wash-coated cordierite filter element. This system is very similar to the Engelhard DPX DPF system and, in general, they should behave similarly.

Figure 6. DCL MineX Sootfilter® DPF System on the haul truck #99942

The DCL DPF system was initially installed and had accumulated approximately 800 hours on vehicle #92535. After the system failed to passively regenerate over the production cycle of #92535, it was cleaned and reinstalled on LHD #99942.

DPF selection rationale

NIOSH and the partners desired to obtain data on the filtration media used in commercially available DPFs and a novel disposable medium which showed promise. The media were the following: 1) a cordierite wallflow monolith from Corning used by Engelhard DPX, CleanAir Systems, ECS Cattrap, and DCL Mines, 2) a silicon carbide wallflow monolith from Ibiden used by DCL for BlueSky), and 3) disposable high temperature pleated "paper" medium from Donaldson. The detailed description of the cordierite and silicon carbide monolith media is available elsewhere [Schnakenberg and Bugarski 2002, DieselNet]. A short description of the Donaldson medium is given in the section on the Mac's Mining Repair/Donaldson P604516 Filtration System.

The other dimension of this study was to test DPF systems that employ both passive and active regeneration schemes. The Engelhard DPX, DCL Mines, and CleanAir Systems DPF systems are passive systems. The CleanAir Systems DPF was selected because it showed promise of having wide applicability because of its low regeneration temperature. It uses a unique combination of a light wash-coat of a platinum-based catalyst and a cerium-platinum-based fuel borne catalyst. The system presented a viable alternative to platinum-catalyzed DPF systems such as Engelhard DPX and DCL MineX that are known for their tendency to increase secondary emissions of nitrogen dioxide. The DCL

BlueSky system is an active system which required the off-shift return of the vehicle to a regeneration station. This and similar active DPF systems have been rejected so far by mine operators on the presumption that their operation would be excessively complicated and demanding. The ECS Cattrap can be generally classified as a active/passive system, because, although it requires regeneration, the period of regeneration corresponds to regular engine maintenance and poses little operational burden. The Mac's Mining Repair/Donaldson P604516 uses two disposable filters and may be washed but is intended to be replaced, not regenerated. Coal mine tests are reporting 100 hours of operation before the filter needs to be replaced or washed.

The newly introduced DPF systems were installed on the vehicles and used in the production for at least two days prior to the testing in the isolated zone. This time was used to 1) verify the performance of the system with respect to DPF regeneration, 2) examine various operational issues and 3) condition the DPF medium. The Donaldson filters were new and had virtually no running time on them prior to testing.

The mine has been successfully operating passive DPF systems on heavy-duty trucks that were generally experiencing higher engine loads. Their experience with medium and light-duty vehicles has not been as positive because passive DPF systems installed on such vehicles have failed to reliably regenerate. Therefore, mine officials have been intensively searching for a solution for these vehicles.

Fuel formulations

All the diesel-powered vehicles used in underground operations at Stillwater Nye mine are fueled with #1 diesel supplied by local refinery (Cenex, Columbus, Montana). This particular fuel exceeds MSHA requirements [30 CFR 57. 5065 1995] for diesel fuels used in underground mines. #1 diesel is significantly more expensive than #2 diesel. Using #1 instead of # 2 diesel was part of the mine's efforts to reduce exposure of underground miners to diesel emissions. At the request of the mine, NIOSH included a test of #2 diesel fuel.

The neat biodiesel for this study was supplied by Griffin Industries, Cold Spring, Kentucky (Biodiesel G 3000). The B20 and B50 blends were made at the surface shop at the Nye mine. The quantities of #2 diesel and neat biodiesel in the blends were determined volumetrically.

Figure 7. Mixing and storage vessels for B20 and B50 biodiesel #2 diesel fuel blends

The #2 diesel that is used by diesel-powered vehicles for surface operations at the Stillwater Nye mine was supplied from the same refinery as #1 diesel.

The fuel samples of #2 diesel, B20 (20% biodiesel and 80 % #2 diesel) and the selected fuels were sent for detailed analysis to Southwest Research Institute (SwRI), San Antonio, Texas. The selected properties of the fuels are summarized in columns 4 through 6 in Table 3. The Cenex refinery provided some limited data on the properties of their fuels supplied to the Nye mine (see **Error! Reference source not found.** columns 7 and 8). Griffin Industries also provided a certificate of the analysis for the biodiesel G3000 they supplied. Some of the information from the certificate is included in Table 3**Error! Reference source not found.** (see column 9)

Table 3. Results of fuel analysis

Type of analysis	**Method**	**Units**	**SwRI**			**Cenex**		**Griffin**
			#2 diesel	**B20**	**B50**	**#1 diesel**	**#2 diesel**	**B100**
1	2	3	4	5	6	7	8	9
Cetane Number	ASTM D613	N/A	43.2	47.6	51.5	42.8	43.2	53.5
Hydrocarbon Type								
Aromatics	ASTM D1319	Vol %	30.9	N/A	N/A	N/A	N/A	N/A
Olefins		Vol %	2.1	N/A	N/A	N/A	N/A	N/A
Saturates		Vol %	67.0	N/A	N/A	N/A	N/A	N/A
Density	ASTM D4052	g/ml	0.85	N/A	N/A	0.82	0.85	N/A
Sulfur Content	ASTM D5453	ppm	299	238	159	125	366	25
Nitrogen Content	ASTM D4629	ppm	28.0	36.3	43.4	N/A	N/A	N/A
Oxygen	By difference	% wt.	NA	2.49	5.56	N/A	N/A	N/A
Heat of Combustion	ASTM D240	BTU/ lb	18335	17853	17164	N/A	N/A	N/A
Flash Point	ASTM D93	°C	71.1	73.3	78.9	57.2	66.1	>120
Viscosity, 40 °C	ASTM D445	mm^2/s	NA	2.61	3.25	N/A	N/A	4.65

A 500-gallon tank (Figure 8) with fuel for this study was temporarily located in the isolated zone in a sealed-off crosscut about halfway in the test course on 52E. A hand pump was used to transfer fuel to the fuel tanks of the test vehicles. The volume of the transferred fuel was measured using an electronic fuel meter (Great Plains Industries, Wichita, Kansas). The reservoirs on the tested vehicles were filled to the same level prior to and after each test. The measured values were used to estimate fuel consumption of the tested vehicles.

The fuel consumption of the engine powering #92526 was measured using a portable fuel metering system (Max Machinery, Series 710, Model 213). The capacity of the fuel metering system was not sufficient to measure the fuel consumption of Deutz engines powering #92128, #92133, and 92506, because an excess of fuel was supplied to those engines for the purpose of cooling the cylinders. The electrical components of the fuel metering system failed during the test on #99442 with #2 diesel fuel.

Figure 8. Fueling station in isolated zone

The initial plan was to fill the 500-gallon tank in the isolated zone with #1 diesel and use it as the baseline fuel for this study. Unfortunately, the tank was filled with # 2 diesel from the large surface reservoir designated for use by surface vehicles. The estimated percentages of #1 and #2 diesel fuels in the #1diesel/#2 diesel blends supplied to the test vehicles are given in Table 4. The fuel tanks of the vehicles used for tests with biodiesel blends and #2 diesel were drained prior to the tests and fueled from the verified sources. The tests involving LHD #99942 were run after the mistake with filling the supply tank with #2 diesel was discovered. The appropriate fuels were dispensed to the reservoir of LHD #99942. For the tests intended to show the difference between #1 and #2 diesel fuels with LHD #92506, the fuel actually differed very little (89.6 vs. 100 % #2 diesel) and these tests can serve to demonstrate the repeatability of the isozone test method. The effects of the two fuels on the emissions were examined during the tests involving #99942 but this time with fuel from the verified source.

Table 4. Fuel used in this study

Vehicle	Test	Exhaust System Configuration	Date	Fuel
#92128	Baseline	Muffler	05/26/03	#1 (27.5%) / #2 (72.5%) diesel
	DPF	Engelhard DPX	05/26/03	#1 (47.3%) / #2 (52.7%) diesel
#92133	Baseline	Muffler	05/22/03	#1 (19.1%) / #2(80.9%) diesel
	DPF	CleanAir Systems	05/22/03	#1 (31.4%) / #2(68.6%) diesel

Vehicle	Test	Exhaust System Configuration	Date	Fuel
#92506	Baseline #1 diesel	Muffler	05/23/03	#1 (10.4%) / #2 (89.6%) diesel
	Baseline #2 diesel	Muffler	05/23/03	#2 (100%) diesel
	DPF	DCL BlueSky	05/21/03	#1 (75.0%) / #2 (25.0%) diesel
	Disposable DPF	Donaldson P604516	05/23/03	#1 (14.7%) / #2 (85.3%) diesel
#92526	Baseline #1 diesel	Muffler	05/27/03	#1 (74.1%) / #2 (25.9%) diesel
	Baseline/ DOC	DOC and muffler	05/27/03	#1 (52.2%) / #2 (47.8%) diesel
	DPF	ECS Cattrap	05/24/03	#1 (94.8%) / #2 (5.2%) diesel
	Biodiesel B20	DOC and muffler	05/28/03	#2 (80.0%) / bio (20%) diesel
	Biodiesel B50	DOC and muffler	05/28/03	#2 (50%) / bio (50%) diesel
#99942	Baseline #1 diesel	Muffler	05/29/03	#1 (100%) diesel
	Baseline #2 diesel	Muffler	05/30/03	#2 (100%) diesel
	DPF	DCL MineX	05/29/03	#1 (100%) diesel

The 1-gallon biodiesel fuel samples for the analysis at SwRI (San Antonio, Texas) were collected from the 55-gallon drums containing B20 and B50 blends. A sample of #2 diesel fuel was also collected for the similar analysis conducted by SwRI

Griffin Industries also provided a certificate of analysis for the biodiesel G3000 they supplied. Some of the information from the certificate is included in Table 3 (see column 9)

Isolated zone testing

The major part of this study was dedicated to establishing performance of the selected control technologies using isolated zone testing. These tests were designed to be a compromise between the genuineness of in-situ measurements of concentrations and corresponding exposures, and repeatability and accuracy of the emissions measurements conducted under research laboratory conditions. The Isolated zone tests allowed the operation of vehicles under conditions and over duty cycles that closely mimic actual production duty cycles. In addition, these tests were not compromised by artifacts usually generated in laboratory conditions while attempting to simulate real-life conditions and processes. Conversely, laboratory accuracy and repeatability cannot be matched in isolated zone testing primarily because engines loaded by vehicles and controlled by humans rather than by tightly controlled loads provided by an engine dynamometer.

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 zone with and without control technologies. 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. The efficiency of each aftertreatment system was determined by comparing the pollutant concentrations with the system installed to those concentrations resulting from operating the same vehicle over the same duty cycle with only a muffler. In the tests designed for the assessment of the effects of fuel formulations, the emissions from the vehicles fueled with alternative fuels were compared to those from the same vehicle when fueled with baseline diesel fuel.

All tests performed in the isolated zone over the 10-day study are listed in Table 5.

Table 5. List of the tests performed in the isolated zone

Vehicle	Test Type	Exhaust System Configuration	Date	Operator
#92128	Baseline for DPF	Muffler	05/26/03	Jim
	DPF	Engelhard DPX	05/26/03	Jim
#92133	Baseline	Muffler	05/22/03	Ed
	DPF	CleanAir Systems	05/22/03	Ed
#92506	Baseline for DPF s with fuel 1	Muffler	05/23/03	Chad
	Baseline for DPF s with fuel 2	Muffler	05/23/03	Chad
	DPF	DCL BlueSky	05/21/03	Charlie
	Disposable DPF	Donaldson P604516	05/23/03	Chad
#92526	Baseline for DPF and DOC	Muffler	05/27/03	Chad
	Baseline for biodiesel/DOC	Engelhard PTX and muffler	05/27/03	Chad
	DPF	ECS Cattrap	05/24/03	Chad
	Biodiesel B20	Engelhard PTX and muffler	05/28/03	Chad
	Biodiesel B50	Engelhard PTX and muffler	05/28/03	Chad
#99942	Baseline for DPF / #1 diesel	Muffler	05/29/03	John
	Baseline for DPF / #2 diesel	Muffler	05/30/03	John
	DPF	DCL MineX	05/29/03	John

Test site

The 1750-ft (533 m) isolated zone was located in 52E ramp in the east section of the Stillwater Nye Mine. The upstream end of the zone was situated approximately 492-ft (150 m) from the portal. The elevation of the portal is approximately 5000 ft (1525 m) above see level. The location of the isolated zone relative to the portal is shown in Figure 9. The average cross-sectional dimensions of the isolated zone opening were approximately 12 ft (3.6 m) by 9 ft (2.7 m). The ramp has a 9% rise towards the downstream end.

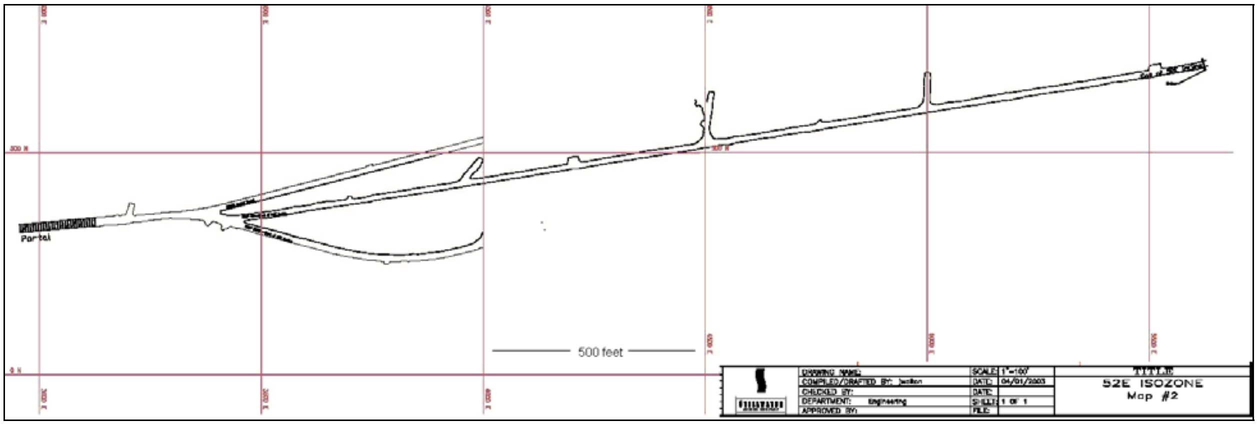

Figure 9. Isolated zone, 52E entry, Stillwater Nye Mine

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

1. It is isolated from the 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 is not be compromised by portal traffic.
4. The zone is sufficiently long and the opening is relatively small to ensure thorough air mixing at planned ventilation rates and uniform contaminant distribution across the drift at the downstream sampling station.
5. The ventilation controls allow relatively uniform air quantity adjustment and maintenance during the tests.
6. Power to operate 117VAC instruments is available at the downstream and upstream sampling stations.

The schematic of the isolated zone is shown in Figure 10 and Figure 11. The tested vehicles were operated over the simulated duty cycles between the upstream and downstream load/dump points that were approximately 1000 feet (305 m) apart. The upstream sampling station was located approximately 300 ft (91 m) upstream of the upstream load/dump point. The downstream sampling station was located approximately 450 ft (137 m) downstream of downstream sampling station. A third sampling point was located on the vehicle. The ventilation control doors were located approximately 200 ft (61m) downstream of the downstream sampling station. The refueling station was located in one of the sealed stopes half way between upstream and downstream load/dump points. Significant quantities of waste rock, sufficient to sustain duty cycle for LHD vehicles, were available on upstream and downstream load/dump points.

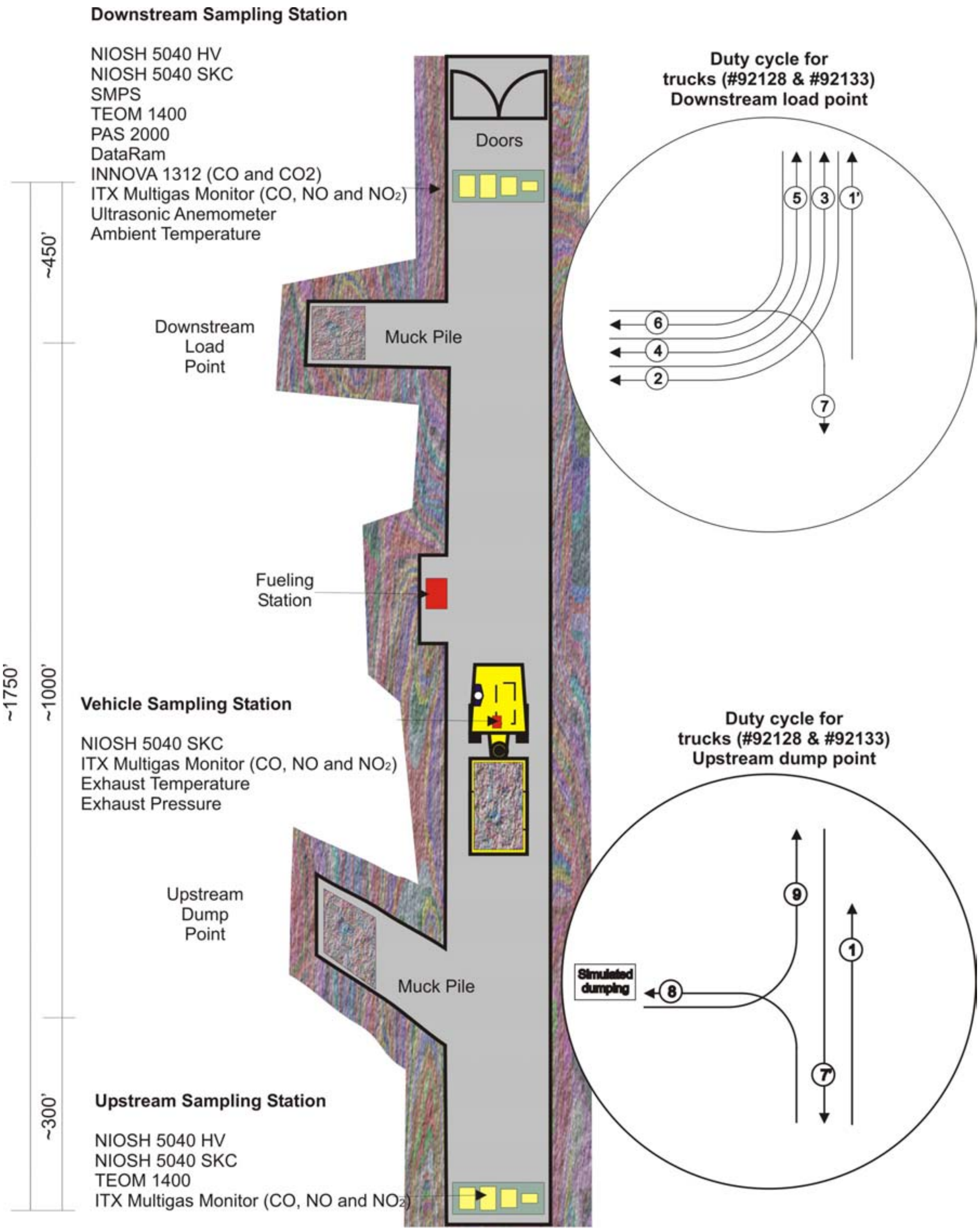

Figure 10. The isolated zone and duty cycles for the trucks #92128, and #92133

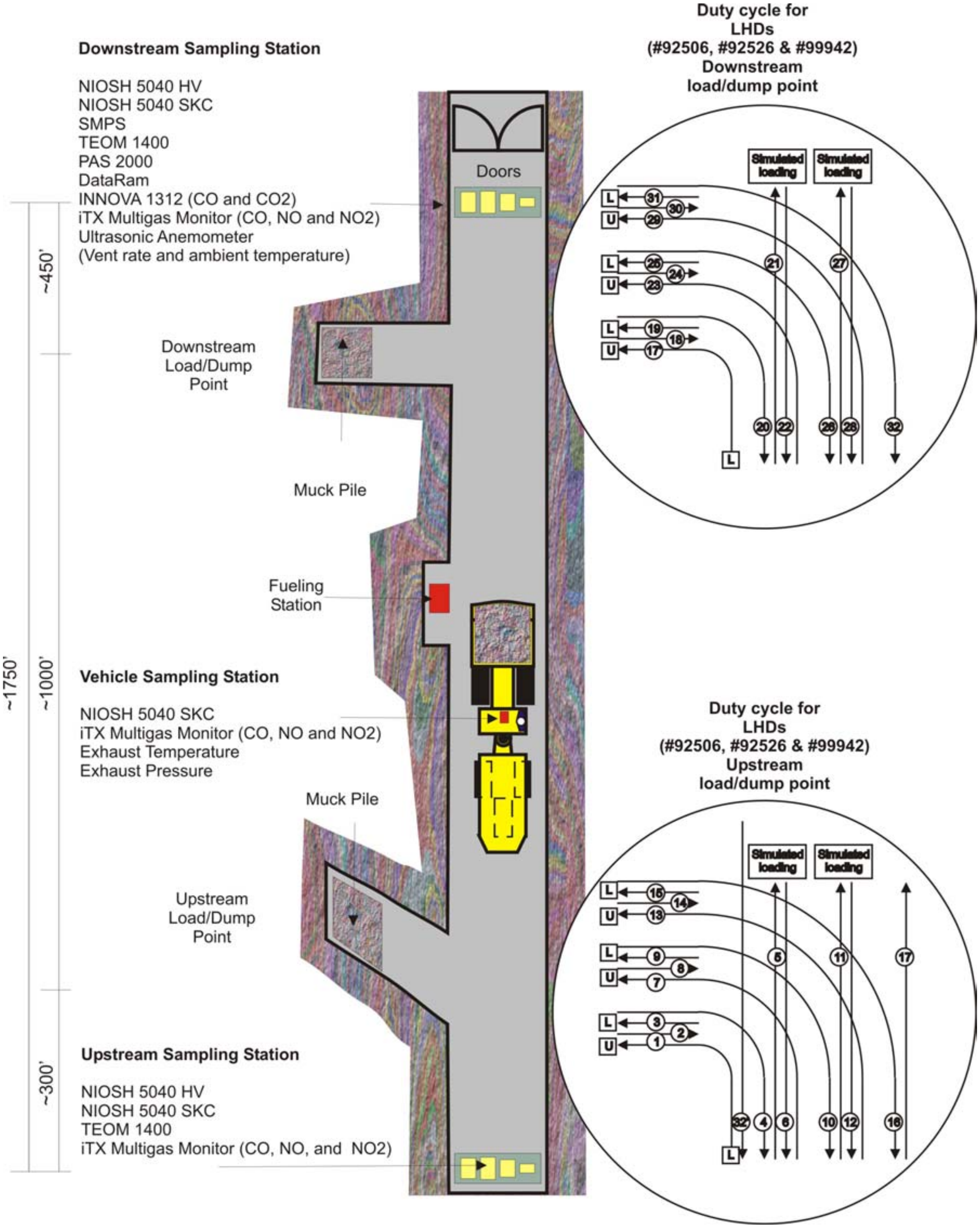

Figure 11. The isolated zone and duty cycle for the LHDs #92506, #92526, and #99942

Duty cycles

NIOSH and Stillwater Nye mine personnel, including experienced vehicle operators, developed two defined, conservative, simple and repeatable duty cycles, one for haul trucks and one for the LHDs. Both test cycles simulated a production cycle typical for the equipment.

The duty cycle for trucks

The duty cycle for trucks #92128 and #92133 is shown in Figure 10. It consisted of two major tasks simulating loading, one at the loading point and one at the dumping point, and two tramming events occurring between those points. The trucks were operated with a box loaded with ore for the entire cycle to keep the cycle simple and reduce variability. For safety reasons, the cycle was designed to keep the operator facing the direction of the travel when the trucks were tramming up or down the ramp. The trucks started the cycle at the upstream dumping point by hauling a full box of ore up the ramp to the loading point. At the loading point the operators simulated a loading cycle by repositioning the trucks for loading by an imaginary LHD. It was assumed that three buckets were required to load each of the trucks. Tramming down the ramp toward the dumping point followed the loading cycle. At the dumping point the operator simulated unloading the box by engaging the hydraulics and loading the engine at which time a new cycle would start.

Two full cycles, designated as warm-up cycles, were executed during each test prior to the start of sampling at each of the three stations. The warm-up cycles allowed the driver to become familiar with the cycle and to allow some build up of pollutants prior to initiation of sampling. The tests were usually terminated after completing number of full cycles. The duration of a complete duty cycle for trucks averaged eight minutes. The length of each test was dictated by the required time to acquire an adequate DPM sample for EC analysis.

Both the operator and vehicle were kept the same for each pair of efficiency comparison tests (see Table 5). This practice reduced potential error due created by driving habits and other human factors.

The duty cycle for LHDs

The duty cycle for LHDs #92506, #92526, and #99942 is shown in Figure 11. It consisted of two very similar major load/dump tasks, one occurring at each of the load/dump points and two tramming events occurring between those points. The LHDs started their cycles at the upstream load/dump point with the bucket loaded with ore. The operator would first take the vehicle into the upstream stope and unload the bucket, retreat for the length of the vehicle then advance forward and load the bucket again. The next step was to back the vehicle out of the stope and advance for two lengths of the vehicle up the ramp. At that location the operator would engage the hydraulics to simulate loading of an imaginary truck and then back the vehicle to the starting point. This loading operation would be repeated three times. After the third execution, the loaded LHD vehicle would tram up the ramp to the downstream load/dump point. The LHS would execute three load/dump tasks similar to that performed at the upstream location. At the end of the load/dump session at the downstream point the vehicle would tram loaded down the ramp to the upstream starting point to complete the cycle. It would then initiate a new cycle.

In each test, two full warm-up cycles were executed prior to the start of sampling. The tests were usually terminated after completing a number of full cycles. The duration of the duty cycle for LHDs averaged thirteen minutes. The length of the tests was dictated by the required time for DPM sampling.

The LHDs #92526 and #99942 were operated by the same operator throughout all tests involving those vehicles (see Table 5). The LHD #92506 was operated by the same operator for three out of four tests. A different miner operated the vehicle during the test with DCL BlueSky.

Equipment, instrumentation, and methods for ambient sampling, measurements, and analysis

The description of various equipment, instrumentation, and methods used in this study to collect particulate samples or directly measure concentrations of particulates and selected gases is given below.

Standard DPM sampling method

The sampling train used for DPM sampling was identical to the one used by Mine Safety and Health Administration (MSHA) for DPM compliance monitoring [66 Fed. Reg. 5706 and corrections 66 Fed. Reg. 35518 2001]. It consisted of a flow controlled MSA Elf Model pump from Mine Safety Appliances Company, Pittsburgh, PA, a 10 mm Dorr-Oliver cyclone, and an SKC DPM cassette from SKC, Inc., Eighty Four, PA. The SKC DPM cassette contained a single stage impactor and two stacked 37 mm tissue quartz fiber filters. The pumps were operated at 1.7 l/m. 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 II bubble flow meter from Sensydine, Clearwater, FL. If the measured flow rates deviated more than 5 percent from the 1.7 lpm the pumps were recalibrated.

Exposed SKC DPM cassettes were shipped to NIOSH PRL and analyzed by the NIOSH PRL analytical laboratory for elemental carbon content using the NIOSH 5040 Analytical Method.

High volume DPM sampling procedure

The preliminary analysis indicated that if the standard sampling procedure was used in the isolated zone study, extremely long sampling times would be required to collect sufficient material to obtain accurate carbon analysis using the NIOSH 5040 Analytical Method. Therefore, NIOSH designed a high volume sampling train (Figure 12) to accelerate the collection of adequate sample mass. This was accomplished by increasing sampling flow rate and decreasing the area of the collection filter. The sampling flow rate was increased by merging into a single stream the flows from five preclassifiers, each consisting of a 10-mm Dorr-Oliver cyclone followed by a USBM single stage diesel impactor with a 0.8 µm cut point. It was absolutely crucial to maintain flow rate of 1.7 lpm through the cyclones and impactors in order to ensure their proper size selection performance. That was achieved by designing a symmetrical plenum that distributed the total flow rate of 8.5 lpm uniformly among the five streams. Each of the preclassifier assemblies was connected to a plenum chamber by a 3-foot long section of conductive tubing. The outlet of the plenum was directly connected to a stainless steel 25-mm filter holder containing two 25-mm tissue quartz fiber filters (Tissuequartz 2500QAT, Pall Corporation, Ann Arbor, MI) placed in tandem.

The total sampling flow rate was controlled with Model HFC 302 mass flow controllers from Teledyne, Hampton VA. The mass flow controllers were calibrated by the manufacturer, and checked using a Gillibrator. The Model 0523-101Q high volume rotary vane pump from Gast Company, Benton Harbor, MI, was used to pull the sample though the filter.

The three-way valve and bypass line incorporated in the system allows steady operation of the mass flow controller and pump, and minimizes transient effects on sampling flow rates while facilitating the initiation and termination of sampling.

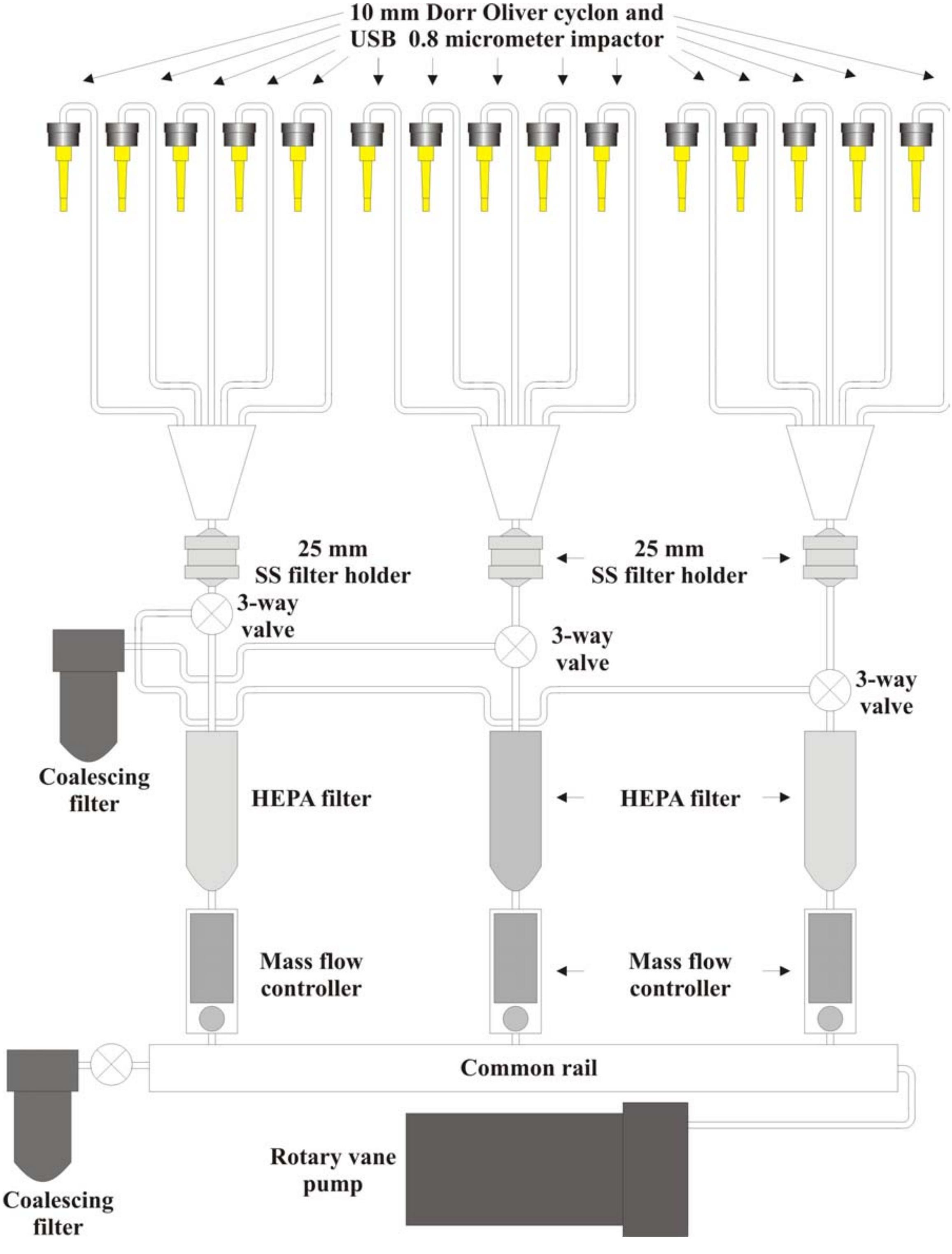

Figure 12. The high volume DPM sampling train

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

Two TEOM Series 1400a ambient particulate monitors from Rupprecht & Patashnick Co. Albany, NY, were used to provide a continual read-out of concentrations of total particulate matter (TPM) under 0.8 μm. One was located at the upstream station, the other at the downstream sampling station. The 10 mm Dorr-Oliver cyclone and USBM diesel impactor with a 0.8 μm cut-off were used as pre-classifiers. The sampling flow rate of 1.7 lpm was maintained throughout the study

The TEOM is a gravimetric instrument that draws air through a filter at a constant flow rate, while continuously weighing the filter and calculating near real-time mass concentrations. The tapered element is the heart of the mass detection system. The tapered element is in essence a hollow cantilever beam that supports a mass (the sample filter) and oscillates at a frequency that depends on the spring constant of the tapered element and the mass, a disposable filter element, at its free end. The sample stream is drawn through this filter from the hollow tapered element which is connected to the suction side of the sampling system. As particulate mass collects on the filter, the vibration frequency of the tapered element decreases. By frequent measurements of the tapered element frequency, the TEOM calculates the increase in mass that has accumulated on the filter. The concentration of TPM can be calculated by dividing the accumulated mass by the volume of air flow across the filter during the time period over which the frequency change is measured.

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

During this study the flow rate on both the upstream and downstream TEOM was set at 1.7 liters per minute. A cyclone and impactor were used as preclassifiers to the TEOM allowing only particles with average aerodynamic diameter (D_{50}) smaller that 0.8 μm. The average ambient concentrations of TPM were recorded and saved every 10 seconds. The reported concentrations were averaged over the periods required to collect particulate samples for carbon analysis using high volume sampling methodology.

Measurement of size distribution and particle numbers using a scanning mobility particle sizer

The scanning mobility particle sizer (SMPS) Model 3926 from TSI Inc., St. Paul MN, consisting of an electrostatic classifier Model 3080L and a condensation particle counter (CPC) Model 3025A, was used at the downstream sampling station to periodically measure size distribution and number of particles in the range between 10 and 392 nm.

The flow of monodispersed aerosol was maintained at 0.6 lpm throughout the study. The sheet flow was maintained at 6.0 lpm. At the established polydispersed aerosol flow rate the inlet impactor had a cut-off point of 0.46 µm. The CPC was operated in high-flow mode to minimize diffusion losses. The samples were collected using 90-second up-scan and 15-second down-scan. The instrument was operated using a dedicated laptop computer and Aerosol Instrument Manager Software (TSI Inc. St. Paul, MN).

Although the duty cycles for all tested vehicles were extremely transient, the resulting aerosol distributions in the mine air were made quasi-steady by relative movements of the vehicles and ventilation air. The effects of the technologies on size distribution and count concentrations of aerosols in mine air were assessed on the basis of the analysis performed on results of the measurements conducted while vehicles were performing the portion of the duty cycle at the downstream load/dump point, a point nearest the location of the SMPS.

The distributions and count concentrations were found to be extremely dependent on the position of the vehicles relative to the instrument.

Concentration of O_2, CO, NO and NO_2 measured by an Industrial Scientific iTX multi-gas monitor

The ambient concentrations of carbon monoxide, nitrogen dioxide and nitric oxide were measured at all three sampling locations using iTX multi-gas monitors built by Industrial Scientific, Oakdale, PA. One of the iTX multi-gas monitors was dedicated to each of the sampling location for the duration of the isolated zone testing (iTX s/n 064-downstream grid, iTX s/n 065-upstream grid and iTX s/n 199-test machine operator). The ambient concentrations were measured every 10 seconds and stored into the monitor's memory.

The iTX is a diffusion gas monitor based on electrochemical cell technology. The instrument continuously monitors and simultaneously displays all gasses sampled. The data logging capability of these monitors was used during the study.

The iTX gas monitors were calibrated with certified concentrations of Industrial Scientific branded calibration gases prior to and upon completion of isolated zone testing. Each iTX was checked between the tests by coupling it to the iTX DS1000 Docking Station. The iTX DS1000 Docking Station is an automated instrument management system which consists of a master control and PC interface station. The Docking Station provides automatic calibration and instrument diagnostics as well as maintaining instrument database records.

The iTX gas monitors were (the only instruments) removed from the Isozone at the end of each test. On surface, the logged data was downloaded to a laptop PC after each test.

Ambient concentration of CO and CO_2 measured by an INNOVA 1312 photoacoustic multigas monitor

The ambient concentrations of carbon monoxide (CO) and carbon dioxide (CO_2) at the downstream sampling station were measured by an INNOVA 1312 Photoacoustic Multi-gas Monitor (INNOVA, Naerum, Denmark). The INNOVA 1312 Photoacoustic Multi-gas Monitor uses a photoacoustic infrared detection method to measure CO and CO_2 and has a limit of detection in the ppb range. During a gas concentration measurement, a sample of air is drawn into an analysis cell within the INNOVA. The cell is then sealed off and light is sent from the infra-red source via a chopper (pulsating light) through an optical filter. The optical filter only transmits light in a defined wavelength range and this light enters the cell. If there is gas in the cell which absorbs light of this wavelength, a pressure wave is created and this is measured by microphones mounted within the cell. The greater the concentration of the absorbing gas in the cell, the greater the pressure (sound) wave it creates. The optical filter is calibrated to measure the relationship between the measured sound signal and the concentration of the absorbing gas in the cell.

The instrument was calibrated by the manufacturer and the calibration was checked before the study. The background CO_2 concentrations were determined on the basis of the 12-hour measurements conducted during the night hours when there were no diesel-powered vehicles in the zone. During each of the tests the concentrations of CO and CO_2 were measured at the downstream sampling station and stored into memory approximately every 62 seconds. The stored values were downloaded to a laptop PC at the conclusion of every test.

Measurements of exhaust temperature and engine backpressure

The exhaust temperatures upstream of the DPF systems were measured continuously during the tests using a Model KMQSS-125G-6, K-type thermocouple from OMEGA, Inc. The engine backpressure was measured using a Kavlico Model P356 differential pressure sensor built by Kavlico Corp., CA. The output from the thermocouples and pressure sensor were logged at a rate of 0.2 Hz using a MiniLogger portable data logging system from Logic Beach, La Mesa, CA and accompanying 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 at the approximate center of the drift at the downstream sampling station (Figure 13) using an Anemosonic UA6 digital ultrasonic anemometer from Airflow Developments Limited, High Wycombe, England. The anemometer sensor was located in the center of the steel grid supporting the DPM samplers. The output from the anemometer was sampled every

2 seconds. A 5-sample average was computed and stored into memory creating a log of 10-sec averages using a MiniLogger portable data logging system from Logic Beach, La Mesa, CA and accompanying software from HyperWare.

The air velocities were also measured periodically using a vane anemometer while conducting a moving traverse across the entry. The logged entry velocities were converted to air quantities by multiplying the velocity times the entry cross-sectional area. These resulting air quantities were used to adjust the downstream pollutant concentrations to a value that would prevail at the MSHA nameplate ventilation rate for the engine being tested. The MSHA nameplate ventilation rate is estimated quantity of ventilation air needed to maintain concentration of CO, CO_2, NO, and NO_2 emitted by the diesel engine bellow corresponding ACGIH TLV values for those gases. This ventilation rate is calculated on a basis of the emissions of aforementioned gases determined while engine is operated over 8 modes of ISO 8174. Normalizing the results with respect to MSHA ventilation rates was found to be advantageous for better understanding and easier comparison of the results, although metal mines including Stillwater mine are not required to provide this quantity of the ventilation air in their workings.

Figure 13. Downstream sampling station showing instrumentation and grid supporting DPM samplers, anemometer, iTX gas monitor

Analysis of the samples collected using standard and high volume method

The samples that were collected on quartz fiber filters, using standard and high volume sampling procedures, were analyzed by the NIOSH PRL analytical laboratory for elemental carbon content using NIOSH Analytical Method 5040 [NIOSH 1999, Birch and Cary 1996].

The analysis was performed following the procedure described for the carbon analyzer from Sunset Laboratories, Forest Grove Oregon. A blank (heat-treated quartz fiber filter) and sugar standard were run daily before analysis of the samples.

Calibrated punches were used to remove a section from the exposed area of a filter. The punch with a surface area of 0.72 cm^2 was used for heavily loaded samples while a punch with an area of 1.5 cm^2 was used for other samples. The cut-out is placed in to the oven of the carbon analyzer and analyzed following the procedure described in the NIOSH Manual of Analytical Methods and in Birch ME and Cary RA [1996]. The temperature steps for the OC portion were set to 200, 450, 650, and 870 °C. Typical times at each temperature were increased so that peaks for both OC and EC could be fully resolved.

NIOSH method 5040 analyzes for OC and EC in two different stages. In the first stage, the OC is measured by ramping the oven temperature over four progressively higher temperature steps programmed into the instrument, with the last step being at about 870 °C in a pure helium atmosphere. The EC does not evolve because there is no oxygen for it to react with to form a gas to evolve at the set temperature. The evolved OC is oxidized to CO_2, reduced to CH_4, and finally measured using a flame ionization detector (FID).

In the second stage, the EC is measured by reducing the oven temperature to about 600 °C and then raising the temperature back up to around 900 °C in a He/ O_2 atmosphere (oxygen is now present to react with the EC to form CO_2). The EC is then measured in the same way as the OC. The NIOSH method 5040 also corrects for pyrolysis of OC and carbonates.

Two types of samplers were used in the isozone study of control technologies. One was a high volume sampler designed by NIOSH for this study and the other was a SKC DPM cassette. Both samplers had two quartz filters placed in tandem. The first filter was used to collect particulate matter. However, the quartz filter will also adsorb vapor phase OC that is not particulate or part of DPM. The second filter behind the first filter was used to correct for this adsorbed vapor phase OC by, in theory, adsorbing the same amount of vapor phase OC as the first filter. The EC was only in particulate form and all of the EC will collect on the first filter. At this time, only the primary or first filter was analyzed.

Sampling and measurement methodology

Three sampling stations were established for each of the tests in the isolated zone. The upstream sampling station was located approximately 300 ft (91 m) upstream of the upstream load/dump point. The downstream sampling station was established approximately 450 ft (137 m) downstream of the downstream load/dump point and 200 ft

(61 m) upstream of the ventilation doors. The third sampling station was located on each of the tested vehicles.

Upstream sampling station

The following methods were used to determine concentrations of the particulate matter at the upstream station:

1. A standard sampling procedure was used to collect elemental carbon (EC) samples for carbon analysis (NIOSH Analytical Method 5040);
2. A high volume sampling procedure was used to collect particulate samples for carbon analysis (NIOSH Analytical Method 5040);
3. A TEOM Series 1400a ambient particulate monitor was used for real time measurements of total particulate matter under 0.8 µm;

An iTX Multigas monitor was used on the upstream station to measure concentrations of carbon monoxide (CO), nitric oxide (NO) and nitrogen dioxide (NO_2).

The downstream sampling station

The following methods were used to determine concentrations of the particulate matter on the downstream station:

1. The standard sampling procedure was used to collect particulate samples for carbon analysis (NIOSH Analytical Method 5040);
2. The high volume sampling procedure was used to collect particulate samples for carbon analysis (NIOSH Analytical Method 5040);
3. The TEOM Series 1400a ambient particulate monitor was used for real time measurements of total particulate matter under 0.8 µm;
4. The Scanning Mobility particle analyzer was used to measure size distribution and count concentrations of aerosols;
5. A PAS 2000 real-time PAH monitor from EcoChem Analytics, West Hills, CA was used for real-time measurements of concentrations of polyaromatic hydrocarbons (PAHs) and EC.

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

1. The ITX Multi-gas monitor was used for real-time measurements of concentrations of CO, NO, and NO_2 , and
2. The INNOVA 1312 photoacoustic multigas was used for real time measurements of concentrations of carbon monoxide (CO) and carbon dioxide (CO_2)

The vehicle sampling station

The vehicle sampling stations were established on the each of the sampling vehicle. The stations were located approximately two feet from the operator. At this sampling location the standard sampling procedure was used to collect particulate samples for carbon analysis. The iTX Multi-gas monitor from Industrial Scientific, Oakdale, PA was incorporated in this sampling station. It was used for real-time monitoring and recording of concentrations of CO, NO, and NO_2.

The distribution of the standard and high volume samplers across the upstream and downstream stations is shown in Figure 14.

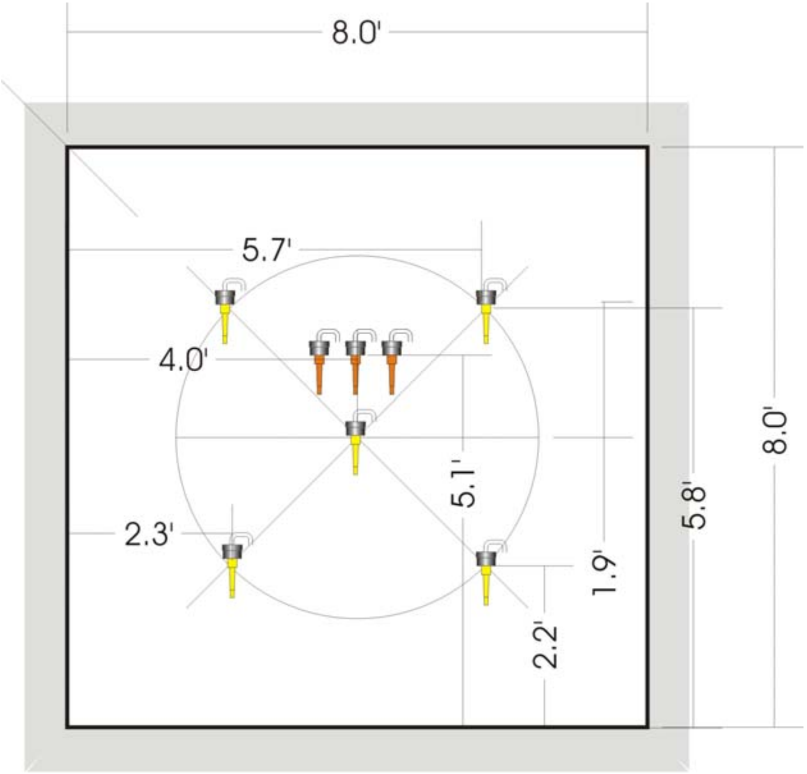

Figure 14. Distribution of samplers across sampling station showing the locations of the high volume sampling heads (in triplicate) and three standard samplers

Sampling strategy

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

1. The vehicles were brought to the fueling station prior to the tests and topped with fuel. While the vehicles were fueled, the operator would be briefed on the details of the test protocol and instructed on the duty cycles;
2. After refueling the operator would perform two warm-up cycles;
3. At the end of the second warm-up cycle the vehicles were stopped on the upstream load/dump point and all particulate matter samplers and all real time sampling instrumentation at all three sampling stations were turned on. At that time the test would officially commence.
4. The objective was to collect at least 30 μg of elemental carbon on the sampling filters used at the downstream sampling station. The length of the tests was estimated on a basis of the real-time measurements of particulate concentrations at the downstream sampling station using the TEOM 1400a. When enough material was collected on the high volume (or even the standard downstream samplers), the pumps at the downstream, the vehicle, and the upstream sampling stations would be stopped and the test would be terminated;
5. The actual sampling on and off times and total sampling times for the standard and high volume samples were recorded.
6. The sampling flow rates were checked on a daily basis and, if necessary, the pumps were recalibrated.

The measurements with real-time instrumentation were initiated prior to the beginning of DPM sampling period and stopped after the end of the sampling period for the standard samplers which usually continued beyond the sampling period for the high volume samplers.

Normalization procedure

In order for one to determine the results of the application of control technology, the test conditions for the control and the baseline to which it is compared need to be as similar as possible. In our tests, the tested technology and its baseline used the same vehicle, the same operating cycle/scenario which we created, and the same driver when possible. We initially did not attempt to use the same ventilation rate, since we were measuring ventilation and could adjust the concentrations measured to be at the same ventilation rate. We recognized that there will be differences between the baseline run and the run using control technology. In particular we thought we would need to run the tests with the control technology for a much longer period and at lower ventilation rates to ensure the collection of sufficient sample material for analysis. We also measured the amount of fuel used during each test and attempted to log the real-time fuel consumption as additional measures to ensure the similarity of the test runs by comparing the fuel consumed per one complete cycle. Lastly, we measured and logged in real time the CO_2 downstream of the test zone so that the average CO_2 concentration could be determined for the sampling period over which elemental carbon was collected.

The use of fuel consumed provides a means for adjusting the test runs to be equal in the amount of fuel used or energy consumed. For example, when comparing the baseline and control technology tests, if one of the tests used more fuel per cycle than the other, the concentrations of the larger would be reduced in proportion to the amount of additional fuel used. We have not pursued this avenue for these tests although we have the fuel consumption data.

The use of simultaneously determined carbon dioxide (CO_2) concentrations as a means for ensuring similarity of testing is perhaps the best method to ensure that the control technology is being compared on equal footing between baseline and test run. This concept originated in contract work of the Bureau of Mines and Michigan Technology University in the early 1980's. The assumption is that the emissions of a particular pollutant (gas or DPM), when divided by the fuel used, would be a constant for a particular duty cycle (such as the ones we defined for the Isozone testing). The amount of fuel used is directly proportional to the CO_2 emissions; that is, the ratio of DPM emissions to CO_2 emissions is a constant. The relationship also includes the assumption that the control technology does not alter the CO_2 concentration (true in our case), and the execution of the duty cycle is fairly consistent (the same driver for example). The major advantage is that both the DPM (and other pollutants) and CO_2 concentrations are equally affected by the prevailing ventilation; hence, there is no need to measure or account for ventilation differences between runs. With the condition that two tests are run with reasonably similar duty cycles, as our tests were, CO_2 provides the best parameter for adjusting pollutant concentrations in order to compare the effects of control technology. In the discussion below, all concentrations are *net* concentrations, that is, the concentration of the pollutant in the upstream air has been subtracted out. For CO_2, the natural background of 402 ppm has been subtracted out of the concentrations. In most instances the upstream concentration of elemental carbon, CO, NO, and NO_2 were below our detection limit.

Adjusting (normalizing) for ventilation

The process for adjusting for ventilation differences between any two runs of the same vehicle can be performed in several ways. The concept is fairly easy to grasp: for a constant tailpipe emission rate, if the ventilation is doubled the resultant concentration is halved – that is, there is an inverse relationship between concentration and ventilation. This can be expressed mathematically in the following relation for any pollutant:

Equation 1. Emission Rate relationship to dilution ventilation and resulting concentrations.

$$ER = C_1 \times V_1 = C_2 \times V_2 = C_3 \times V_3 = C_i \times V_i$$

where

ER is the pollutant tailpipe emission rate;

C_i is the *net* pollutant concentration measured at ventilation V_i; and,

V_i is the ventilation rate where the pollutant was measured. (To the degree that the Isozone is free of ventilation sources or leaks, this relationship holds.)

We chose to present both the gaseous and elemental carbon concentrations adjusted to the MSHA nameplate ventilation rate for the engine used in any particular test run. In doing this, the concentrations would be presented at a known ventilation rate so they could be useful to others who might want to perform calculations to get the concentration at a different ventilation rate, and so that the concentration would be approximately representative of that for the prevailing ventilation rate in the workplace. Thus, for example, the emission rate for a baseline test, which resulted in a measured concentration at baseline ventilation, was converted to the equivalent concentration that would be measured at the MSHA nameplate rate by the following formula:

Equation 2. Adjusting (normalizing) measured concentration to what it would be at MSHA nameplate ventilation rates.

$$\frac{C_{Test} \times V_{Test}}{V_{MSHA}} = C_{MSHA}$$

The above is applied to both the baseline and test runs for the control technology.

Control technology efficiency calculations using normalized concentrations

The basic equation for expressing the performance of a control technology to reduce a pollutant concentration is the following:

Equation 3. Fundamental pollutant reduction efficiency equation based on emission rates.

$$\text{Control Tech Efficiency (\%)} = \left(1 - \frac{ER_{CT}}{ER_{BL}}\right) \times 100\%,$$

where

ER_{CT} is the pollutant tailpipe emission rate when the control technology (CT) is being used; and,

ER_{BL} is the pollutant tailpipe emission rate without the control technology, the baseline (BL).

When the concentrations are adjusted (normalized) to the same ventilation rate as they have to be when performing this comparison, the equation becomes (for MSHA vent rates) the following:

Equation 4. Control efficiency using concentrations adjusted to MSHA nameplate ventilation rate.

$$\text{CT Efficiency}\,(\%) = \left(1 - \frac{C_{\text{MSHA}}^{CT}}{C_{\text{MSHA}}^{\text{BL}}}\right) \times 100\%\,,$$

where,

C_{MSHA}^{CT} and C_{MSHA}^{BL} respectively represent the measured concentration for the control technology test run converted to its MSHA ventilation rate equivalent and the measured concentration for the baseline test converted to its MSHA ventilation rate equivalent.

Normalizing to CO_2

As described above, Michigan Technological University espoused, and other researchers have used, the assumption that the emission rate of a pollutant divided by the CO_2 emission rate is, on the average over vehicle operation, fairly constant. Furthermore, this ratio holds for measured concentrations in the ambient air and is wholly independent of the prevailing ventilation rate. Thus we can define a parameter, an engine-specific and somewhat duty cycle specific tailpipe emission characteristic for the engine, as the ratio of a pollutant emission rate to the CO_2 emission rate. The introduction of a control technology largely affects the pollutant emission rate and not the CO_2 emission rate in most cases.

Thus the control efficiency equation becomes the following for a concentration of pollutant P:

Equation 5. Control technology reduction efficiency using characteristic pollutant-CO_2 concentration ratios.

$$\text{CT Efficiency}\,(\%) = \left(1 - \frac{\dfrac{[\text{P}]_{\text{CT}}}{[\text{CO}_2]_{\text{CT}}}}{\dfrac{[\text{P}]_{\text{BL}}}{[\text{CO}_2]_{\text{BL}}}}\right) \times 100\%\,,$$

where the "[]" designate concentrations, and CT and BL describe the control technology test and baseline runs respectively. In both instances, the background CO_2 concentration of 402 ppm must be subtracted out so that $[CO_2]$ represents the *net* increase in concentration due to engine operation.

We used this equation to compute the elemental carbon reduction efficiencies for the control technologies tested. [Note: We decided to disregard the data from several tests in which the ventilation rate was low and leakage from the isolated zone was suspected because the absolute concentrations of the CO_2 were inconsistent with runs at higher ventilation rates. However, the leakage, probably would affect both CO_2 and EC (and the gases) equally, and a control technology performance estimate could be computed using the above formula. The remaining issue is that the leak was at the midpoint of the isozone with the result that the downstream concentrations would represent different proportions of the duty cycle performed upstream and downstream of the leak for different total ventilation rates. Thus, we have chosen not to present the results of those test runs in this report.]

Exhaust emission testing

The isolated zone tests were complimented with a series of DPM and gaseous emissions measurements performed directly from the exhaust systems of the tested vehicles. The objective of the exhaust pipe emission measurements was to verify the performance of the tested engines and control technologies evaluated in the isolated zone study. The measurements were made for the majority of evaluated configurations. This part of the study was a joint effort of NIOSH and the Stillwater maintenance department. The tests took place in the main surface repair facility at Nye mine.

Engine operating conditions

The exhaust pipe emissions were obtained while each test vehicle was parked in the shop and the engine was operated under selected steady-state conditions:

1. torque converter stall (TCS) at intermediate speed, and at full throttle,
2. high idle (rated speed, no load), and
3. low idle (idle speed, no load).

These conditions were assumed to be the only safe and repeatable conditions suitable for testing an engine in stationary conditions without using a chassis dynamometer.

TCS was assumed to be the most suitable method to significantly load engines that are coupled with an automatic transmission through a torque converter. This mode can be achieved by applying the vehicle's brakes and loading the engine by making the torque converter work against a transmission that is engaged in the highest gear. Under such conditions, energy produced by the engine is converted into heat and dissipated in the torque converter system. The length of the tests at this mode was limited by the fact that the torque converter cooling system is usually not capable of dissipating the generated amount of energy for an extended period of time. In order to prevent permanent damage of the torque converter the load was taken off the torque converter when the cooling fluid exceeded a maximum allowed temperature. Because the TCS condition results in the highest engine load and consequently the highest DPM and gaseous emissions of all conditions available for testing vehicles in field conditions, it was assumed to be the most suitable for such testing

At High idle mode brakes were applied, the transmission was placed in neutral, and the engine speed was maintained at rated speed. Typically, DPM emissions were substantially lower than those found at TCS conditions.

At low idle mode brakes were applied, the transmission was placed in neutral, and engine speed was maintained at idle speed. Again, DPM emissions typically are substantially lower than those on high idle and TCS.

Equipment, instrumentation, and methods for measurement of exhaust pipe emissions

When aftertreatment systems were tested, samples were collected from sampling ports located upstream and downstream of the systems. The effects of the after treatment technologies on the emissions were determined by comparing results obtained from the sampling ports located upstream and downstream of the systems. In the case of tests involving fuel formulations the emissions were obtained at the tailpipe for different cases. The effects were determined by comparing results of the similar tests conducted with different fuel formulations.

The inlet side of each of the test DPF systems was equipped with at least two 0.5-in NPT ports made with SS pipe couplings that were welded over a 0.5-in (13-mm) to 0.75-in (19-mm) hole in the exhaust pipe.

All NIOSH emissions measurements were repeated at least 3 times for each of the test conditions. The test procedures remained uniform across all the engine/vehicle configurations.

NIOSH used the following methods and instrumentation for measurement of DPM and gaseous emissions in the exhaust systems of the test vehicles:

1. An ECOM Model KL portable emissions analyzer from ECOM America, Norcross, GA was used to measure O_2, CO, NO and NO_2.
2. The same portable emissions analyzer was used to sample DPM for Bacharach smoke number and to obtain samples on tissue quartz for carbon analysis

Stillwater Nye mine maintenance personnel used their Enerac 400 Micro-Emission Monitoring System (EMS) emission monitoring system from Energy Efficiency Systems Westbury, New York to measure O_2, CO, NO and NO_2 following their own test protocol of logging data through a single pass throughout the test conditions.

Both the ECOM Model KL and the Enerac 400 EMS utilized standard electrochemical sensors to measure concentrations of O_2, CO, NO and NO_2. The emissions of CO_2 were calculated.

Results and Discussion

Ventilation rates

NIOSH measured the ventilation rates continuously over the course of each of the tests at the downstream sampling station using a digital ultrasonic anemometer fixed to the center of the grid holding the DPM samplers. The charts of the ventilation logs are presented in Figure 15 through Figure 19.

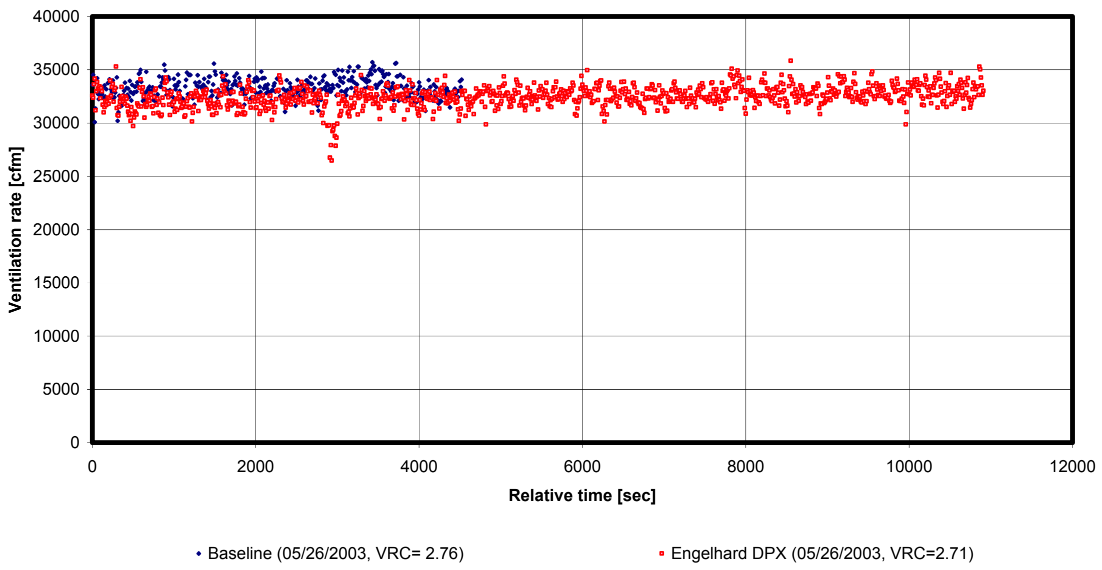

Figure 15. Ventilation rates for the tests involving #92128

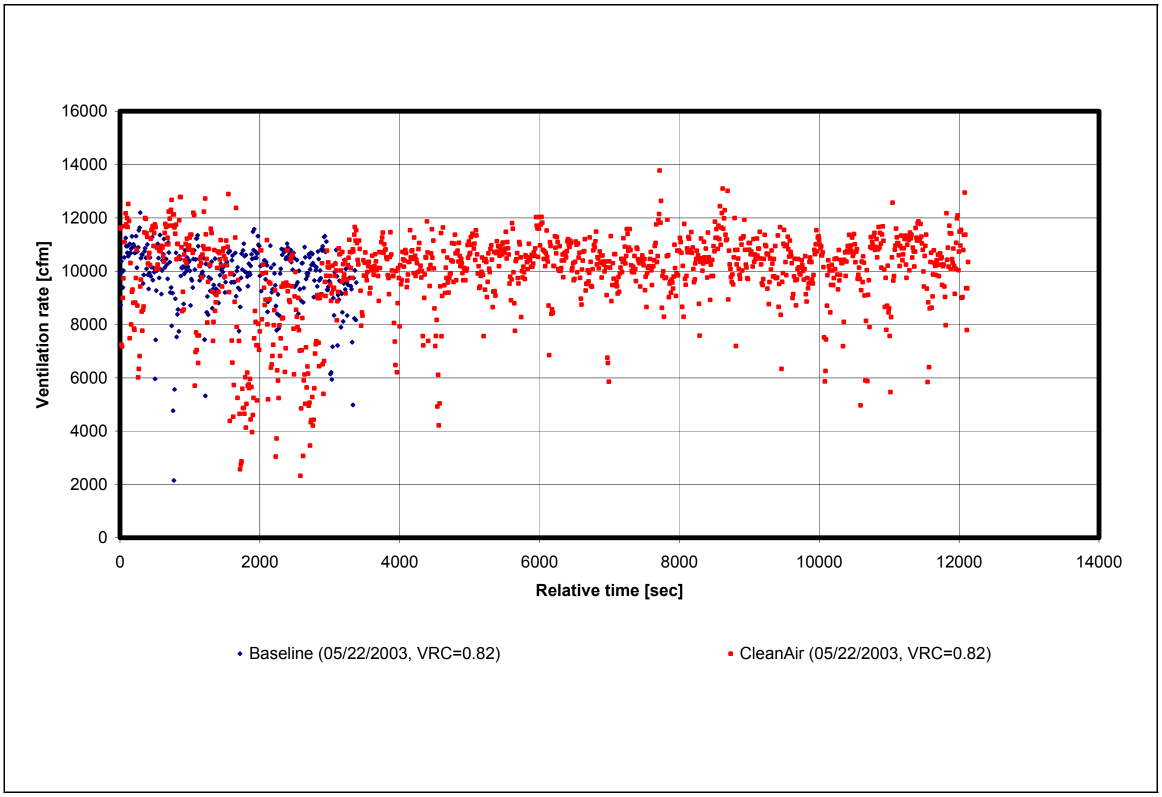

Figure 16. Ventilation rates for the tests involving #92133

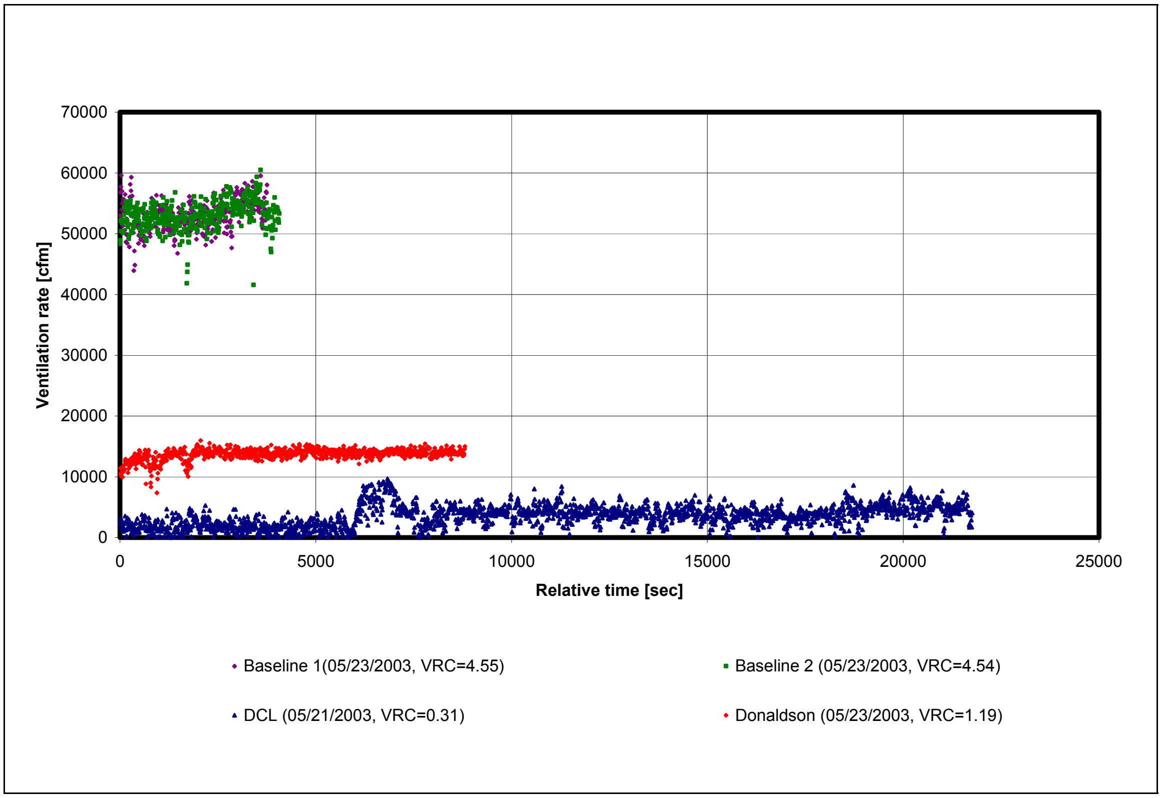

Figure 17. Ventilation rates for the tests involving #92506

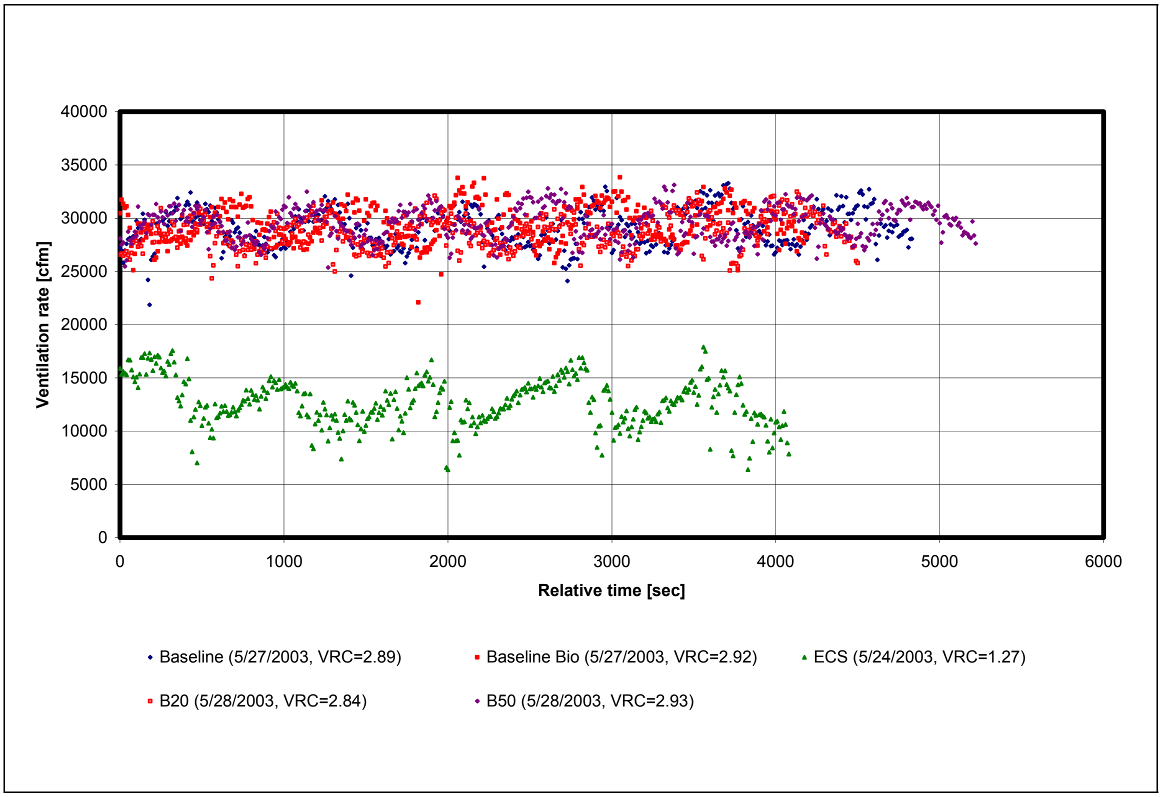

Figure 18. Ventilation rates for the tests involving #92526

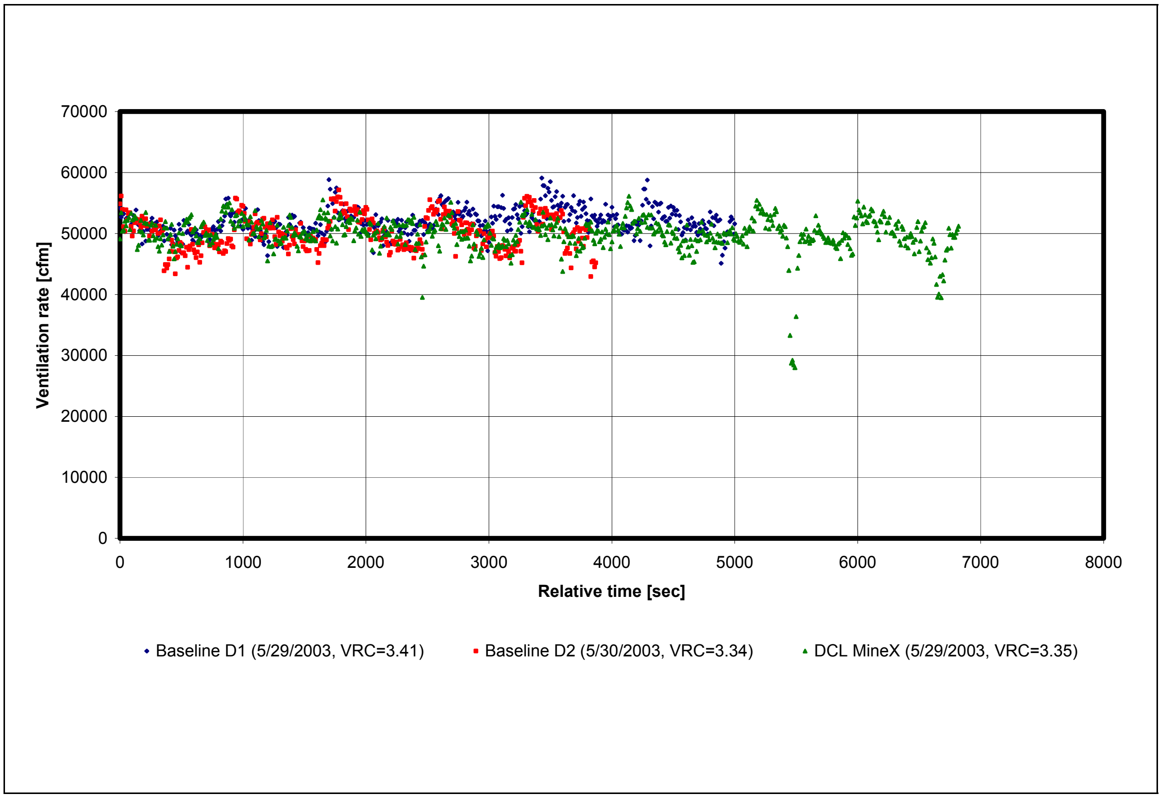

Figure 19. Ventilation rates for the tests involving #99942

The average ventilation rates normalized with respect to MSHA approved ventilation rates for the tested engines are given in Table 6.

Table 6. Average ventilation rates normalized with respect to MSHA ventilation rates and contribution of the tested vehicles/configurations to concentrations of carbon dioxide at downstream sampling station

Test type	Date	Average ventilation rates normalized with respect to MSHA ventilation rates		Contribution of the vehicles to CO_2 concentrations [ppm]	
		High volume sampling period	Standard sampling period	Maximum	Average
#92128 Haul Truck, MSHA vent 12000 cfm					
Baseline	05/26/03	2.77	2.77	3432	2522
Engelhard DPX	05/26/03	2.71	2.71	3391	2316
#92133 Haul Truck, MSHA vent rate 12000 cfm					
Baseline	05/22/03	0.82	0.82	1361	1226
CleanAir Systems	05/22/03	0.82	0.82	1487	1337
#92506 LHD, MSHA vent rate 11500 cfm					
Baseline, #1 diesel	05/23/03	4.56	4.62	5866	1702
Baseline, #2 diesel	05/23/03	4.55	4.61	5472	1799
DCL BlueSky	05/21/03	0.31	0.31	715	553
Donaldson	05/23/03	1.19	1.19	1677	1360
#92526 LHD, MSHA vent rate 10000 cfm					
Baseline	05/27/03	2.89	2.91	7418	3297
Baseline/ PTX	05/27/03	2.92	2.95	7220	3419
ECS Cattrap	05/24/03	1.27	1.27	3291	2409
Biodiesel B20/ PTX	05/28/03	2.84	2.87	7048	3424
Biodiesel B50/ PTX	05/28/03	2.93	2.95	7220	3453
#99942 LHD, MSHA vent rate 15000 cfm					
Baseline, #1 diesel	05/29/03	3.41	3.46	8338	2447
Baseline, #2 diesel	05/30/03	3.34	3.35	8626	2459
DCL MineX	05/29/03	3.33	3.33	8254	2311

The isolated zone tests can be divided into two groups with respect to the ventilation rate that prevailed during each of the tests. During the first four days of the study (05/21 through 05/24) the ventilation rates were maintained, generally speaking, below or in the neighborhood of MSHA ventilation rates for the particular vehicle (see Figure 16, Figure 17, Figure 18, and Table 6). The ventilation rates for the rest of the tests were significantly higher than the MSHA engine nameplate ventilation rates (see Figure 15, Figure 17, Figure 18, Figure 19, and Table 6).

The tailpipe emission measurements showed that none of the tested control technologies had a significant effect on the CO_2 emissions. This and the fact that CO_2 emissions can be related to total fuel consumed by diesel engines are the reasons that ambient concentrations of CO_2 were used to examine the validity of the tests done in the isolated zone. The analysis of the results on the contribution of the vehicles to the concentration of CO_2 in mine air at the downstream sampling station (see Table 6) showed that the tests conducted while the ventilation rates were maintained below or in the neighborhood of the MSHA ventilation rates had significantly lower CO_2 contributions from the vehicles.

This is evident for the tests involving the DCL Bluesky and the Donaldson filtration systems conducted with LHD #92506 in the isolated zone and for the test involving the ECS Cattrap DPF system conducted with LHD #92626. The additional evidence of the potential problems with the tests conducted while ventilation rates were maintained below or in neighborhood of MSHA ventilation rates are the CO_2 concentrations observed for the baseline cases involving haul trucks #92128 and #92133. The tailpipe emissions measurements Table 16 showed that CO_2 emissions at high idle, low idle and torque converter stall are almost identical for those two trucks that were powered with similar model engines (Deutz BF6M1013FC and BF6M1013ECP). However, the contributions of those vehicles to the concentrations of CO_2 at the downstream sampling station were significantly different. The observed concentrations were two-fold higher for #92128 than for #92133 (see Table 6).

Since a clear explanation for the presented phenomena is not available at this time, the authors opted to analyze and discuss only the results of the isolated zone tests that were conducted while the ventilation rates were maintained significantly above the MSHA ventilation rates. The exception is the two tests conducted with haul truck #92133. Since the ventilation rates were almost identical and fairly constant during those two tests (Figure 16), the authors believe that those tests are valid and thus included the discussion on the effects of the CleanAir Systems DPF system on EC emissions in the report.

The effects of control technologies on elemental carbon concentrations

The results of the elemental carbon analysis on the samples collected using the high volume samplers are presented in Table 7 and Table 8. In Table 7, the EC concentrations were adjusted to that which would be measured when the engine-appropriate MSHA nameplate ventilation rate would prevail. The MSHA vent rate approximates the nominal ventilation for normal operating conditions. The data provides the concentration at a specific ventilation quantity from which the concentration may be computed for a different air quantity.

The coefficients of variation (CV) for the triplicate samples are also presented in Table 7. The CV represents the agreement among the three samples taken in parallel at each of the five sampling points. Sample volume, slight spatial differences in actual airborne EC concentrations and the analytical error inherent to the NIOSH Method 5040 contribute to the CV. The CVs for the elemental carbon results in this study ranged from 1.6 to 10.6 %. The CV does not take into account the uncertainty in ventilation measurement.

The primary reason for measuring airborne elemental carbon was to determine its reduction from the use of the control technologies evaluated in this study. Reduction computations were made by comparing the concentration of the contaminant of interest when operating with and without control technologies, under similar conditions. As described earlier in this report (page 38), two different methods were used to normalize the data for comparison of control technology to the baseline. The first method used ventilation rates to normalize data from different tests (see Equation 4, page39) and the results are shown in Table 7. The second method used carbon dioxide concentrations to normalize (see Equation 5, page 41) the data and these are presented in Table 8. The CO_2 concentrations used for normalization were adjusted for background CO_2 concentrations of 402 ppm. Note that with one exception, the calculated reduction efficiencies of the control technology are nearly identical for both normalization methods.

As mentioned previously, several of the tests were discarded because of unexplainably low CO_2 concentrations found at low ventilation rates. However, for the two tests on vehicle #92133, although the ventilation rates were low, they were nearly identical, resulting in identical CO_2 levels for both baseline and tests run with the DPF system. As a result of this consistency, the data for these tests were included in this report.

Table 7. Elemental carbon results normalized with respect to ventilation rates

Test type	EC		Reductions normalized by vent rate [%]
	[µg/m^3]	CV [%]	
#92128 Haul Truck, MSHA vent rate 12000 cfm			
Baseline	1182.0	5.3	
Engelhard DPX	51	3.2	96
#92133 Haul Truck, MSHA vent rate 12000 cfm			
Baseline / CDT	1038	10.6	
CleanAir Systems / CDT	15	5.3	99
#92506 LHD, MSHA vent rate 11500 cfm			
Baseline, #1 diesel	938	3.0	
Baseline, #2 diesel	1051	6.6	-12
#92526 LHD, MSHA vent rate 10000 cfm			
Baseline	1328	1.6	
Baseline / PTX	1365	2.0	-3
Biodiesel B20 / PTX	1015	4.7	26
Biodiesel B50 / PTX	703	4.3	48
#99942 LHD, MSHA vent rate 15000 cfm			
Baseline, #1 diesel	1112	7.7	
Baseline, #2 diesel	1222	4.0	-10
DCL MineX	149	2.6	88

Table 8. Elemental carbon results normalized with respect to CO_2 concentrations

Test type	EC	CO_2	EC/CO_2	Reductions normalized with CO_2 [%}
	[µg/m^3]	[ppm]	[µg/m3/ppm]	
#92128 Haul Truck, MSHA vent rate 12000 cfm				
Baseline	427	878	0.486	
Engelhard DPX	20	855	0.023	95
#92133 Haul Truck, MSHA vent rate 12000 cfm				
Baseline / CDT	1265	1499	0.844	
CleanAir Systems / CDT	18	1618	0.011	99
#92506 LHD, MSHA vent rate 11500 cfm				
Baseline, #1 diesel	206	1126	0.183	
Baseline, #2 diesel	231	1133	0.204	-12
#92526 LHD, MSHA vent rate 10000 cfm				
Baseline	459	1082	0.425	
Baseline / PTX	466	1189	0.392	8
Biodiesel B20 / PTX	358	1126	0.318	19
Biodiesel B50 / PTX	240	1133	0.212	46
#99942 LHD, MSHA vent rate 15000 cfm				
Baseline, #1 diesel	326	752	0.433	

Test type	EC	CO_2	EC/CO_2	Reductions normalized with CO_2 [%}
	[µg/m^3]	[ppm]	[µg/m3/ppm]	
Baseline, #2 diesel	366	814	0.450	-4
DCL MineX	45	745	0.060	87

The effects of control technologies on concentration of total particulate matter (TPM) under 0.8 µm

This chapter summarizes the results of the total particulate matter (TPM) measurements conducted at the upstream and downstream sampling stations using two TEOM 1400a ambient particulate monitors. A 10 mm cyclone and impactor was used as a preclassifier to eliminate all particles with an average aerodynamic diameter larger than approximately 0.8 µm. This preclassifier train was identical to those used for the high volume samplers.

The observed concentrations of TPM measured at the upstream sampling station were negligible and therefore they were not used in this analysis. The normalized TPM concentrations measured at the downstream monitoring station are presented in Table 9. These concentrations are normalized (see Equation 2, page 40) with respect to the MSHA ventilation rates specific for each of the engines powering the tested vehicles.

Table 9. Concentrations of TPM under 0.8 µm the downstream sampling station

Test Type	Concentrations of TPM [µg/m^3]		Reductions [%]
	Ave.	Max.	Ave.
#92128 Haul Truck, MSHA vent rate 12000 cfm			
Baseline	1343.9	1536.3	--
Engelhard DPX	341.7	411.6	75%
#92506 LHD, MSHA vent rate 11500 cfm			
Baseline #1 diesel	3964.1	7313.2	--
Baseline #2 diesel	N/A	N/A	--
#92526 LHD, MSHA vent rate 10000 cfm			
Baseline	1631.9	2083.0	--
Baseline / PTX	1874.6	2324.6	--
Biodiesel B20 / PTX	1698.8	2084.8	9%
Biodiesel B50 / PTX	1416.6	1800.7	24%
#99942 LHD, MSHA vent rate 15000 cfm			
Baseline #1 diesel	1433.6	2140.2	--
Baseline #2 diesel	1735.1	2739.2	-21%
DCL MineX	369.6	588.1	74%

The effects of the control technologies on TPM concentrations were expressed in terms of the percent reductions that were calculated using normalized average values, Equation 4, page 39. These results show that both the Engelhard and DCL MineX DPF systems reduced the TPM in the mine air by approximately 75%. These reductions were lower than those shown in Table 7 for EC collected on the high-volume samples (88% - 96%). However, the difference can be attributed to the fact that the TEOM measures total particulate mass gravimetrically while carbon analysis accounts only for the elemental carbon fraction of total particulate mass. It can be speculated that particulate matter in the treated exhaust contains higher fractions of sulfates, bounded water, and organic carbons than untreated exhaust. These aerosols that are transparent to the carbon analysis can contribute significantly to the total mass of PM measured by the TEOM. The TEOM results also showed that biodiesel blends have the potential to reduce the concentrations of TPM in mine air. However, as with the results from the DPF tests, the TEOM results showed a lower percent efficiency than that measured using the EC method.

The plot shown in Figure 20 presents the time trace of concentrations measured by the TEOM during the baseline test of LHD #99942. The peaks and valleys shown on this plot are due in part to the variation in vehicle duty cycle and in part to the relative position of the vehicle to the downstream sampling location. The time traces of the other measured emissions show similar trends. The near real-time TEOM data proved extremely useful as they allowed estimates of the mass of DPM collected on the filters, used for carbon analysis, at any given time during the tests. These estimates were used to determine the necessary lengths of the high-volume and the standard sampling periods.

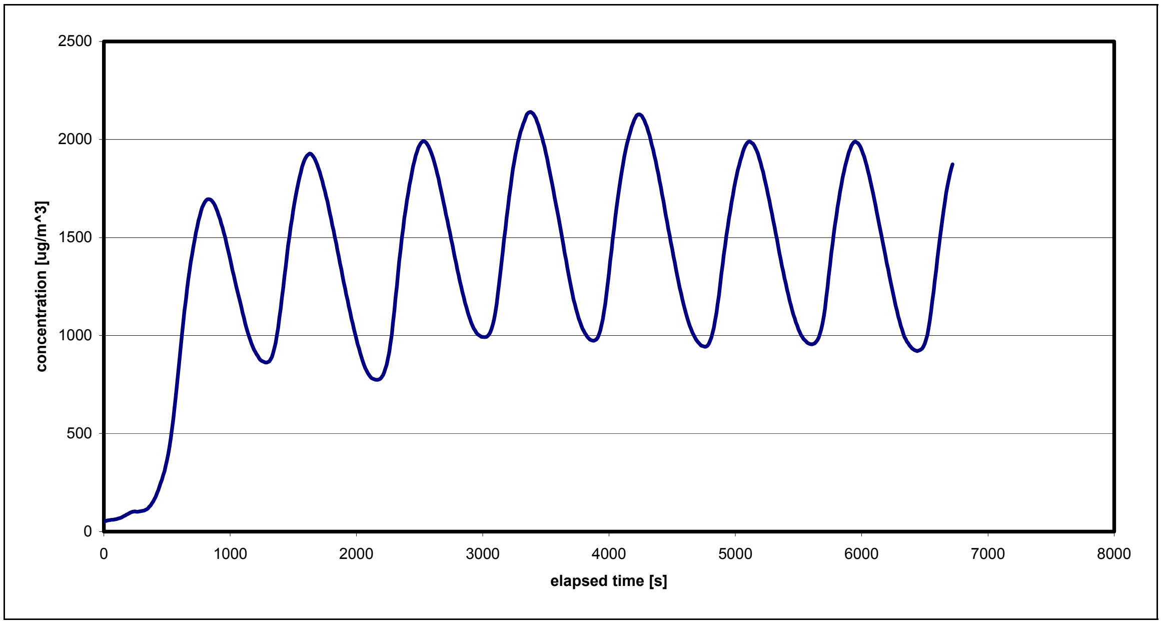

Figure 20. TPM concentrations at downstream sampling station for baseline test on LHD #99942 (5/29/03)

The effects of control technologies on count and size distribution of particles

This chapter summarizes the results of the measurements of size distributions and concentrations of aerosols at the downstream sampling station accomplished using a scanning mobility particle sizer (TSI Inc., St. Paul, Minnesota, Model 3936). Only the results of the measurements made while vehicles were performing their duties at the downstream loading/dumping point in the isolated zone are presented in this report.

The results are presented in Table 10 and Figure 21 though Figure 26. The statistical parameters and plots for two or three typical measurements are also shown for each of the test cases. The geometric means and geometric standard deviations are supplied for each of those distributions. The average geometric means and average total particulate concentrations are calculated for each set of data. The average total aerosol concentrations measured at the prevailing ventilation rates are normalized with respect to the MSHA ventilation rates specific for each of the tested vehicles. The effects of the tested control technologies on the total number of particles in the mine air are expressed as the percentage of change in total particulate count in the mine air with respect to the selected baselines. For the majority of the cases the tests where vehicles were operated with mufflers and standard fuel were considered to be the baseline cases. The exceptions were the tests that were conducted with the objective of assessing the effects of the biodiesel blends. In these cases, the test conducted with the LHD #92526 equipped with a diesel oxidation catalytic converter (Engelhard Corporation, Iselin, New Jersey, Model PTX) and muffler was considered to be the baseline.

Table 10. Effects of control technologies on concentration of aerosols in mine air

Vehicle	MSHA Vent. Rate (VR) [cfm]	Test Type	Date	Vehicle Operator	Geo. Mean [nm]	Geo. Std. Dev.	Average Geometric Mean [nm]	Average Total Particle Conc. @ MSHA VR [#/cm^3]	Change in Total Particle Conc. [%]
#92128	12000	Baseline (muffler)	05/26/03	Jim	71.64	1.83	67.28	2.88E+08	N/A
					65.84	1.83			
					64.35	1.90			
		Engelhard DPX	05/26/03	Jim	45.14	1.44	43.74	5.17E+08	79.6
					43.46	1.47			
					42.63	1.44			
#92506	11500	Baseline #1 /#2 diesel (muffler)	05/23/03	Chad	83.75	1.63	78.18	9.14E+08	
					72.61	1.68			
		Baseline #1 /#2 diesel (muffler)	05/23/03	Chad	81.34	1.66	79.91	8.23E+08	-9.9
					82.02	1.66			
					76.39	1.80			
#92526	10000	Baseline (muffler)	05/27/03	Chad	85.05	1.68	85.74	6.82E+07	N/A
					86.43	1.67			

Vehicle	MSHA Vent. Rate (VR) [cfm]	Test Type	Date	Vehicle Operator	Geo. Mean [nm]	Geo. Std. Dev.	Average Geometric Mean [nm]	Average Total Particle Conc. @ MSHA VR [#/cm^3]	Change in Total Particle Conc. [%]
		Baseline (PTX and Muffler)	05/27/03	Chad	72.22	1.75	72.40	7.32E+07	7.4
					72.59	1.74			
		Biodiesel B20 (PTX)	05/28/03	Chad	65.83	1.66	65.92	9.72E+07	32.7
					66.01	1.65			
		Biodiesel B50 (PTX)	05/28/03	Chad	63.32	1.60	61.76	9.11E+07	24.4
					60.21	1.61			
#99942	15000	Baseline #1 diesel (muffler)	05/29/03	John	74.41	1.64	75.42	3.97E+07	N/A
					76.60	1.65			
					75.24	1.65			
		Baseline #2 diesel (muffler)	05/30/03	John	81.57	1.65	81.93	4.85E+07	22.2
					81.68	1.63			
					82.53	1.63			
		DCL MineX	05/29/03	John	40.70	1.58	38.06	7.09E+07	78.7
					35.49	1.57			
					37.99	1.59			

The carbon analysis and TEOM measurements showed that dramatic reductions in mass concentrations of elemental carbon and particulate matter in mine air were achieved with the tested diesel particulate filters. Since both tested DPFs, Engelhard DPX and DCL MineX, offered dramatic reductions in the number of larger particles, it can be concluded that the size selective measurements qualitatively agree with those results (see Figure 21 and Figure 22). The size distributions of the particles that are observed for the tests with filtered exhaust are characterized with significantly lower geometric means and higher peak concentrations than the size distributions observed during the tests with unfiltered engines/vehicles. The distributions of particles generated by vehicles equipped with a muffler were characterized by geometric means (GM) ranging from 64 to 87 nm. In contrast, the distributions of particles generated by vehicles equipped with diesel particulate filters were characterized by a GM ranging from 35 to 45 nm (see Table 10). Additionally, a significant increase in the number of the particles, approximately 80 percent, was evident for both cases when mufflers were replaced with DPFs (see Table 10). Since carbon analysis shows very low mass concentrations of the elemental carbon in the samples collected during the same tests with filtered exhaust, it can be stipulated that those particles contain primarily other known constituents of DPM such as organic carbons, sulfates, and water. Unfortunately, since appropriate samples were not gathered, chemical analysis of the DPM samples is not available to confirm this hypothesis.

It is important to note that the distributions and concentrations of aerosols in the observed size range are highly dependant on the ambient conditions. The formation of aerosols could be significantly affected by the natural cooling process occurring in the isolated zone and the high relative humidity that prevailed during the tests. Average ambient temperatures of approximately 25 °C (77 °F) were recorded at the upstream sampling station and average ambient temperatures of approximately 10 °C (50 °F) were recorded at the downstream sampling station. The average relative humidity measured at the downstream station during the tests was approximately 90 %.

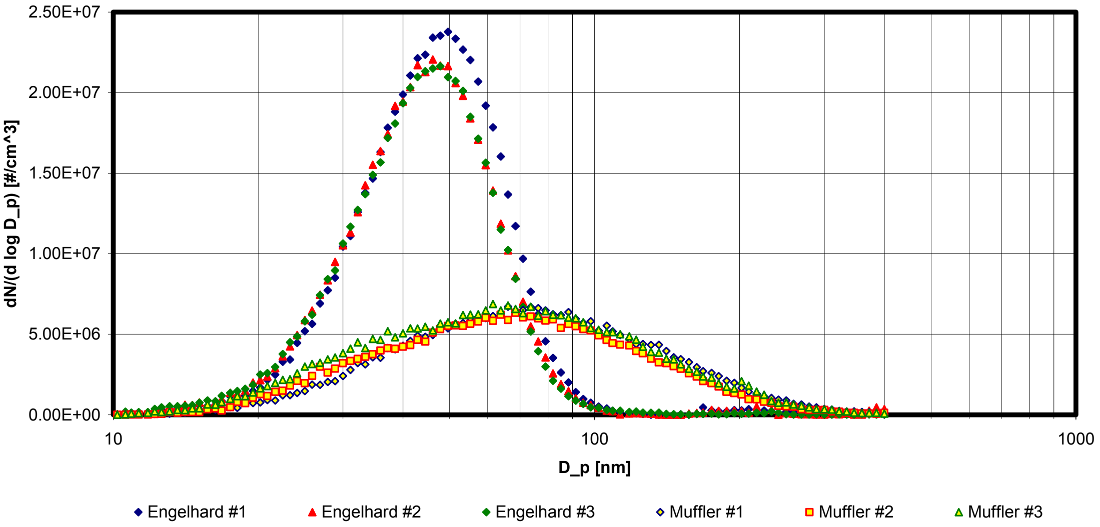

Figure 21. Size distribution of aerosols in mine air for truck #92128 - Engelhard DPX DPF vs. Muffler

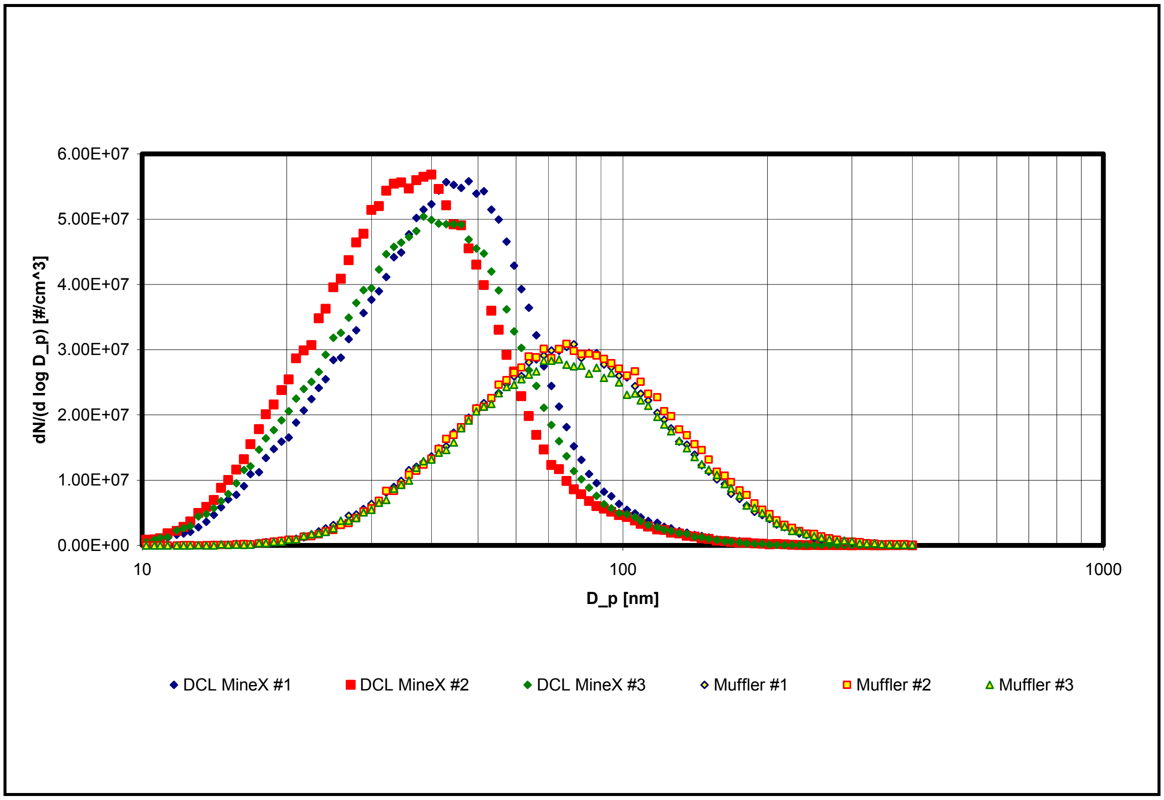

Figure 22. Size distribution of aerosols in mine air for LHD #99942 - DCL MineX vs. Muffler

Due to an unfortunate mistake in supplying fuel for a number of the tests, including those conducted with LHD #92506 (see chapter on fuel), the two tests that were designed to show the effects of the fuel formulation (#1 vs. #2 diesel) on the emissions were actually two tests conducted under very similar conditions. Since both tests were conducted with approximately a 90% #2 and 10% #1 diesel blend supplied to the engine, these tests were seen as an opportunity to examine repeatability of the applied test methodology. The results of the size selective measurements shown in Figure 23 agree with the other measurements used in this study, showing relatively good inter-test agreement.

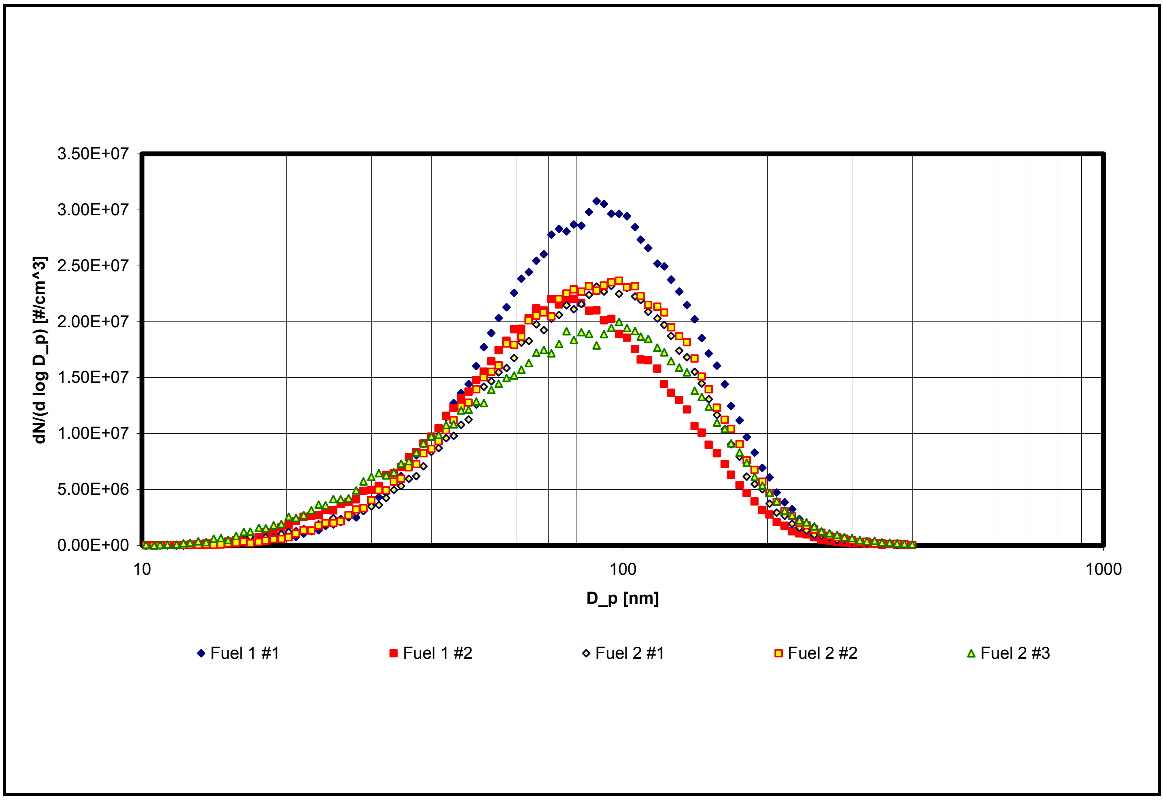

Figure 23. Size distribution of aerosols in mine air for truck #92506 equipped with muffler - Fuel 1 vs. Fuel 2

The effects of the diesel oxidation catalytic converter (Engelhard PTX) on the size distribution of aerosols are apparent from Figure 24. The size distributions of the particles that are observed for the tests with the DOC are characterized with somewhat lower geometric means (72.40 vs. 85.74 nm) and higher peak concentrations ($1.75*10^7$ vs. $1.50*10^7$ #/cm^3) than the size distributions observed during tests with the muffler alone (see Table 10 and Figure 24). Approximately a 7 percent increase in the number of the particles was found when the muffler was replaced with a DOC/muffler combination (see Table 10).

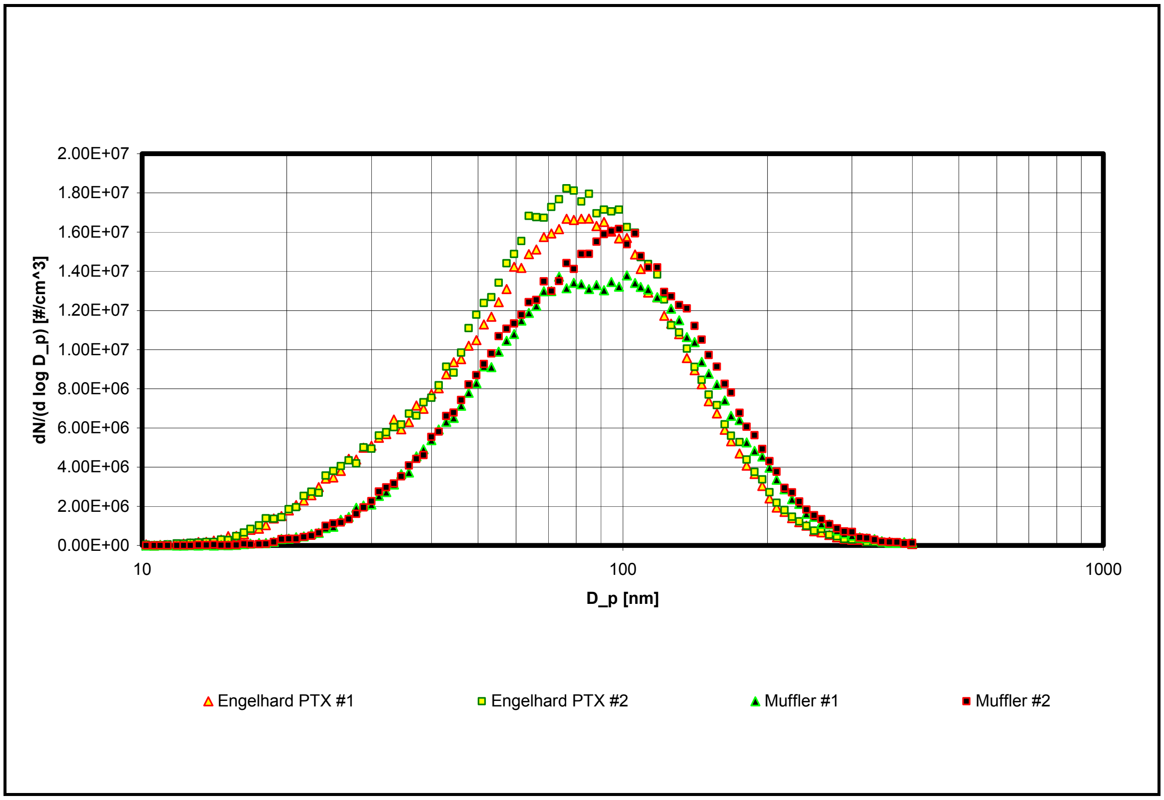

Figure 24. Size distribution of aerosols in mine air for LHD #92526 - Engelhard PTX/Muffler vs. Muffler

Figure 25 illustrates the effects of blending biodiesel with #2 diesel on the size distribution of aerosols in the mine air. The results indicate that the size distributions of the particles for the cases when these particular biodiesel blends were used were characterized with somewhat lower geometric means and higher peak concentrations than the size distributions observed during the tests with #1 diesel (see Table 10 and Figure 25). The average geometric means for B50 blend (50% biodiesel and 50% #2 diesel, GM = 61.76 nm) and B20 blend (20% biodiesel and 80% #2 diesel, GM = 65.92 nm) indicate that increasing the biodiesel fraction of a blend might result in decreasing the geometric means for the size distributions. In addition, a significant increase in the number of particles was found when a biodiesel blend was supplied to the engine (see Table 10). These results do not indicate a potential trend in the relationship between the biodiesel fraction in a blend and total number of particles emitted.

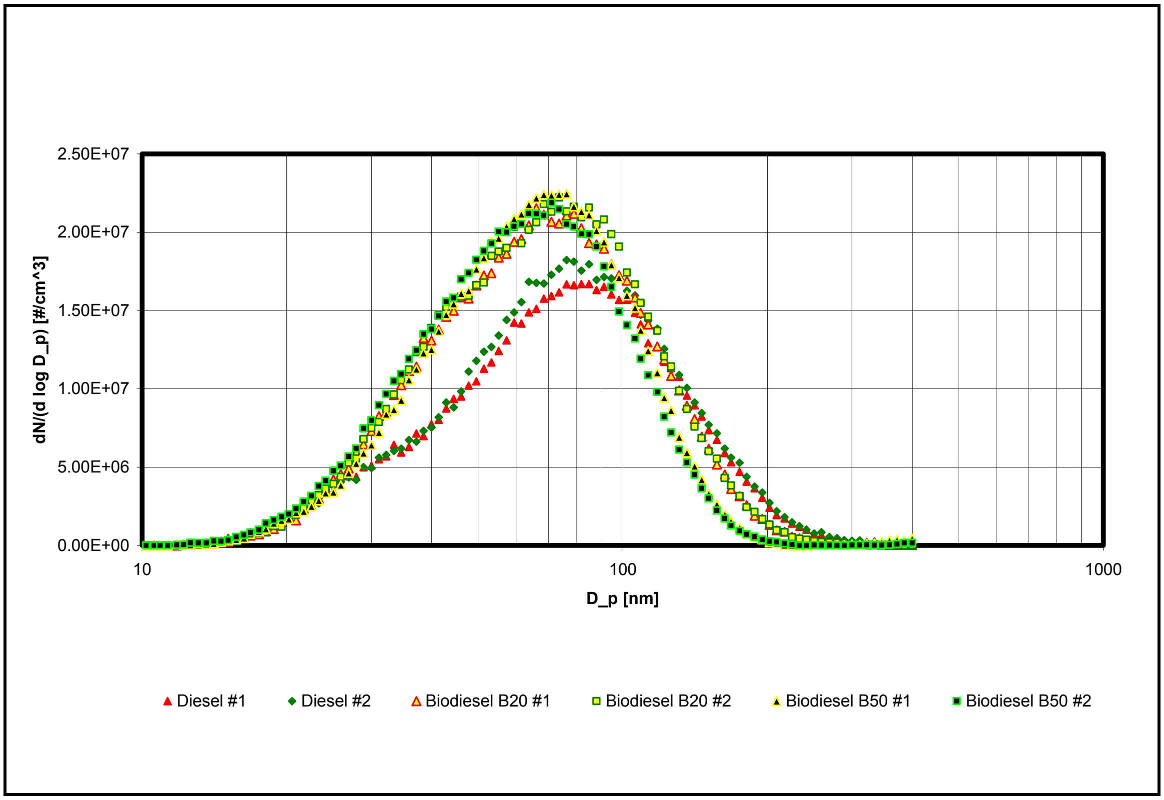

Figure 25. Size distribution of aerosols in mine air for LHD #92526 equipped with DOC (Engelhard PTX) and muffler - #2 diesel vs. Biodiesel B20 vs. Biodiesel B50

The effect of diesel fuel formulation (#1 vs. #2 diesel) on the size distribution of aerosols is shown in Figure 26. The size distributions of the particles that were observed during the tests with #2 diesel showed, on average, higher geometric means (81.93 vs. 75.42 nm) and higher peak concentrations ($3.16*10^7$ vs. $3.01*10^7$ #/cm^3) than the size distributions observed for the tests with #1 diesel (see Table 10 and Figure 26). Approximately a 22 % increase in the number of the particles was found when #2 instead of #1 diesel was fueled to the engine (see Table 10). This finding is corroborated by the TEOM results, which also showed an increase in the mass concentration in mine air exceeding 20% when #2 instead of #1diesel was fueled to the engine.

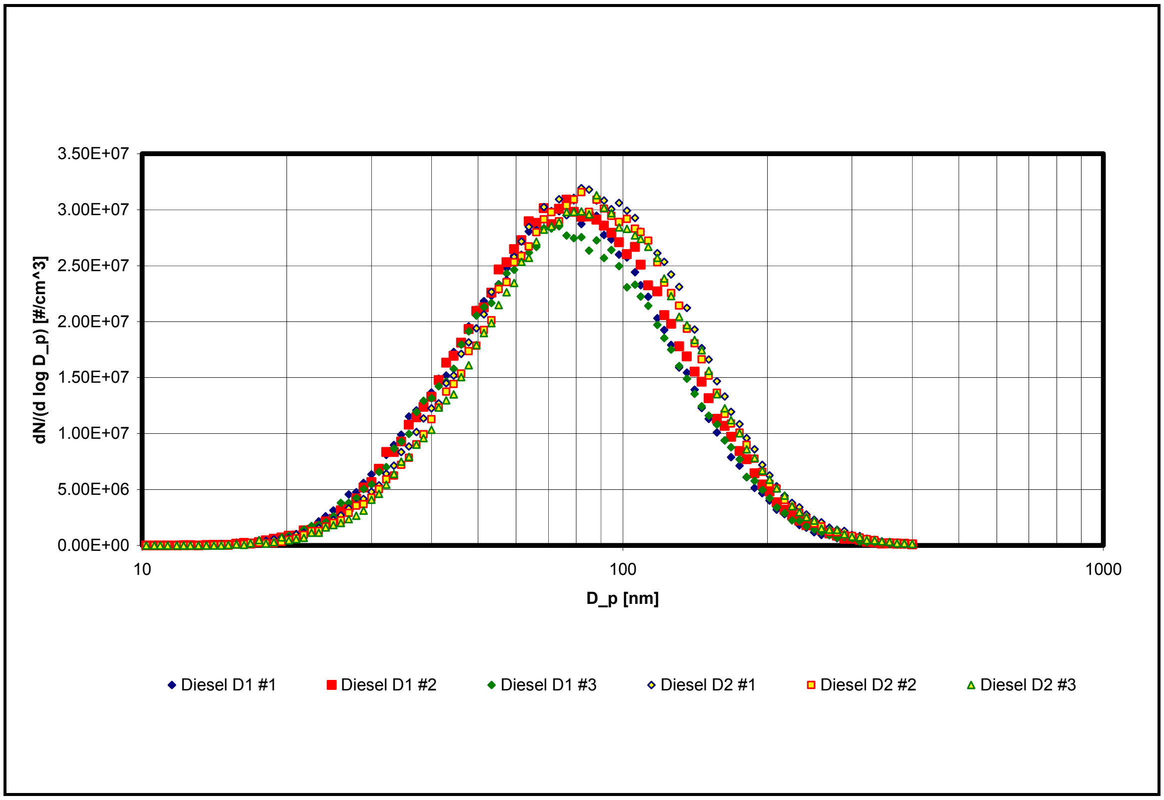

Figure 26. Size distribution of aerosols in mine air for LHD #99942 equipped with muffler - #1 diesel vs. #2 diesel

The effects of control technologies on ambient concentrations of carbon monoxide (CO), carbon dioxide (CO_2), nitric oxide (NO), and nitrogen dioxide (NO_2)

The normalized average and maximum concentrations of carbon monoxide (CO), carbon dioxide (CO_2), nitric oxide (NO), and nitrogen dioxide (NO_2) measured at the downstream sampling station are shown in Table 11. The concentrations of CO_2 were measured using INNOVA 1312 and concentrations of CO, NO, and NO_2 were measured by iTX multi-gas monitors. The obtained concentrations were normalized with respect to the MSHA ventilation rates specific for each of the engines powering the tested vehicles (Equation 2, page 39). The observed background concentrations of CO, NO, and NO_2 at the upstream sampling station were negligible and therefore there was no need to use them to correct the downstream concentrations. The CO_2 concentrations shown in Table 11 include the background CO_2 concentrations which averaged 402 ppm. This was done to facilitate the comparison of the measured CO_2 values with the ACGIH time weighted average (TWA) threshold limit values (TLVs) adopted by MSHA for the underground metal/nonmetal mining regulations (30 CFR Part 57.5001).

Table 11. Normalized concentrations of carbon monoxide (CO), carbon dioxide (CO_2), nitric oxide (NO), and nitrogen dioxide (NO_2) at downstream sampling station

Test Type	**CO [ppm]**		**CO_2 [ppm]**		**NO [ppm]**		**NO_2 [ppm]**	
	Max.	**Ave.**	**Max.**	**Ave.**	**Max.**	**Ave.**	**Max.**	**Ave.**
#92128 Haul Truck, MSHA vent 12000 cfm								
Baseline	11.1	6.7	3834	2924.2	22.2	17.0	1.1	0.6
Engelhard DPX	0.0	0.0	3793	2718.1	16.2	5.0	4.9	1.3
#92133 Haul Truck, MSHA vent 12000 cfm*								
Baseline	3.3	2.6	2208	1229	7.4	6.0	0.4	0.2
Clean Air + CDT	0.0	0.0	2384	1327	7.4	6.6	1.0	0.7
#92506 LHD, MSHA vent rate 11500								
Baseline, #1	23.1	3.3	6268	2104.4	23.1	7.2	2.3	1.3
Baseline, #2	23.0	4.3	5874	2201.1	23.0	6.8	2.3	1.2
#92526 LHD, MSHA vent rate 10000								
Baseline	23.3	6.0	7820	3699.4	43.7	19.4	3.5	1.5
Baseline + PTX	0.0	0.0	7622	3821.4	50.1	22.5	4.4	1.8
Biodiesel B20+PTX	0.0	0.0	7450	3825.5	45.9	21.2	4.0	1.7
Biodiesel B50+PTX	0.0	0.0	7622	3855.3	53.1	23.5	4.7	1.9
#99942 LHD, MSHA vent rate 15000								
Baseline, #1	31.2	4.9	8740	2848.8	48.5	16.6	3.5	0.9
Baseline, #2	26.8	4.5	9028	2861.2	46.8	16.7	3.0	0.8
DCL MineX	0	0.0	8656	2712.8	40.0	12.1	5.7	2.1

* The absolute values of the data for this vehicle is questionable, e.g., CO_2 is low compared to other vehicles; however, the relative changes between baseline and DPF test are quite possibly valid.

Carbon monoxide (CO)

The average and maximum normalized concentrations of CO, shown in Table 11, are significantly below the TWA TLV for CO of 50 ppm. The concentrations of CO were found to be practically undetectable for cases when the catalyzed diesel particulate filters from Engelhard and DCL, and the diesel oxidation catalytic converter from Engelhard (see Table 11) were fitted to the tested vehicles. Even in the cases when the engines were fitted with mufflers, the concentrations of CO were relatively low. The CO concentrations observed in the isolated zone are in the limits of concentrations estimated on the basis of the tailpipe emissions measurements.

Carbon dioxide (CO_2)

The average and maximum concentrations of CO_2 observed for the tests conducted during the study are shown in Table 11, Figure 27, Figure 28, and Figure 29. Both average and maximum CO_2 concentrations at the downstream station were below the TWA TLV for CO_2 (5000 ppm) during the tests with haul truck #92128. For the tests involving the other tested vehicles the average normalized concentrations of CO_2 were found to be under the TWA TLV for CO_2, but the peak concentrations were found to be significantly over the TWA TLV (see Table 11, Figure 27, Figure 28, and Figure 29).

The concentrations of CO_2 were found to be unaffected by the tested diesel particulate filters from Engelhard and DCL, and the diesel oxidation catalytic converter from Engelhard (see Table 11). The concentrations observed in the isolated zone are in the limits of concentrations estimated on the basis of the tailpipe emissions measurements.

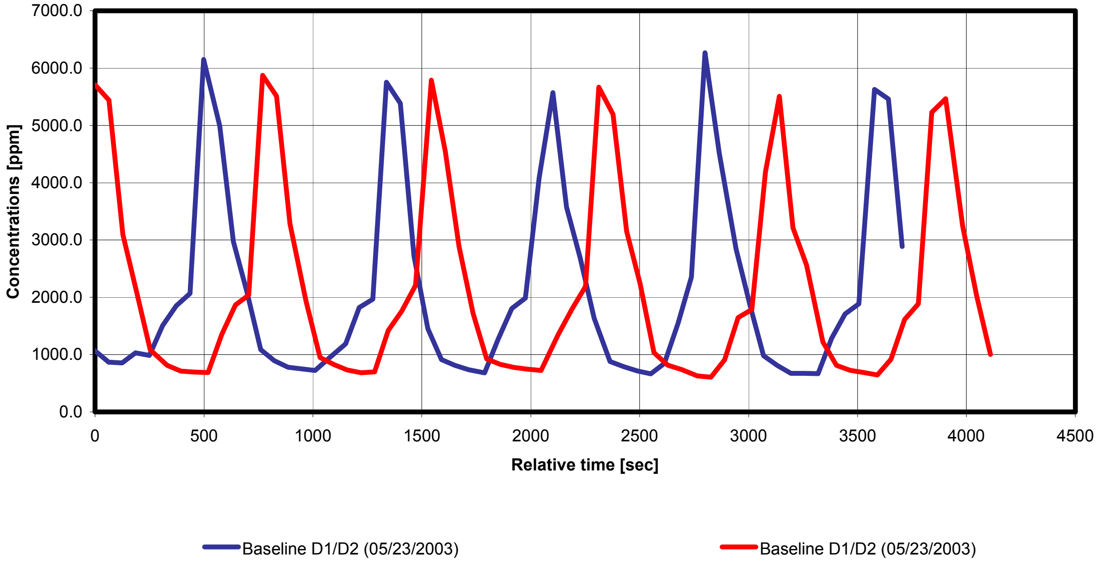

Figure 27. Normalized CO_2 concentrations for the tests with LHD #92506

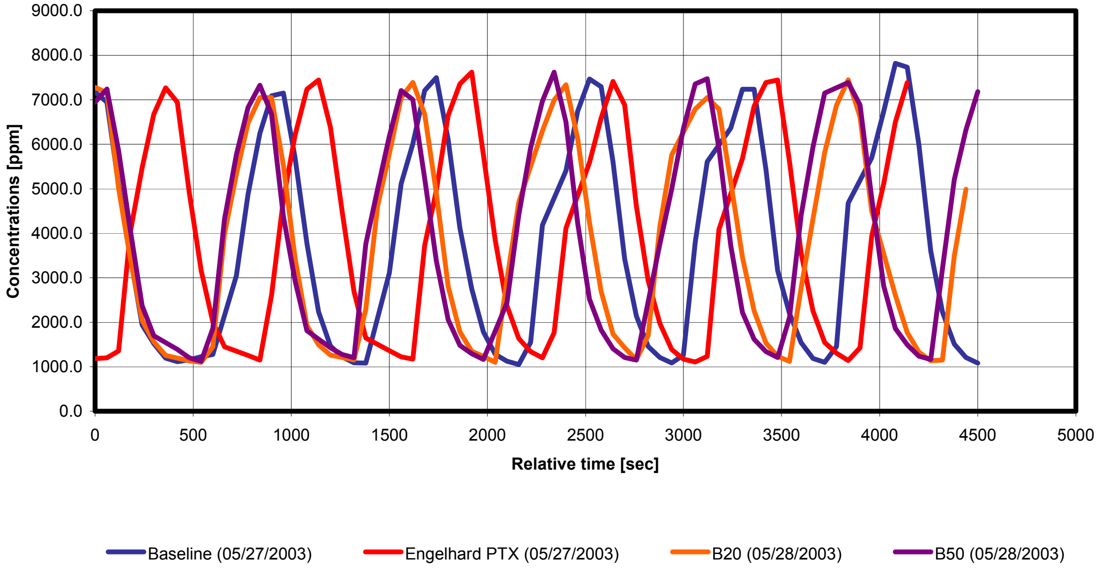

Figure 28. Normalized CO_2 concentrations for tests the LHD #92526

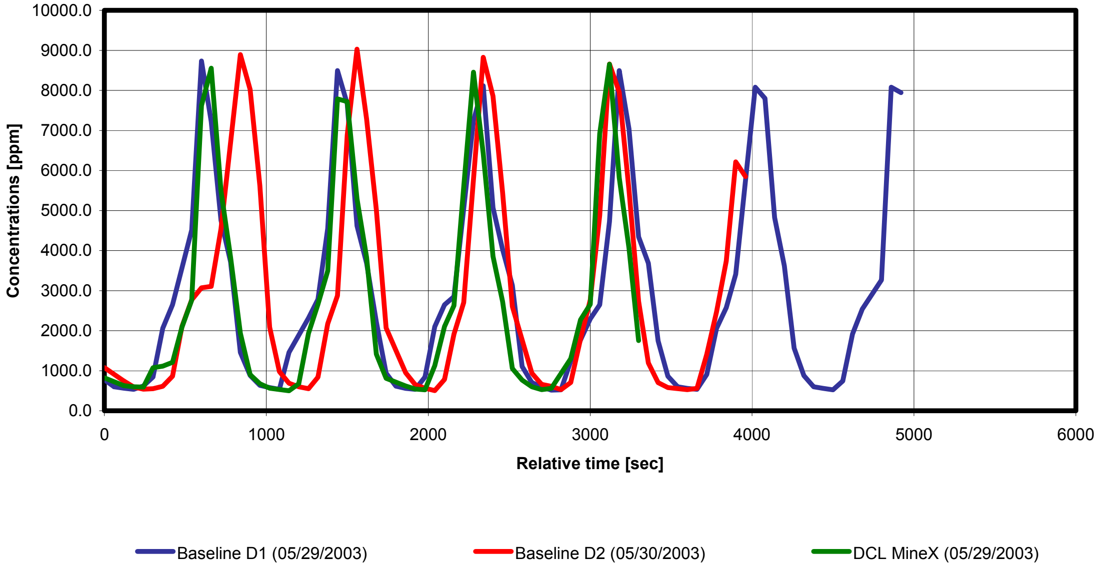

Figure 29. Normalized CO_2 concentrations for the tests with LHD #99942

Nitric oxide (NO)

The average normalized concentrations of NO shown in Table 11 were found to be somewhat lower than the TWA TLV for NO of 25 ppm. In the case of LHDs #92526 (see Table 11 and Figure 30) and #99942 (see Table 11, and Figure 31) the peak normalized concentrations were found to be significantly above the TLV. An analysis of the results shown in Table 11 revealed that the average and peak concentrations of NO were slightly lower for the tests when the vehicles were equipped with DPF systems rather than with mufflers. The analysis also showed that the biodiesel blends slightly increased the concentrations of NO over the baseline established with #1 diesel fuel.

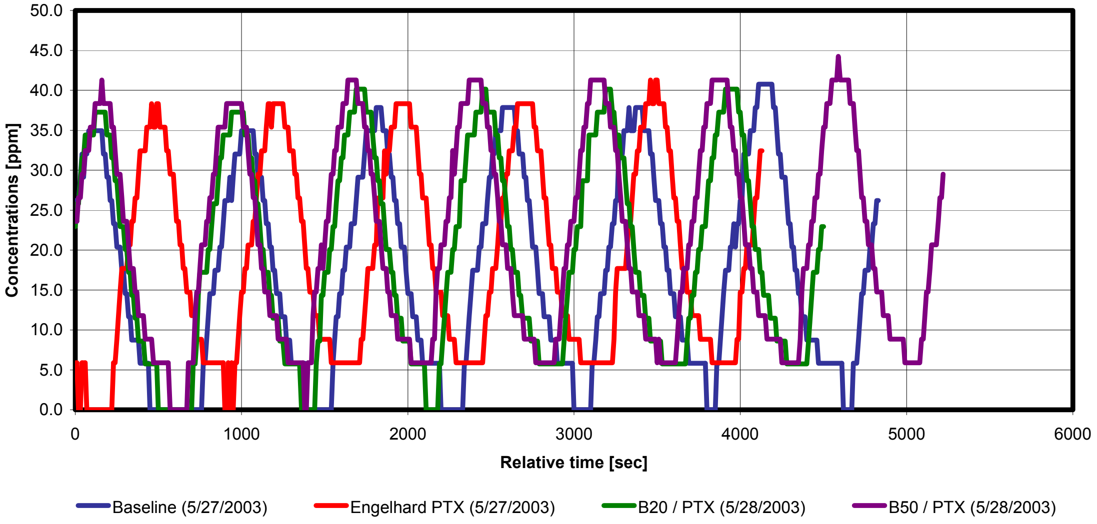

Figure 30. Normalized NO concentrations for the tests with LHD #92526

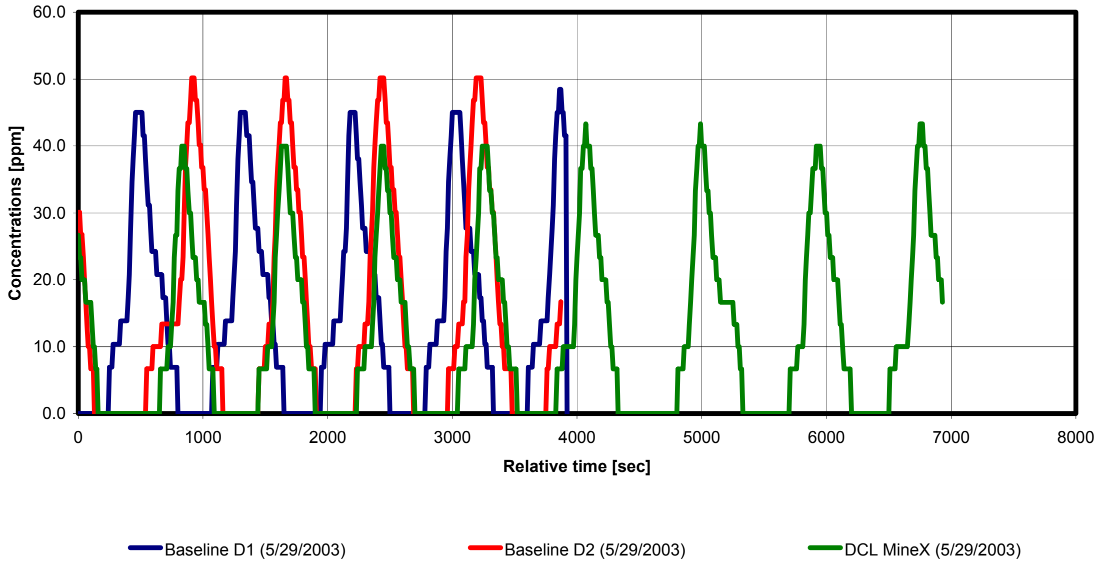

Figure 31. Normalized NO concentrations for the tests with LHD #99942

Nitrogen dioxide (NO_2)

Assessing the effects of the DPF systems, particularly those that were wash-coated with a platinum catalyst, on concentrations of NO_2 in mine air was one of the major objectives of this study. The results of the NO_2 measurements, presented in Table 11, show that the average normalized concentrations of NO_2 increased approximately two times (1.3 vs. 0.6 ppm) when haul truck #92128 was equipped with Engelhard DPX DPF system instead of a muffler. Comparable increases (2.1 vs. 0.9 ppm) in NO_2 concentration was observed for the DCL MineX DPF system and also for the CleanAir system (0.7 vs. 0.2 ppm) (see Table 11). It is important to note that if the required MSHA ventilation rates were maintained during the tests, the average concentration of NO_2 over the test periods would not have exceeded 3 ppm, the long term exposure limit for NO_2. It is also important to note that during the test involving #99942 equipped with DCL MineX, the MSHA ventilation rate normalized peak concentrations exceeded 5 ppm, the short term exposure limit (STEL) for NO_2 , on several occasions (see Figure 33). An analysis of the data showed that the average and peak concentrations of NO_2 were only slightly higher in the cases when LHD #92526 was fueled with biodiesel blends instead of regular diesel fuel. The results of the test when LHD #92526 was fitted with the Engelhard PTX DOC and a muffler showed insignificantly higher NO_2 emissions than when only the DOC was fitted to the vehicle.

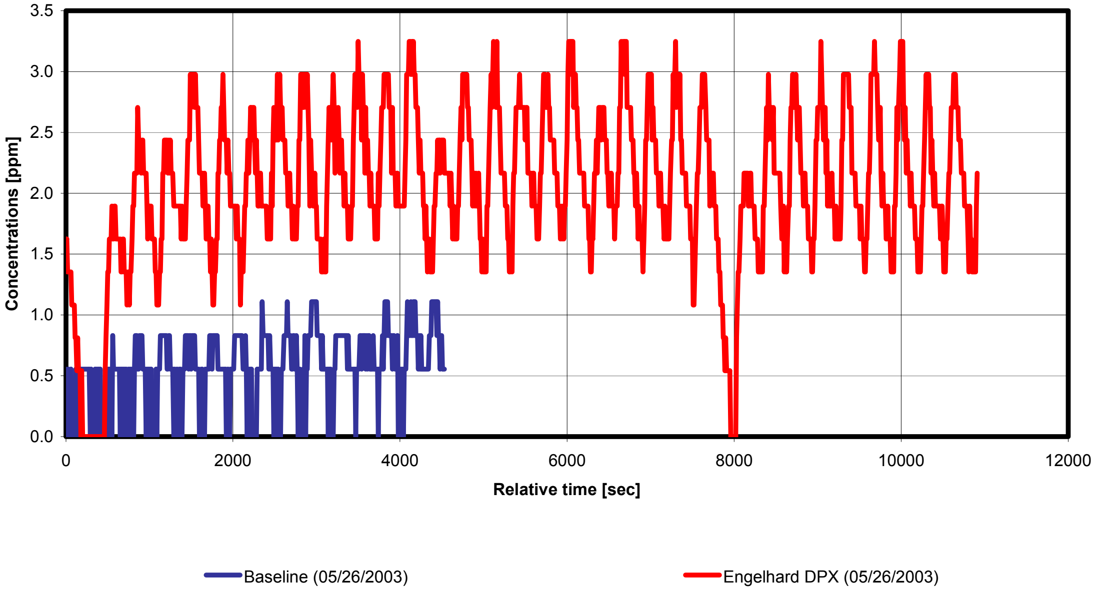

Figure 32. Normalized NO_2 concentrations for the tests with haul truck #92128

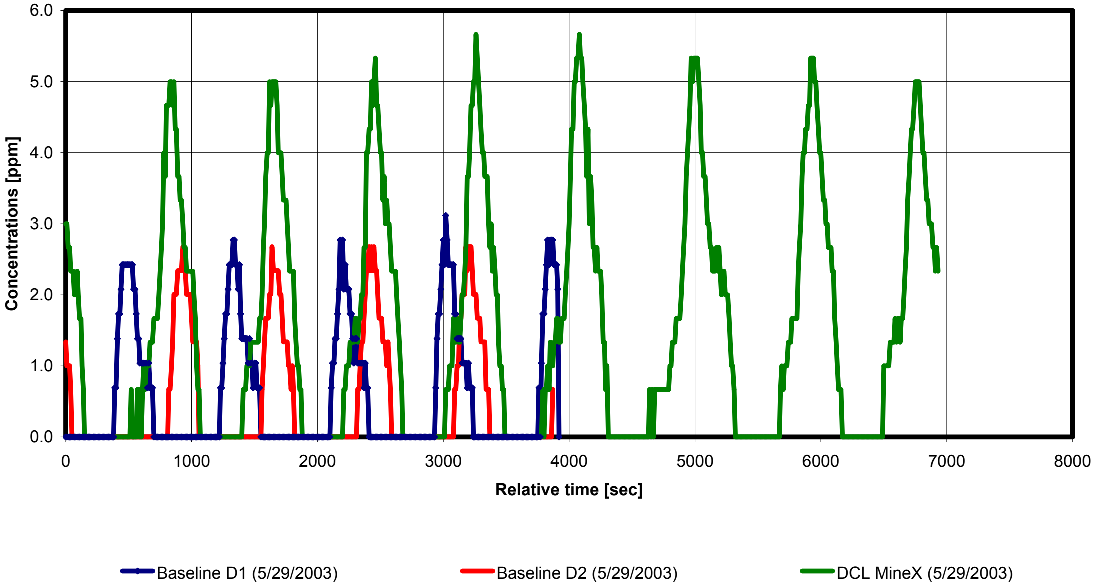

Figure 33. Normalized NO_2 concentrations for the tests with LHD #99942

It is important to note that the discussion presented in this section is based on the measurements conducted at the downstream sampling station. The area samples collected at this station were primarily used to evaluate the performance of the tested control technologies. However, concentrations of CO, NO, and NO_2 were also measured with an iTX multigas monitors at the sampling stations established on the tested vehicles. Since those sampling stations on the vehicles were located relatively close to the operators, these results can be used to estimate the exposure of the operators to the gases and particulate matter. The concentrations of the measured gases at the downstream and vehicle stations were found to be comparable, and, in a majority of the cases, slightly higher peaks were observed by the instrument used at the vehicle sampling stations (see Figure 34). This indicates that the operators might have been exposed to concentrations that are somewhat higher than those shown in Table 11.

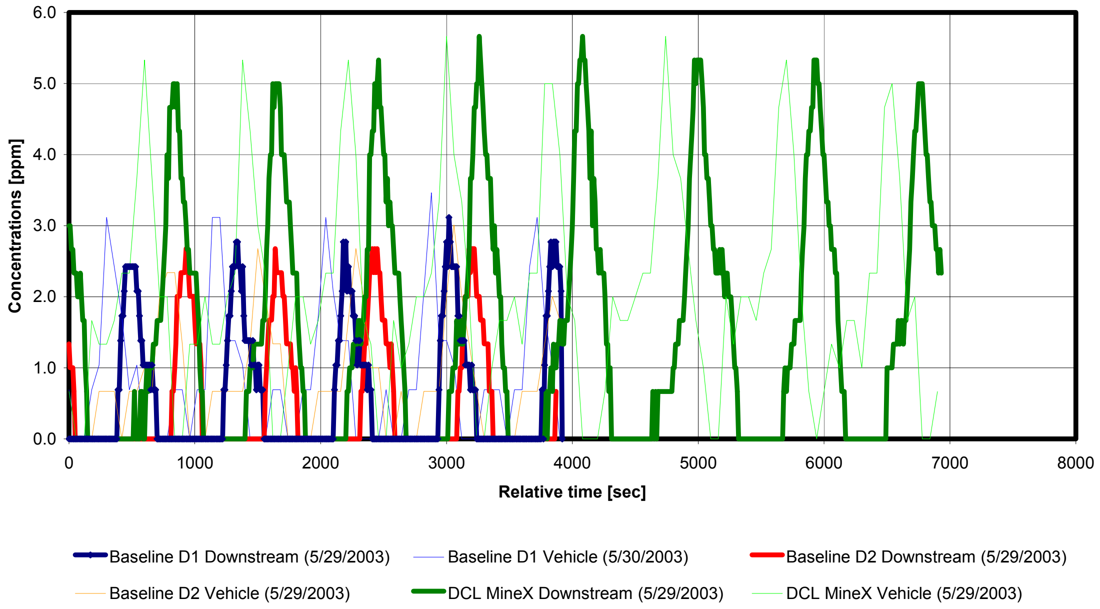

Figure 34. Normalized NO_2 concentrations at downstream and vehicle sampling stations for the tests with LHD #99942

Analysis of exhaust temperature and back pressure data

A 4-channel Logic Beach MiniLogger was used to record 10-second average exhaust backpressure, exhaust gas temperature and a surface temperature. It was also used to record the analog output of the Max fuel flow metering system when that device was installed on the Caterpillar engines and working. Because fuel was used for engine cooling, the fuel flow rate for Deutz engines was beyond the range of the Max fuel flow metering system.

We examined the exhaust temperatures for all test runs and determined the 70th percentile temperature (the temperature that the exhaust temperature was below 70% of the time, or T_{30} the temperature exceeded 30% of the time.) for each run. The temperatures below 130 °C were excluded from considerations. T_{30} is considered as a benchmark for matching various DPF passive regeneration schemes to exhaust temperatures. T_{30} was determined by using the NIOSH spreadsheet referenced in the NIOSH-MSHA DPF selection guide accessible from the NIOSH Mining Toolbox on the WEB.

We examined the exhaust backpressures when diesel particulate filters (DPFs) were used. We were looking for decreases in back pressure while the exhaust temperatures were high, or a general decreasing trend in backpressure throughout the test run. Either of these signs would indicate that the exhaust temperature was sufficient to burn off some of the DPM/soot collected by the DPF.

In some instances the temperature data from one or both channels appeared erratic. A post test check of the data logger and sensor performance at PRL confirmed that it was still accurate. However, there may have been some interference on the data from the connection to the Max fuel flow metering system.

Table 12 shows the results of the analysis of the vehicle exhaust logs.

Table 12. Results of the on-board temperature and exhaust backpressure logs

Test Type	T30 Temperature	Backpressure	DPF Regenerates?
	[°C]	Ranges min-max:start min-max:end	
#92128 Haul Truck			
Baseline	260.0	2 to 15	
Engelhard DPX	265	35 to 100	No
#92133 Haul Truck			
Baseline (+ CDT)	410	NA	
Clean Air + CDT	440	16-62; 2.5-9	Yes
#92506 LHD			
Baseline, #1 diesel	455	NA	
Baseline, #2 diesel	455	NA	

Test Type	T30 Temperature	Backpressure	DPF Regenerates?
	[°C]	Ranges min-max:start min-max:end	
DCL BlueSky	490	12-28; 35-80	No
Donaldson	370	.25 to 2.3	NA
#92526 LHD			
Baseline	460	2 to 11	
Baseline + PTX	440	4.5 to 11.5	
ECS CATTRAP	240	10 to 33	No
Biodiesel B20+PTX	440	6 to 11.5	NA
Biodiesel B50+PTX	Faulted	5 to 11.5	NA
#99942 LHD			
Baseline, #1 diesel	Faulted	faulted	
Baseline, #2 diesel	500	12 to 25	
DCL MINEX	Faulted	faulted	?

Vehicle #92128

Baseline for Engelhard

Exhaust temperatures over the sampling run were quite low with T_{30} at about 260° C; the data appeared erratic. The other temperature channel exhibited the same erratic behavior. The exhaust backpressure is not relevant but varied between 2 and 15 inches water gage (WG).

Engelhard DPX, aged Platinum Catalyzed DPF

Exhaust temperature logs appear peculiar: one channel ranges from about 22 to 460 °C with a high frequency component whereas the other channel is a moderated temperature with smoother behavior. The former was chosen as the exhaust gas temperature. Both were analyzed: The T_{30} for the exhaust temperature was only 300° C whereas the T_{30} for the surface temperature was about 260° C. Based on the exhaust temperature, the Engelhard DPF should not regenerate. The backpressure ranges from about 35 to 100 inches WG and shows a bimodal distribution at the lower and upper ranges. Backpressures were excessive. They did not decrease over the test run, and DPF regeneration is not evidenced.

Vehicle #92133

Baseline for CleanAir Systems

Temperature analysis showed T_{30} of 410° C, compared to 430° C when the DPF was installed.

CleanAir Systems with CDT fuel additive

BP varied from 15 to 60 in WG at the start of the run and decreased to 2 to 10 in WG at the end of the 3 hour and 22 minute test run. The graph of BP and exhaust temperature, Figure 35, presents a striking example of DPF regeneration. T_{30} over the test run computed to be 440° C. Although the CleanAir DPF system regenerated during testing, the fact that it arrived loaded from production indicates that it may not be regenerating during actual production cycles. The history of the system just prior to testing is not currently known.

Figure 36 shows the graphical results of the temperature frequency analysis performed by the spreadsheet mentioned earlier. The intersection of the 30% horizontal with the 1 minus the cumulative frequency line shows the T_{30} temperature at 440° C.

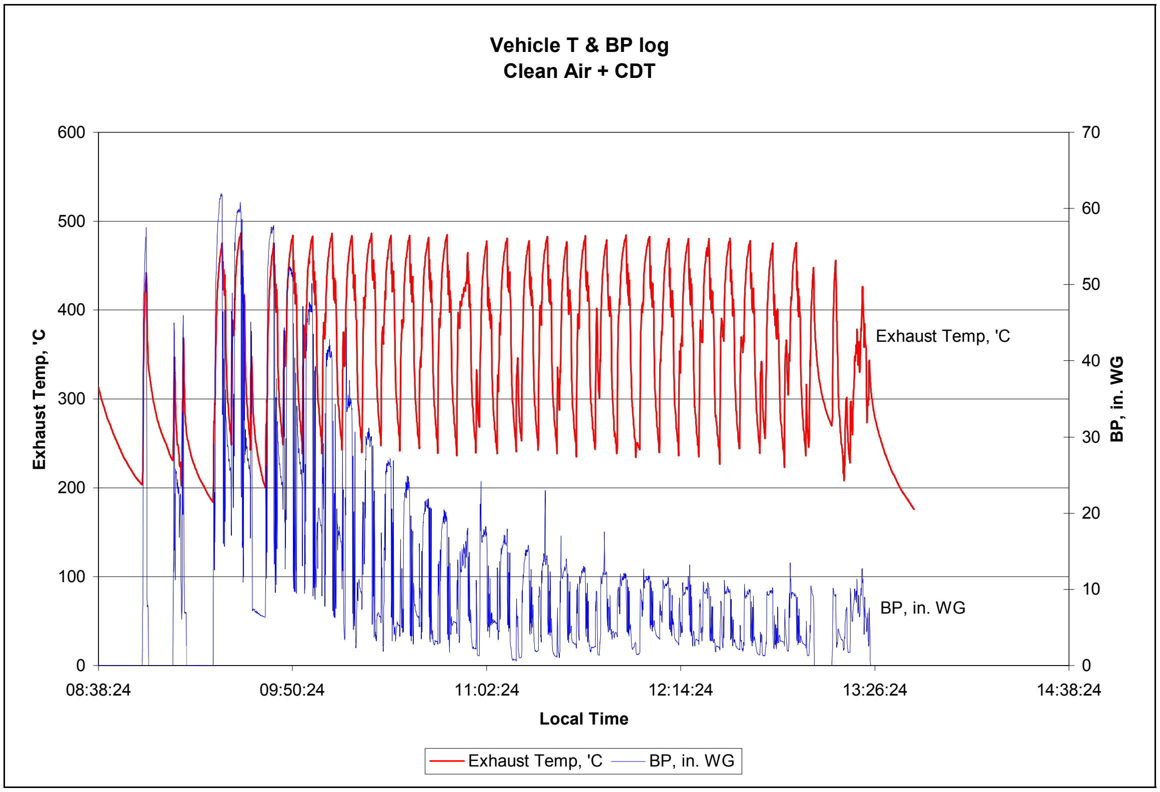

Figure 35. Vehicle exhaust temperature and backpressure log during the isozone test run

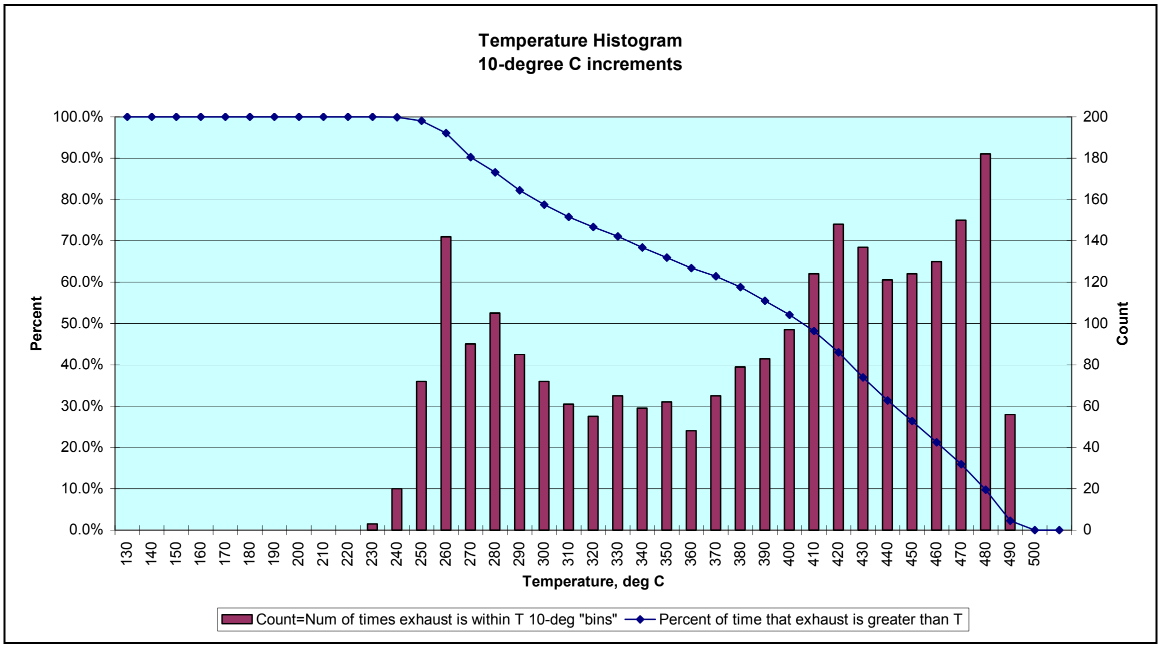

Figure 36. Temperature frequency distribution and "more than" type cumulative frequency distribution used to determine T_{30}

Tailpipe emissions testing

The vehicle logger was recording during the emissions testing in the shop. Close examination of the temperature and backpressure traces reveal the occurrence of regeneration. This is shown in Figure 37 in a box around the area of interest. The top trace representing exhaust temperature rises slowly, whereas the lower trace representing backpressure rises then falls rapidly before plunging even lower. The latter precipitous fall represents the engine going to idle, whereas the preceding decrease as exhaust temperature rises indicates soot removal.

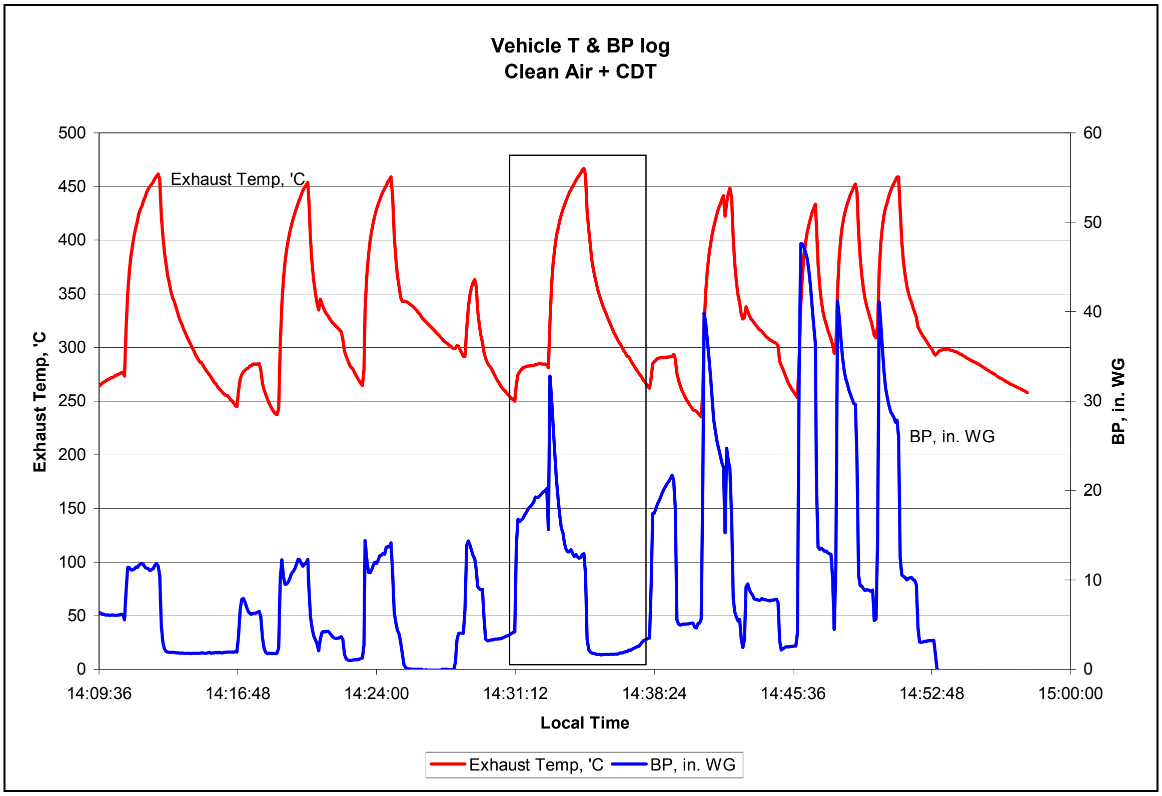

Figure 37. Exhaust T and BP during emissions testing showing DPF regeneration

Vehicle #92506

Baseline #1 diesel and baseline #2 diesel

T_{30} for both runs was between 450° C and 460° C.

Donaldson disposable high temperature filter

This filter was not supposed to regenerate and did not.

Backpressure range was constant over the length of the test, which was too short considering that the filter was clean and new and clean filters do not filter as well as when they are partially loaded. The BP range was nominally <0.5 to 2.25 inches WG.

T_{30} for the run time in isolated zone (longer than the time needed to collect sample), which included warm-ups but no idle time, was about 370° C. This can be compared to the T_{30} of 490 °C for the same vehicle during the DCL BlueSky run. The location of the temperature sensor may have been different since different exhaust system configurations were used.

DCL Blue Sky DPF

Backpressures ranged from 12 to 28 inches at the start of the test (range results from engine load and speed) to 35 to 80 inches WG at the end of the test. T_{30} was 490 °C. This DPF did not regenerate and was not supposed to by design, although it does have a platinum catalyst.

Vehicle #92526

Baseline
Baseline with PTX oxidation catalyst
Baseline with PTX and B20 Biodiesel blend
Baseline with PTX and B50 Biodiesel blend

The backpressure and temperature data from these four runs are similar. Note that the PTX may have introduced some exhaust back pressure. T_{30} was about 440 °C for all cases; however there is concern from the look of the temperature data that the temperature logging may have been faulty for the B50 run.

ECS Cattrap with DOC

T_{30} was 340 °C. There was no evidence of regeneration. T_{30} required for the base metal catalyst for regeneration is about 400 to 420 °C.

Vehicle #99942

Baseline on #1 and #2 diesel fuel
DCL MineX

We failed to get a reliable temperature log for the #1 diesel run; T_{30} for the run on #2 diesel fuel showed a T_{30} of 500 °C. This temperature was much higher than for Vehicle #92526 whose engine was also a 3306 DITA but was derated. This relation was expected. The back pressure for the #2 run registered between 12 and 25 in WG but there was no restriction other than a muffler, so the data must be in error. All other back pressure and temperature data were deemed faulty.

Results of the Tailpipe Emissions Measurements

Particulate matter emissions, Elemental Carbon

The elemental carbon results from the tailpipe measurements are summarized in this chapter. The results of the analysis and calculated reductions observed for the tested control technologies are presented in Table 13.

Table 13 : Effects of control technologies on elemental carbon emissions

Test Type	EC [µg/m^3] HI		EC [µg/m^3] TCS		Reduction of EC [%]	
	Up stream	Down stream	Up stream	Down stream	HI	TCS
#92128 Haul Truck						
Engelhard DPX	2369	< 920	18230	< 920	> 61	> 95
#92133 Haul Truck						
Clean Air	6043	< 920	33537	< 920	> 85	> 97
#92506 LHD						
DCL BlueSky	5282	1055	23316	< 920	80	> 96
Donaldson	3353	< 920	18230	1748	> 72	90
#92526 LHD						
ECS Cattrap	8898	< 920	8254	< 920	> 90	> 89
Baseline, PTX	16049	11529	8230	6712	28	18
Biodiesel B20, PTX	13798	12532	5641	4858	14	31
Biodiesel B50, PTX	9890	8690	4537	4217	38	45
#99942 LHD						
DCL MineX	40838	< 920	16417	< 920	> 98	> 94

The NIOSH 5040 method has a limit of quantification (LOQ) of approximately 1.5 µg/filter. This LOQ was converted into an equivalent concentration for the exhaust volume sampled. If the EC sample taken after the control technology was below the LOQ, the downstream concentration was assigned the LOQ equivalent concentration and used to compute the EC reduction efficiency of the aftertreatment technology. This procedure resulted in a conservative estimate of the control efficiency. For most of the high idle mode tests, the EC was below the LOQ, and the baseline was so low that it was not possible to calculate a reduction with confidence. The results of the analysis on the samples collected at TCS mode show that the tested DPF systems were over 90 % efficient in removal of elemental carbon (see Table 13 and Figure 38). Figure 38 presents the reduction of EC emissions for TCS mode. The yellow bars show the reductions calculated with actual results while red bars show the minimum reductions that were calculated using LOQ values instead of the actual results that were below LOQ.

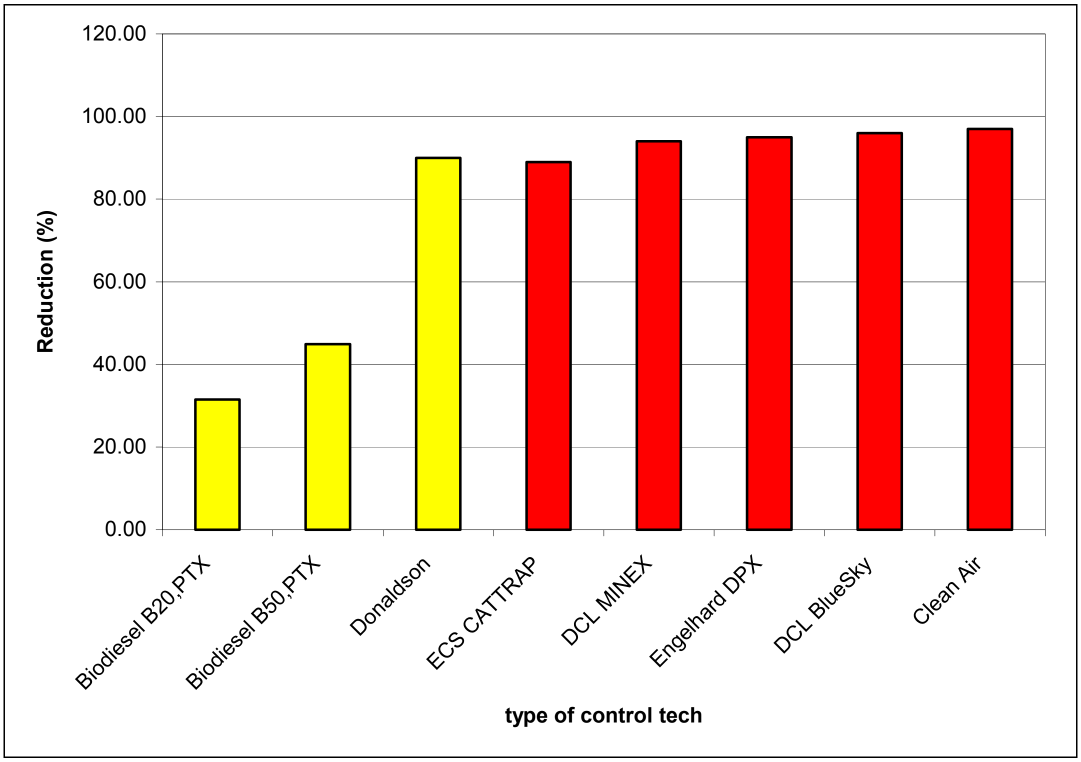

Figure 38: Reduction of EC emissions at TCS mode

It is interesting to note that the Engelhard PTX DOC reduced the EC emissions by 18 % at the TCS and 28 % at HI, although the PTX DOC was only expected to affect the OC part of DPM.

Particulate matter emissions, Bacharach Smoke Numbers

This section summarizes the results of the Bacharach Smoke number tests collected during tailpipe emission measurements. In this study the Bacharach Smoke number was used as a qualitative measure to estimate the effectiveness of the DPF's tested. This was accomplished by pulling a sample both upstream and downstream of the DPFs. The Bacharach smoke number methodology was discussed in detail earlier in this report, page 42. Typically when a DPF is working effectively, the smoke number should be zero. Upstream values for the smoke number can range anywhere from 3 to 10. The results from the smoke number tests are presented in Table 1. For each of the DPFs tested, the Bacharach smoke numbers for upstream samples ranged from 3 to 9 while all the samples downstream of the DPFs measured zero. These data indicate that this method can be used to estimate the efficacy of DPFs, and further signify that the DPF's tested in this study were working effectively.

Table 14. Effects of control technologies on DPM emissions: Bacharach smoke number

Test Type	Bacharach smoke number HI		Bacharach smoke number TCS	
	upstream	Downstream	Upstream	Downstream
#92128 Haul Truck				
Engelhard DPX	3.0	0.0	7.0	0.0
#92133 Haul Truck				
Clean Air	3.0	0.0	4.0	0.0
#92526 LHD				
Biodiesel B20, PTX	8.0	8.0	7.5	6.0
Biodiesel B50, PTX	7.5	7.5	7.5	6.0
#99942 LHD				
DCL MineX	9.0	0.0	8.0	0.0

The results indicate significant reductions of DPM concentrations in the exhaust by tested DPF systems (Engelhard DPX, CleanAir Systems, and DCL MineX). The Bacharach smoke numbers obtained upstream and downstream of the tested DOC showed insignificant reductions in DPM by DOC (Engelhard PTX).

The Bacharach smoke numbers presented in Table 14 do not show significant reductions of DPM concentrations in the exhaust for biodiesel blends. The numbers presented were sampled upstream and downstream of the diesel oxidation catalyst and no difference is apparent between the upstream and downstream samples. The qualitative nature of this methodology makes it less effective at measuring small decreases in DPM.

Emissions of carbon monoxide, carbon dioxide, nitric oxide, and nitrogen dioxide

The effects of tested control technologies on emissions of CO, CO_2, NO, and NO_2 were estimated on a basis of the measurements made upstream and downstream of tested control technologies. The gases were measured for three operating conditions, LI, HI, and TCS, using ECOM KL (NIOSH) and ENERAC 400 EMS (Stillwater).

The effects of the biodiesel blends on gaseous emissions were obtained by comparing the results of emissions measurements obtained upstream of the Engelhard PTX DOC on the #92526 fueled with the biodiesel blend to the results upstream of the ECS Cattrap when the #92526 was fueled with #1 diesel fuel). The effects of the Engelhard PTX DOC on the gaseous emissions were evaluated by comparing the upstream to the downstream measurements conducted during the tests on #92526 fueled with biodiesel blends.

The agreement between ECOM KL and ENEARAC 400 EMS was found to be within the experimental error. The discrepancies in some of the readings can be explained by differences in the protocols used by the instruments.

The results of the CO concentration measurements are given in Table 15. The catalyzed DPF systems and DOC tested in this study reduced drastically the concentrations of CO. The Donaldson disposable filter also surprisingly reduced CO emissions. The extremely high concentrations of CO in the exhaust of the LHD #92506 at HI conditions indicate serious problems with the engine fueling system. The CO emissions from the other vehicles were within the manufacturers specifications.

Table 15. CO concentrations

Test Type	CO [ppm] HI		CO [ppm] LI		CO [ppm] TCS		Instrument
	Up-stream	Down stream	Up-stream	Down stream	Up-stream	Down stream	
#92128 Haul Truck							
Engelhard DPX	217.0	0.0	197.0	0.0	136.0	0.0	ECOM
	204.0	0.0	170.0	0.0	131.0	0.0	Enerac
#92133 Haul Truck							
CleanAir Systems	314.0	2.0	100.0	0.0	114.0	0.0	ECOM
	301.0	0.0	110.0	0.0	109.0	11.0	Enerac
#92506 LHD							
DCL BlueSky	2437.0	1329.0	168.0	3.0	386.0	3.0	ECOM
	2207.0	910.0	208.0	0.0	460.0	0.0	Enerac
Donaldson	N/A	N/A	N/A	N/A	N/A	N/A	ECOM
	2960.0	1359.0	248.0	79.0	268.0	210.0	Enerac
#92526 LHD							
ECS Cattrap	278.0	2.0	N/A	N/A	106.0	0.7	ECOM
	238.0	0.0	168.0	0.0	98.0	0.0	Enerac
Biodiesel B20, PTX	18.7	17.5	158.0	1.0	70.7	1.0	ECOM
	167.0	16.0	173.0	0.0	74.0	4.0	Enerac
Biodiesel B50, PTX	203.0	22.0	N/A	N/A	75.0	6.0	ECOM
	174.0	21.0	159.0	0.0	76.0	13.0	Enerac
#99942 LHD							
DCL MineX	375.7	0.0	N/A	N/A	228.5	0.0	ECOM
	343.0	0.0	125.0	0.0	215.0	0.0	Enerac

The calculated concentrations of CO_2 in the exhaust of the tested vehicles/configurations are shown in Table 16. The CO_2 emissions were not significantly affected by any of the control technologies.

Table 16. CO_2 concentrations

Test Type	CO_2 [%] HI		CO_2 [%] LI		CO_2 [%] TCS		Instr-ument
	Up-stream	Down stream	Up-stream	Down stream	Up-stream	Down stream	
#92128 Haul Truck							
Engelhard DPX	4.9	4.9	2.9	0.4	8.6	8.0	ECOM
	4.5	4.5	2.5	2.5	8.2	8.2	Enerac
#92133 Haul Truck							
CleanAir Systems	4.2	4.4	2.1	2.3	8.0	8.1	ECOM
	4.5	4.5	2.3	2.3	8.1	8.1	Enerac

Test Type	CO_2 [%] HI		CO_2 [%] LI		CO_2 [%] TCS		Instr-ument
	Up-stream	Down stream	Up-stream	Down stream	Up-stream	Down stream	
#92506 LHD							
DCL BlueSky	N/A	N/A	N/A	N/A	N/A	N/A	ECOM
	6.4	6.4	2.6	2.6	10.5	10.5	Enerac
Donaldson	N/A	N/A	N/A	N/A	N/A	N/A	ECOM
	5.1	5.1	1.1	1.1	8.3	8.3	Enerac
#92526 LHD							
ECS Cattrap	5.5	5.6	N/A	N/A	7.5	7.5	ECOM
	5.2	5.2	2.4	2.4	7.0	7.0	Enerac
Biodiesel B20, PTX	4.8	4.8	2.5	2.4	6.8	7.0	ECOM
	4.7	4.7	2.1	2.1	6.6	6.6	Enerac
Biodiesel B50, PTX	4.6	4.7	N/A	N/A	6.7	7.0	ECOM
	5.3	5.3	2.7	2.7	5.3	5.3	Enerac
#99942 LHD							
DCL MineX	5.4	5.3	N/A	N/A	9.3	9.3	ECOM
	5.4	5.4	2.5	2.5	9.1	9.1	Enerac

The results of the NO emissions measurements are summarized in Table 17 and Figure 39. The CleanAir Systems DPF system did not significantly affect NO emissions. The NO emissions were significantly affected by the other tested systems. They were significantly lower for the Engelhard DPX , the ECS Cattrap, and the DCL MineX for all test modes. In the case of the DCL BlueSky and the Donaldson filtration systems the effects on the NO emissions were found to be strongly dependent on the engine operating conditions. The effects of biodiesel blends could be characterized as marginal.

Table 17. NO concentrations

Test Type	NO [ppm] HI		NO [ppm] LI		NO [ppm] TCS		Instr-ument
	Up-stream	Down stream	Up-stream	Down stream	Up-stream	Down stream	
#92128 Haul Truck							
Engelhard DPX	439.5	360.0	414.0	3.0	500.0	341.0	ECOM
	434.0	389.0	412.0	292.0	506.0	427.0	Enerac
#92133 Haul Truck							
CleanAir Systems	240.0	281.0	176.0	161.0	407.0	374.0	ECOM
	260.0	283.0	188.0	188.0	435.0	415.0	Enerac
#92506 LHD							
DCL BlueSky	124.0	203.0	284.0	278.0	476.0	355.0	ECOM
	172.0	214.0	300.0	303.0	491.0	443.0	Enerac
Donaldson	213.0	N/A	N/A	N/A	423.5	N/A	ECOM
	163.0	287.0	373.0	151.0	529.0	474.0	Enerac
#92526 LHD							
ECS Cattrap	186.5	143.0	245.0	N/A	427.0	301.7	ECOM
	204.0	146.0	240.0	85.0	452.0	259.0	Enerac
Biodiesel B20, PTX	189.3	192.0	240.0	215.0	491.7	483.0	ECOM
	209.0	208.0	211.0	213.0	492.0	492.0	Enerac

Test Type	NO [ppm] HI		NO [ppm] LI		NO [ppm] TCS		Instr-ument
	Up-stream	Down stream	Up-stream	Down stream	Up-stream	Down stream	
Biodiesel B50, PTX	161.0	159.0	225.0	N/A	449.0	426.0	ECOM
	205.0	196.0	226.0	176.0	487.0	440.0	Enerac
#99942 LHD							
DCL MineX	206.0	150.5	N/A	N/A	547.0	438.5	ECOM
	250.0	159.0	329.0	113.0	607.0	523.0	Enerac

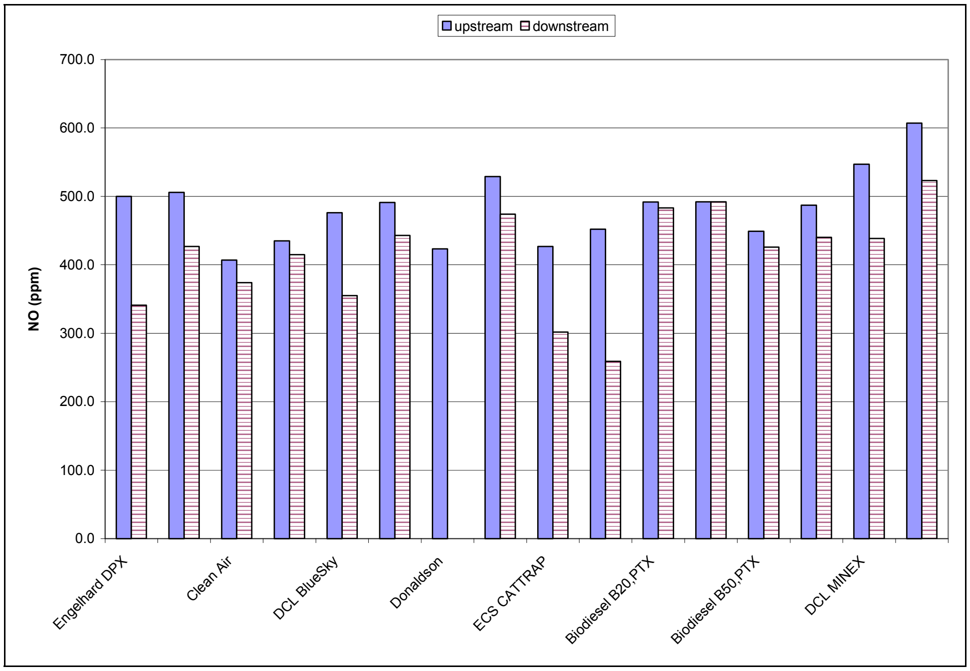

Figure 39. NO Emissions in TCS mode

The results of the NO_2 emission measurements are summarized in Table 18 and Figure 40. Significantly higher NO_2 concentrations were observed downstream than upstream of the platinum coated filters tested in this study (Engelhard DPX and DCL MineX). Four fold increases in NO_2 emissions were observed at TCS conditions. The significant increases in NO_2 emissions were also observed for ECS Cattrap system that had an ECS DOC installed on its outlet. That system increased NO_2 emissions almost six fold at TCS conditions. The ECS DOC was new and was installed with the DPF. The NO_2 concentrations need to be closely monitored in the underground work areas where vehicles equipped with these filters, that have high potential of converting NO to NO_2, are used.

The results of these measurements show no significant increase in NO_2 emissions when biodiesel blends B20 (20% biodiesel, 80% #2 diesel) and B50 (50% each biodiesel and #2 diesel) were used instead of #1 diesel.

Table 18: NO_2 concentrations

Test Type	NO_2 [ppm] HI		NO_2 [ppm] LI		NO_2 [ppm] TCS		Instr-ument
	Up-stream	Down stream	Up-stream	Down stream	Up-stream	Down stream	
#92128 Haul Truck							
Engelhard DPX	58.0	98.0	73.0	3.0	25.0	89.0	ECOM
	87.0	121.0	72.0	170.0	23.0	101.0	Enerac
#92133 Haul Truck							
CleanAir Systems	51.0	12.0	21.0	43.0	25.0	39.0	ECOM
	51.0	8.0	10.0	38.0	11.0	7.0	Enerac
#92506 LHD							
DCL BlueSky	83.0	6.0	40.0	50.0	16.0	16.0	ECOM
	48.0	0.0	51.0	65.0	2.0	14.0	Enerac
Donaldson	-	-	-	-	-	-	ECOM
	28.0	1.0	61.0	0.0	0.0	1.0	Enerac
#92526 LHD							
ECS Cattrap	34.0	59.0	55.0	-	17.0	121.0	ECOM
	31.0	81.0	68.0	177.0	31.0	163.0	Enerac
Biodiesel B20, PTX	22.0	16.0	34.0	36.0	16.0	36.0	ECOM
	215.0	213.0	257.0	251.0	501.0	509.0	Enerac
Biodiesel B50, PTX	21.0	21.0	18.0	-	12.0	40.0	ECOM
	6.0	3.0	43.0	41.0	6.0	8.0	Enerac
#99942 LHD							
DCL MineX	28.3	68.0	-	-	17.5	89.5	ECOM
	10.0	85.0	29.0	190.0	10.0	45.0	Enerac

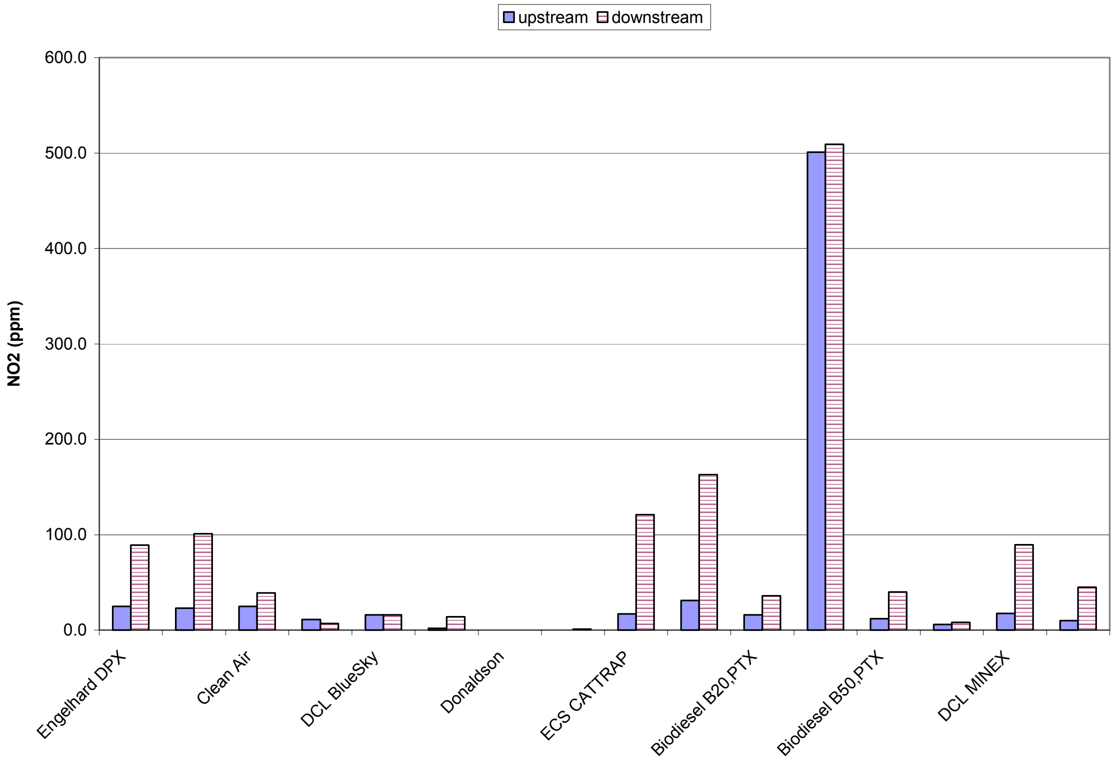

Figure 40. NO$_2$ Emissions in TCS mode

Implementation of the DPF Systems

The costs of the DPF systems and their installations are summarized in Table 19.

Table 19. Costs and installation issues related to implementation of DPF systems

Vehicle	Equip. Type	Engine Type	DPF System	DPF cost	Mounting Location	Mechanic Hours	Hardware
#92128	MTI 1604 Haul Truck	BF6M1013 ECP	Engelhard DPX 9308	$5,500.00	Original DOC Brackets	12 hours mechanical $360.00 *(move original DOC mounts to get trap close to turbo)*	Structural modifications Clamps Heat Wrap $1,400.00
#92133	MTI 1604 Haul Truck	BF6M1013C	CleanAir FPA 158W	$4,800 purchase $20.00/125 gal FBC	Original DOC Brackets	7 hours mechanical $210.00 *(to install trap as close to the turbo as possible)*	Clamps Heat wrap $1000.00
#92506	MTI 350 LHD	BF4M1013	DCL BlueSky 3211-SA-6CG1-21	$8,300.00 filter $5,400 regen station	Engine hood *(not suitable location for field use)*	2 hours electrical, 4 hours mechanical $180.00	Flex Pipe Clamps $200.00

Vehicle	Equip. Type	Engine Type	DPF System	DPF cost	Mounting Location	Mechanic Hours	Hardware
#92506	MTI 350 LHD	BF4M1013	Donaldson P604516 (Twin side by side filters)	$1,500 housing ($165.00x2) disposable filters	Engine hood *(not suitable location for field use)*	3 hours mechanical $90.00	Flex Pipe Clamps $200.00
#92526	Elphinstone R 1300 LHD	CAT 3306 DITA	ECS CT 28 Cattrap	$8,300 + $6,000 for spare filter (2 filter elements are required to limit equipment downtime)	Alongside engine on side well *(not suitable location for field use)*	5 hours mechanical $250.00 *Would require chassis modifications for permanent installation/maintenance*	Flex Pipe Clamps Heat wrap $1100.00
#99942	Elphinstone R 1500 LHD	CAT 3306 DITA	DCL MineX 5C57 11	$6,000.00	Original DOC Brackets	2 hours Mechanical $60.00 *(installed in original position)*	Heat Wrap Clamps $1,000.00

The experiences the mine operators gained with the tested DPF systems during these short-term trials are summarized below.

Engelhard DPX 9308

The tested Engelhard DPX system was in use at the Stillwater mine for more that 4600 hours prior to the study. The trap was rotated (end-to-end) twice and baked once since its installation. This system worked according to expectations. In cases when it was retrofitted to vehicles that were operated over favorable duty cycles, the system was found to be a truly passive system. According to the Stillwater mine operators this is probably the best choice for their hard working (high exhaust temperature) heavy-duty equipment.

CleanAir Systems FPA 158W

This system worked as designed and advertised. The system required the use of a fuel borne catalyst. The feasibility of blending the fuel borne catalyst with fuel supplies for an entire fleet still needs to be investigated. As a general statement, it would require approx. $15,000/month to provide the FBC to the whole Stillwater diesel fleet. The effects of the FBC on the performance of the diesel oxidation catalytic converters (DOC's) and the other exhaust aftertreatment systems is not known at this time. The Stillwater mine operators are of the opinion that the cost of the FBC will probably preclude the use of CleanAir Systems DPF system.

DCL Blue Sky 3211-SA-6CG1-21

This active system was originally tested at the Stillwater East Boulder mine but was removed due to the failure of the on-board heating element. During the short trial at the Stillwater Nye mine this system worked as designed. Some issues that mine operators must consider prior to using this system are that it requires downtime for regeneration and requires a regeneration station with electric power and a compressed air supply. Because electric power is not available in the majority of the production zones in the Stillwater mine and historically their equipment does not return to a central station after the work shift, the mine operators deemed it as unpractical.

Mac's Mining Repair/Donaldson P604516

This system worked as designed during the short trial at the Stillwater Nye mine. The filter elements did not sustain any physical damage during the tests. However, the size of the unit and the reputed 100-hr short life span of the filter elements were found to be the major obstacles in implementation of this system. The filter life and operational cost could not be determined, during this study, due to the limited trial period. The Stillwater mine operators do not consider this system to be practical for Stillwater's applications.

ECS CT 28 Cattrap

This DPF system uses a cordierite element that was wash coated with a base metal catalyst. During these short trials the system was found to work as designed. However, because of the short nature of these trials, there was no need to regenerate the filter using the CombiClean regeneration station, thus the regeneration system was not evaluated. Due to the size of the Cattrap system (14"X36"), major equipment modifications were required to install the unit. From the perspective of the Stillwater mine operators the size of the unit, its cost ($8,300 initial plus $6.000 for replacement section) and the cost of the installation make this system an unlikely candidate.

DCL MineX 5C57 11

This passive system was in operation at the Stillwater mine for more than 800 hours prior to the study. Originally this system was installed on an LHD #92535 (R-1300) but was removed due to high back pressures. The exhaust temperatures generated over the duty cycle of this particular machine were not sufficient to secure regeneration of the system. Since installed on #99942, the system has worked as designed and did not require any maintenance during this period. According to the Stillwater mine operators this system is a good choice for high duty cycle machines.

DPF systems at Stillwater

Over a dozen filters have been on trial at the Stillwater mine, for a combined total of over 22,000 hours prior to this study. The majority of the DPF systems are the Engelhard DPX 9308. Only one of these systems installed on a locomotive was replaced due to a failure caused by runaway regeneration. The other installed systems have been virtually maintenance free. The mine also has had positive experience with the DCL 5C5711 MineX DPF system. In their opinion this has been a very good system with the only problem being the inappropriate selection of an application. The two reasons why DCL does not have a larger presence at Stillwater are the company’s desire to standardize their equipment and the fact that the Deutz service group, the major supplier of engines to the mine, supports the Engelhard DPF systems.

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