CASE STUDIES OF MINING EQUIPMENT DIESEL RETROFIT PROJECTS

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Table of Contents

1.0 Introduction

Diesel engines provide important fuel economy and durability advantages for large heavy-duty trucks, buses, and nonroad engines. Diesel-powered equipment has become increasingly employed and recognized as the workhorse in mining since their introduction into underground mining operations since mid-1960s. Diesel engines also have several advantages over gasoline engines in terms of safety. Because diesel engines operate in a lean fuel/air ratio, they produce very low levels of carbon monoxide in the exhaust. This is particularly important for underground mining equipment operating in a workplace with limited fresh air supply. Diesel fuel itself also has a fairly high flash point, reducing the possibility of unwanted fuel ignition and fires underground. Although diesel engines have their advantages, they also have the disadvantage of emitting significant amounts of particulate matter (PM) and oxides of nitrogen (NOx), and lesser amounts of hydrocarbon (HC), carbon monoxide (CO), and toxic air pollutants.

There is growing evidence that exposure to diesel PM adversely impacts human health in a variety of ways. As early as 1988, the International Agency for Research on Cancer (IARC) concluded that diesel particulate is probably carcinogenic to humans. In August 1998, California Air Resources Board identified PM emissions from diesel-fueled engines as a toxic air contaminant. In 2000, the U.S. EPA declared diesel PM to be a "likely human carcinogen." A recent report, "Diesel and Health in America: The Lingering Threat," issued in February 2005 by the Clean Air Task Force, reviews the health impacts of diesel particulate emissions in the U.S. This report states that fine particulate pollution from diesel engines shortens the lives of nearly 21,000 people in the U.S. every year, with health-related damage from diesel PM estimated to total $139 billion in 2010.

In the late 1970's, due to growing concerns over the increased use of diesel engines in underground mines and the possible harmful health effects, the Mining Diesel Emissions Council (MDEC) was established. MDEC is a forum dedicated to improving air quality in underground mines and protecting the diesel operators. MDEC started as a collaborative government consortium among the governments of Canada, United States, and Ontario to jointly fund studies on diesel emissions in underground mines, improve methods of monitoring components of diesel exhaust, and develop methods of controlling them. MDEC holds annual Mining Diesel Emissions Conference to enable the mining communities to report and discuss diesel emissions reduction. More information and copy of the presentation slides from the annual conference can be found at: http://www.dieselnet.com/mdec.

With the growing knowledge of the adverse health impacts from exposure to diesel PM, the Mine Safety and Health Administration (MSHA) adopted 30 CFR 57.5060 in January 2001, limiting the exposure of underground metal and nonmetal miners to diesel particulate matter. Beginning in May 19, 2006, mine operator is required to limit the concentration of diesel PM to which miners are exposed in underground areas of a mine by restricting the average eight-hour equivalent full shift airborne concentration of total carbon, where miners normally work or travel, to 160 micrograms per cubic meter of air (160 TCμg/m3). Starting on January 20, 2007, a miner's personal exposure to diesel PM in an underground mine must not exceed an average eight-hour equivalent full shift airborne concentration of 350 TCμg/m^3. Subsequently, effective on May 20, 2008, a miner's personal exposure to diesel PM in an underground mine must not exceed an average eight-hour equivalent full shift airborne concentration of 160 TCμg/m^3. (See http://www.msha.gov/30cfr/57.5060.htm). To comply with this regulation, the underground mining community is working to identify and evaluate technically and economically feasible emission controls technologies, including diesel particulate filters (DPFs), diesel oxidation catalysts (DOCs), and reformulated fuels.

In order to assist the mining equipment owner/operator in selecting a DPF that would achieve PM reduction required by the regulation, MSHA has released a "Diesel Particulate Matter Control Technologies" document that lists DPFs that have been evaluated by MSHA. MSHA will accept the use of these filters as evidence of compliance with the applicable PM emissions limits. The document (http://www.msha.gov/01-995/Coal/DPM-FilterEfflist.pdf) lists different types of filters, which includes paper/synthetic filters; non-catalyzed DPFs; and catalyzed DPFs, as well as the percent PM efficiencies achieved by the DPF. Another useful tool to aid in the selection of a DPF for a particular mining equipment is the "Diesel Particulate Filter Selection Guide for Diesel-powered Equipment in Metal and Nonmetal Mines" (http://www.msha.gov/nioshmnmfilterselectionguide/dpmfilterguide.htm). This guide assists the diesel mining equipment owner in selecting the appropriate DPF for a particular engine through series of questions. In addition, during June and July 2006, MSHA conducted a series of outreach seminars to assist metal and nonmetal underground mine operators in complying with regulations for the use of diesel powered equipment. The seminars addressed enforcement issues, questions regarding provisions of the final rule, as well as controlling diesel PM exposures in underground mines. The presentations that were given during the seminars are available at: http://www.msha.gov/01-995/dieselpowerpoints2006.asp.

The case studies discussed in this paper focus on those projects that have been completed, or are in progress, that utilize emission control technology on mining equipment. Many of the projects highlight the feasibility of installing verified on-road retrofit technologies on mining equipment and relate some of the lessons learned that may assist others in planning additional mining equipment projects. The limited range of experience with retrofits on mining equipment engines summarized in this report also serves to point out the need for expanding the range of verified retrofit technology options for nonroad diesel applications in general, and mining equipment engines in particular. This paper focuses on technology-based strategies and, where available, provides information on the specific type of technology installed on the type of mining equipment engines, and the emission reductions that were achieved or are expected. For more detailed descriptions of available diesel exhaust emission control technologies that can be retrofit on existing on-road and nonroad diesel engines, please see MECA's companion white paper, *Retrofitting Emission Controls On Diesel-Powered Vehicles* (available on the MECA website at: www.meca.org or the MECA diesel retrofit website at: www.dieselretrofit.org).

2.0 Mining Equipment Diesel Retrofit Case Studies:

2.1 Diesel Emissions Evaluation Program: Evaluation of Diesel Particulate Filter Systems at Stobie Mine

From April 2000 to December 2004, the Diesel Emissions Evaluation Program (DEEP) and Inco's Stobie mine conducted a study on the long-term effectiveness of diesel particulate filter systems (DPFs) to reduce diesel particulate matter (PM) in underground environments. The study was concerned with the ability of the DPF to sustain long-term filtration efficiencies under harsh physical environment that exists for equipment operating in mining service.

Inco's Stobie mine is located on the south rim of the Sudbury ore basin, mining nickel-copper ore. It uses a diesel fleet that is typical of hard-rock mining across the Canadian mining industry. For this project, five heavy-duty Load/Haul/Dump (LHD) scooptrams were selected to represent the primary heavy-duty workhorse in underground mining. One of the units had a dual exhaust Deutz engine and the other four had Detroit Diesel DDC 60 series engines. Four Kubota tractors were also selected to represent the light-duty vehicles that are increasingly being used in transporting underground personnel.

Figure 1: LHD Scooptram

For the heavy-duty LHDs, three different types of filter systems were used:

- Two completely passive systems, one with knitted glass fiber filter and a fuel-borne catalyst (LHD-A) and another with a cordierite honeycomb catalyzed filter (LHD-B).
- Three completely active systems; two with a SiC honeycomb filter that used on-board electrical heating for regeneration (LHD-C) and the other with cordierite honeycomb filter with a built-in burner for regeneration (LHD-D).
- One system that was a mixed passive-active system with SiC or cordierite honeycomb filter (LHD-E). The passive part of the system used a fuel-borne catalyst and the active part used on-board electrical heaters.

For the light-duty tractors, three active filter systems were tested:

- One system with a ceramic fiber filter medium and an on-board electrical heater (T-A)
- One system with a SiC honeycomb filter and an on-board electrical heater (T-B)
- One system with a SiC honeycomb filter and an off-board electrical heater (T-C).

Figure 2: SiC DPF installed on LHD

Figure 3: SiC DPF installed on LHD

Tests on the DPFs were conducted every 250 hours of vehicle operation for heavy-duty machines and monthly for light-duty machines. During the routine periodic tests, an ECOM instrument was used to analyze for NO, NO_2, CO, CO_2, and O_2 and measure Bacharach smoke numbers upstream and downstream of each filter.

DPF specific results are as follow:

- LDH-B: This system had low complexity and required little special attention. Filtration efficiency of soot was greater than 98 percent throughout its 2221 hours of operation. Smoke numbers were reduced to an average of 0.6 downstream from 7.1 upstream.
- LDH-C: The first of the two systems that were tested had marginal filtration efficiencies of 92-94 percent after 300 hours of operation and concerns were raised about whether active regeneration was being routinely practiced by the operators. After a total of 940 hours, the filter had a physical cracks and holes in the honeycomb structure and assumed

that it was the result of inattention to regeneration and the filter was removed. A new system was installed and this system had very good performance, achieving up to greater than 98 percent over its 1.5 years of service. The smoke numbers averaged 1.0 downstream compared to 7.1 upstream and opacity was excellent at 0.4 percent. Reductions in emissions during 8-mode tests gave 93-99 percent PM reduction for one of the filters and 56-85 percent in the other.

- LHD-E: This filter system was installed on a Deutz engine and two identical filters were used because of the need to filter both sides of the dual exhaust. Relatively higher than desired backpressures were experienced by this system and indicated that the amount of fuel-borne catalyst being used was insufficient to achieve passive filter regeneration. In addition, the continued high backpressure indicated that active regeneration was not being routinely practiced by the operators. Filtration efficiencies remained fairly good, ranging from 84 to greater than 99 percent. After 2057 hours of operation, one of the SiC honeycomb filters showed excessive separation between it and its canister. A new cordierite honeycomb was installed as a replacement and accumulated an additional 173 hours of operation before the end of the project. One of the filters was sent to CANMET for post-use testing. A large dent was observed on the outside shell of the filter, but the inside canister at this location was undamaged. The mat holding the ceramic monolith in place in the canister was severely degraded and was likely the cause of the filter being able to move within the canister.
- LHD-D: Because this system used the diesel fuel burner as the central component for regeneration, significant pre-installation fail-safe testing was required. After only 116 hours of operation, the smoke numbers downstream were seen to be increasing to 3 compared to the upstream numbers ranging 6-7. Problems with the control software for this system and indication of soot breakthrough caused the test to be terminated.
- LDH-A: This system was complex due to the controls needed to regulate pumping the fuel-borne catalyst into the vehicle's fuel tank. The system showed very inefficient soot filtration, ranging from 3-70 percent and downstream smoke numbers of 5.5, compared to 7.0 upstream. This system was deemed to have failed with essentially zero hours of operation.
- T-B: This filter successfully accumulated 577 hours of operation over nearly three years with excellent soot filtration efficiencies of greater than 99 percent and very low opacity and downstream smoke numbers. The post-testing done at CANMET showed filtration efficiencies of 94 percent PM mass, 99.9 percent PM particles and 82 percent elemental carbon component.
- T-C: This filter successfully operated for nearly three years, accumulating 864 hours of operation. Two alternating filters were used: one in use while the other was being regenerated externally. Both filters maintained excellent soot filtration efficiencies of about 99 percent. One of the filters was examined in post-use at CANMET. The filtration efficiencies were 95 percent PM mass, 97.8 percent PM particles, and 89 percent elemental carbon component. The discharge side of the filter showed a small area of the honeycomb where soot blowthrough was occurring and borescope images confirmed very small microcracks in some of the channels.
- T-A: This system accumulated 453 hours of operation with marginally acceptable soot filtration efficiency ranging from 77 percent to 94 percent. Relatively high smoke numbers of 3.5 were measured downstream compared to 9.0 upstream. The system was

removed from the testing because the manufacturer announced that it has stopped manufacturing the glass fibers used as the filter medium.

Conclusion:

- Both heavy-duty and light-duty vehicles in underground mining operations can be retrofitted with high efficiency DPF systems for PM reduction. However, all the systems tested in the Stobie Project required more close attention than was desired, although there were a wide variation in the amount of attention needed.
- Taking time to correctly match the vehicle duty with an appropriate DPF is essential for a retrofit program to be successful.
- Proper communication with vehicle operator is essential. Operators must be attentive to non-convent
- Install alerts and alarms for high backpressure or else serious harm could be done to the engine.
- Dashboard signals for the filter are needed in order to give information to the vehicle operator about the filter's effectiveness.
- The increased emission of noxious gases is often the result of the way in which some DPFs regenerate and these emissions, particularly NO_2 must be monitored carefully.
- An emission-based maintenance component of an overall vehicle/engine maintenance program is essential. Proper functioning of a DPF should be evaluated as part of routine maintenance.

More information on this demonstration project is available at: http://www.deep.org/reports/stobiedpf.pdf.

2.2 Noranda Inc.- Brunswick Mine Diesel Particulate Filter Field Study

In 2000, the Diesel Emissions Evaluation Program (DEEP) initiated the Brunswick Mine Diesel Particulate Filter Study with Noranda's Brunswick Mine, with collaboration of Natural Resources Canada-Canada Centre for Minerals and Energy Technology (CANMET), and National Institute of Occupational Safety and Health (NIOSH). The purpose of the Noranda Brunswick Mine project was to determine the effectiveness, durability, reliability, and economic viability of current generation DPF technology when applied in underground mining operations.

The Noranda project team selected four heavy-duty production vehicles to be tested with DPF systems over a period of 4,000 hours. Two of the vehicles that were chosen were load/haul/dump (LHD) vehicles that are used as front-end loaders to dig into a pile of ore, tram the load over a distance, dump it to a transfer point, and return to the load point to repeat the cycle. The other two selected vehicles were haulage trucks that are designed to haul large loads over long distances. The trucks are typically loaded either by an LHD or at an overhead chute. All four vehicles were powered by electronically controlled turbocharged and intercooled engines. The engines in LHDs were rated at 242 kW (325 hp) and the engines in the trucks were rated at 278 kW. Four DPF systems were selected and tested on the vehicles.

Figure 1: Load/Haul/Dump

DPF specific results are as follow:

- DPF A: This DPF system installed on a LDH application comprised of two cordierite wall-flow monolith coated with a base metal catalyst. The filters were installed in parallel in a horizontal orientation through the use of inlet and outlet manifolds. The system was designed to promote passive regeneration. During the study, the filters accumulated over 3,000 engine hours without cleaning and ash removal and for an overall total of 4053 engine hours. The DPF system measured between 99 and 100 percent filtration efficiency of elemental carbon particles when installed new and continued to perform at better than 96 percent efficiency with 4000 operating hours on it.
- DPF B: This DPF system installed on a LDH application comprised of a platinum-catalyzed SiC substrate. The active DPF system was also equipped with a 600 volt electric heater installed at the inlet face of the filter element. In order to regenerate the DPF using the electrical heating system, it was necessary to bring the vehicle to the shop and connect the heater to shore power and connect a source of compressed air to the inlet cone. This was initially planned to regenerate the filter at the end of each shift, although this was an inconvenient requirement opposed by the mine production crews. Initially, the electrical regeneration system caused considerable technical and safety problems. However, during the project it became apparent that the platinum catalyzed filter was able to passively regenerate over the duty cycle and the electrical regeneration system was redundant. The filter system performed well over 4260 hours at 99 percent filtration efficiency of elemental carbon particles.
- DPF C: This DPF system installed on a haulage truck comprised of two parallel SiC substrates with oxidation catalysts in the upstream position. The filter was passively regenerated using an iron/strontium (Fe/Sr) based fuel additive. The additive was expected to lower the temperature at which the regeneration process is initiated. The additive was blended to the fuel in a separate fueling system and the concentration of metals in the fuel was 20 ppm, with a 16 Fe:4 Sr ratio. After an initial period of satisfactory operation, the filter started building excessive engine backpressure due to slow regeneration that occurred despite high exhaust temperatures. After accumulating 2500 operating hours, the filter substrate failure occurred due to uncontrolled

regeneration of the overloaded filter. A replacement unit was also damaged due to uncontrolled regeneration after approximately 1620 operating hours.

- DPF D: This DPF system installed on a haulage truck comprised of cartridges with knitted fiberglass filter media. The filter was passively regenerated using the same Fe/Sr additive used in DPF C. The first DPF system installed was undersized in design, resulting in backpressure problems. After being replaced with a larger unit, the filter performed well. The most significant problem with the system was the large size of the unit, making it difficult to install on the vehicle. Filter efficiency was measured closer to the 90 percent range as compared to 98 percent and higher with the wall-flow monolith systems, although the exhaust back pressure was much lower than the other systems. During the project, the manufacturer took the fiber cartridge design off the market.

Figure 2: Base Metal Catalyzed Cordierite Filter

Figure 3: Pt Catalyzed SiC Filter

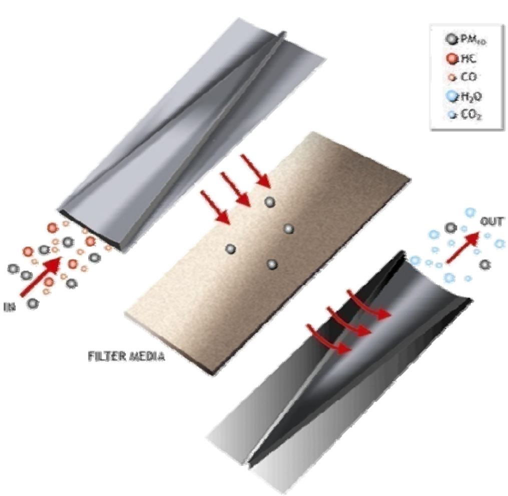
Conclusion:

- This project demonstrated that all tested DPFs were able to provide over 90 percent reduction in the diesel PM mass emissions as well as reductions in ambient PM exposures.
- DPF selection process is a critical factor in successful implementation of the project. Requirements for filter regeneration must be covered in the application engineering from the start and maintenance and operation requirements must be agreed on by all parties for acceptance of the system.
- The study showed that current off-the-shelf DPF technology requires additional custom application engineering in order to be optimized for the each individual application. Careful application engineering is needed in every individual case.
- With more than 2000 operating hours on the systems, all with the exception of the failed DPF C demonstrated concentration near 0.05 mg/m^3 compared to the baseline non-DPF concentration of 0.40 mg/m^3.

More information on this project is available at: www.deep.org/reports/nordpf_final.pdf.

2.3 Evaluation of Partial Flow Diesel Particulate Filters on Mining Equipment

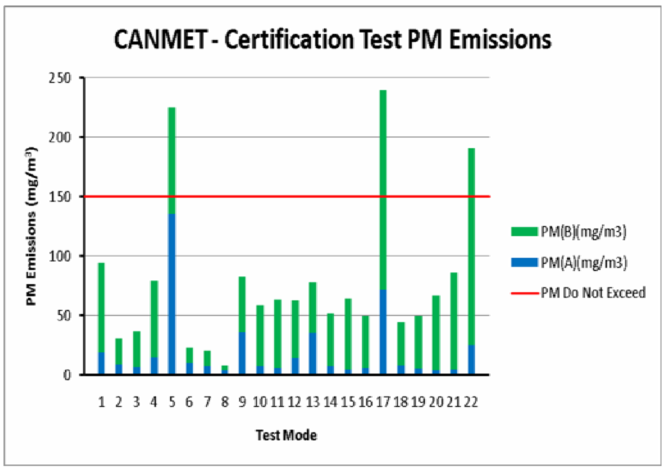
In order to evaluate the efficiency and to validate the commercial applicability of a partial flow diesel particulate filter, an emission control device manufacturer conducted two case studies retrofitting mining equipment with the flow-through filters. The flow-through filter utilizes substrates of alternating layers of corrugated metal foil and flat layers of metal fiber fleece brazed together to produce a flow-through honeycomb structure. The corrugations in the metal foil form alternating trapezoidal ducts with a varying cross sectional area. When installed into the exhaust stream, the design of the alternating trapezoidal ducts creates a pressure differential across the filtration media causing some of the exhaust to pass through the filter media. As the exhaust passes through the filter media, diesel PM is trapped. A precious metal catalyst coating is used to assist with regeneration of the collected PM and oxidize the CO and HC. This coating is also designed to minimize the production of NO_2.



Two case studies were performed to determine the effectiveness of the flow-through filter and to validate its commercial applicability.

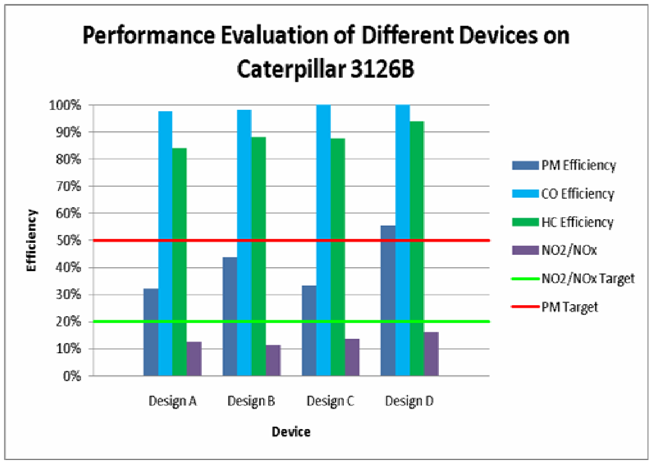
Case Study 1:

The flow-through filter was retrofitted onto a Kubota D902-E2-UV (Tier II) diesel engine, rated power of 21.6 hp at 3200 rpm, and rated torque of 41.4 ft-lb at 2600 rpm. The testing was conducted at the CANMET-MMSL facilities and a 22-mode test was used. The testing demonstrated that the device was capable of reducing PM emissions to acceptable levels under the standard which has a "do not exceed" requirement for PM emissions of 150 mg/m^3 (see below graph of PM certification results). Based on the results of this test, the Kubota D902-E2-UV with the flow-through filter using ultra low sulfur diesel fuel was granted certification and listed on the CANMET-MMSL approved diesel engine list.



Case Study 2:

Four different commercially available design variation of the flow-through filter were evaluated on Caterpillar 3126 B (Tier II) diesel engines, rated power of 183 hp at 2200 rpm, and rated torque of 728 ft-lb at 1400 rpm. The target of the study was to achieve at least 50% reduction of PM and to not increase the NO_2 to baseline NOx emission ratio by more than 20%. The testing was performed at a 3rd party laboratory and an 8-mode test was used. The results from the testing for CO, HC, NO_2/NOx and PM emission performance is shown in the graph below. Only device D was able to meet both targets for PM and NO_2/NOx.



2.4 *Evaluation of Biodiesel Fuel and Diesel Oxidation Catalyst in an Underground Metal Mine*

The University of Minnesota, Inco, CANMET, Michigan Technological University, ORTECH, and the National Institute for Occupational Safety and Health (NIOSH) conducted a demonstration project to evaluate the impact of blended biodiesel fuel and modern diesel oxidation catalyst (DOC) on air quality and diesel emissions. This study was conducted at Inco's Creighton Mine in Sudbury, Ontario in October 1997. Other participants of this study include the Manufacturers of Emission Controls Association, the Ontario Soybean Growers' Marketing Board and the Deutz Engine Company. This study evaluated the mine air quality in a non-producing mine section operating a diesel scoop equipped with modern DOCs. During the first week of the study, a diesel-powered scoop was operated on low sulfur, number 2 diesel fuel (D2). During the second week, the scoop was operated on a 58 percent blend of soy methyl ester (SME) biodiesel fuel and a low sulfur D2. During both weeks, the scoop was equipped with a pair of identical, advanced DOCs. The objective of the field test was to determine the changes in exhaust emissions and to estimate operating costs of operating a test vehicle on a blended SME biodiesel fuel blend with a DOC.

Six identical DOCs with an advanced design catalyst with a ceramic flow-through substrate were used in this evaluation. Four of the DOCs were used, two with each fuel. The other two DOCs were backups and were never used during the tests. Each DOC was conditioned by the manufacturer for about 25 hours using low sulfur D2 fuel. The DOCs were mounted downstream of the exit to the engine exhaust manifold in an area previously occupied by the scoop's own DOC and muffler.

The engine and DOCs were conditioned prior to the beginning of each week of testing with the two fuels. The low sulfur D2 fuel was evaluated during week 1 and the break-in period was about 8 hours. The blended fuel was evaluated during the second week and the break-in period was about 10 hours.

Results:

Data were collected for 11 sampling days, five days with each fuel type and one day with blended fuel and no DOCs.

Effects of DOCs:
The DOCs had similar effects on emissions regardless of exhaust bank or fuel type, effectively oxidizing 99 percent of the CO, although the DOCs also oxidized NO to NO_2, causing 230 percent increase in NO_2 tailpipe concentration.

Table 1: Effect of DOCs on gaseous emissions

Emissions	Diesel Fuel			Blended Fuel		
	Upstream	**Downstream**	**% change**	**Upstream**	**Downstream**	**% change**
CO, ppm	155	10	↓98±10%	174	2	↓99±11%
CO_2, %	8.24	8.58	No change	N/A	N/A	N/A*
NO, ppm	596	546	No change	634	526	↓17±4%
NO_2, ppm	37	120	↑185±78%	51	171	↑233±59%
NOx, ppm	633	666	No change	685	697	No change

* Due to sensor failure, blended fuel CO_2 concentrations were not available

Effects of blended fuel:
There was a 43±28% increase in NO_2 downstream of the DOCs after the fuel was switched from diesel to blended fuel.

Gaseous Pollutants:
Table 2 below summarizes the gas data collected by CANMET at the upwind and downwind sampling locations. Additionally, Inco requested that the DOCs be taken off and an additional day of testing be conducted with the blended fuel without the DOCs. A single day of testing is insufficient for statistical inferences to be drawn, but illustrates the general impact of DOCs on exhaust emissions. DOCs reduce CO and hydrocarbons but may increase NO_2 and SO_2. When used with an oxygenated fuel, such as the blended biodiesel fuel, the NO_2 increase is greater than that observed with a D2 fuel.

Table 2: Gaseous Pollutant Concentrations

Condition	Average CO_2 (ppm)	Average CO* (ppm)	Average NO (ppm)	Average NO_2 (ppm)	Average SO_2 (ppm)
Upwind Sampling Location					
D2 + DOC	435±9	0.0	0.2±0.2	0.7	0.5
D2 + DOC	402±21	0.0	0.3±0.3	0.3±0.1	0.3
D2 + DOC	397±17	0.0	0.1±0.2	0.1	0.1
D2 + DOC	394±14	0.0	0.1±0.1	0.1	0.1
Blend + DOC	485±5	0.0±0.1	0.1±0.1	0.1	0.1±0.1
Blend + DOC	398±10	0.2±0.1	0.3±0.2	0.2	0.2
Blend + DOC	438±12	0.0	0.2±0.2	0.1	0.1
Blend + DOC	425±12	0.0	0.3±0.2	0.2	0.2
Blend	426±15	0.0	0.2±0.2	0.2	0.2
Downwind Sampling Location					
D2 + DOC	1148±247	0.1±0.1	5.6±1.8	1.9±0.6	0.5±0.1
D2 + DOC	1087±230	0.1±0.1	5.2±1.6	2.2±1.0	0.6±0.1
D2 + DOC	1073±255	0.2±0.2	5.2±1.9	1.9±0.7	0.5±0.1

D2 + DOC	1093±267	0.2±0.1	5.3±1.9	2.0±0.7	0.5±0.1
Blend + DOC	1345±286	0.3±0.1	5.4±1.8	2.6±0.9	0.5±0.1
Blend + DOC	1109±286	0.3±0.2	4.9±1.8	2.3±0.9	0.6±0.1
Blend + DOC	1122±291	0.4±0.2	4.4±1.7	2.1±0.8	0.4±0.1
Blend + DOC	1251±341	0.0±0.1	5.0±2.0	2.4±1.0	0.5±0.1
Blend	1164±356	1.3±0.6	6.6±3.0	0.8±0.2	0.7±0.1

* Negative values set to 0.0

Blended biodiesel fuel used in conjunction with a modern DOC offer a passive control option to reduce diesel in an underground mine. The study found that the primary limitation to the use of biodiesel fuel is cost. More information on this project is available at: http://www.deep.org/reports/inco_bio.pdf.

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

In order to determine viability of diesel emissions control technologies in underground mines, the Metal/Nonmetal Diesel Partnership was 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, to conduct a series of comprehensive field evaluations. The 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 diesel particulate matters emissions, such as DPFs, disposable paper filters, diesel oxidation catalyst (DOC), and reformulated fuels. The first of the studies was conducted in the Stillwater Mining Company's Nye Mine, in 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 (conducted from May 19, 2003 to May 30, 2003);
- The objective of the second phase was to assess the effectiveness of DPFs in controlling the exposure of underground miners in actual production scenarios.

The primary part of the study was the series of measurements of the ambient concentrations of diesel PM 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. The ambient measurements were complemented with measurements of PM and gas concentrations in the exhaust system of the tested vehicles while the vehicles were parked and their engines were loaded under stationary conditions.

Vehicles:

The Stillwater Mining selected diesel equipment used in this study to represent typical vehicles and power packages from the Stillwater Nye mine production fleet. The two trucks and three load-haul-dump (LHD) vehicles that were selected are classified as heavy-duty production machines and are representative of the mine fleet, the duty cycle for that type of vehicle and their effect on mine air quality. The engines powering these vehicles are also representative of the fleet. Descriptions of the vehicles used in the study are as follows:

- MTI DT-1604 trucks #92128 and #92133: MTI DT-1604 is a truck with rated load of 32,000 lb and box capacity of 8.2 m^3. Truck #92128 is powered by a Deutz BF6M 1013FC and truck #92133 is powered by BF6M 1013ECP.
- MTI LT 350 LHD #92506: MTI LT 350 is a load-haul-dump with rated load of 750 lb and bucket capacity of 1.9 m^3. This model is powered by a Deutz BF4M 1013C.
- Caterpillar Elphinstone R1300 LHD #92526: Caterpillar Elphinstone R1300 is a load-haul-dump vehicle with rated load of 14333 lb and bucket capacity of 2.8 m^3. This model is powered by a Caterpillar CAT 3306 DITA engine detracted to 123 kW (135 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 LHD #99942: Caterpillar Elphinstone R1500 is a load-haul-dump vehicle with a rated load of 2,2491 lb and bucket capacity of 4.8 m^3. This model is powered by a Caterpillar CAT 3306DITA 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.

Control Technologies:

Control technologies that were installed on the vehicles were six DPF systems to evaluate their effectiveness in reducing the concentration of diesel PM in the underground mine environment. Additionally, the effects of replacing the currently used #1 diesel fuel with the blend of #1 diesel and B20 and B50 biodiesel and with #2 diesel were evaluated. The effects of DOCs on diesel emissions were also examined. Descriptions of the DPF systems that were installed are as follow:

- DPF #1: This DPF system uses a cordierite wall-flow monolith filter element with a proprietary platinum-based catalyst. The DPF should passively regenerate during an engine's duty cycle if the exhaust temperature exceeds 350°C for an extended period of the cycle. Although the system is designed primarily to control diesel PM, significant reductions of CO and unburned hydrocarbons are expected due to the platinum-based catalyst. This DPF system was installed on the MTI DT-1604 truck #92128.
- DPF #2: This DPF system uses a cordierite wall-flow monolith filter element that was "washcoated" with a proprietary platinum-based catalyst. This system is used in conjunction with a fuel additive that contains both platinum and cerium, which allows it to be used effectively at a dosage level substantially lower than other fuel-borne catalysts. The system, with the fuel-borne catalyst, should passively regenerate during the engine's duty cycle if the exhaust temperature exceeds 330°C for extended periods of the cycle. This system was designed to provide DPF regeneration for duty cycles having relatively low exhaust temperatures. The DPF system was installed on the MTI DT-1604 truck #92133 and the fuel additive was mixed into the fuel tank. The system was delivered several weeks before the study and had accumulated approximately 200 hours of run time prior to the testing.

- DPF #3: This DPF system is designed as an active system that does not completely regenerate during the duty cycle and 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. The system uses a silicon carbide wall-flow monolith filter element that allows relatively short 2-hour regenerations. The frequency and length of the regeneration sessions is dependent on engine PM emissions. This system was made available for this study by the Stillwater East Boulder mine. The heating elements were replaced and the system was installed on LHD #92506. Due to the limited space available on the vehicle, the system was installed with a temporary arrangement and was used only during the evaluation in the isolated zone and shop. The system was removed immediately after the tests and was not evaluated in the production because the mine was not able to provide the necessary infrastructure in production zones to support electrically regenerated systems.
- DPF #4: This DPF system is in the developmental stages and uses two high temperature disposable filter elements. The two filter elements were evaluated as part of a temporary setup that was custom fitted to the LHD #92506. Because the 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 exhaust flow rate.
- DPF #5: This DPF system is a passive system that uses a base metal catalyst coated cordierite monolith that partially regenerates during engine operation but might also require periodic cleaning using a regeneration station. The system should passively regenerate during the duty cycle if the exhaust temperature exceeds 390°C for a significant portion of the engine operating time. The frequency of the periodic cleaning is dependant on the ability of the system to regenerate during the duty cycle, although the manufacturer predicted that cleaning would be necessary approximately every 250 hours, the same period as scheduled preventive maintenance sessions. This system was installed on the LHD #92526. The DPF system tested on this vehicle also included a DOC mounted downstream of the DPF. The DOC is designed to reduce emissions of CO and unburned HCs. The system was decommissioned shortly after the trial.
- DPF #6: This system uses a platinum washcoated cordierite filter element and is very similar to DPF #1. The system was installed on LHD #99942.

Below is a summary table of the vehicles and the DPF systems that were installed for this study.

Vehicle #	Vehicle Type	Engine Model	DPF Media	DPF Regeneration
92128	MTI DT-1604 truck	Deutz BF6M 1013FC	Cordierite	Platinum washcoat
92133	MTI DT-1604 truck	Deutz BF6M 1013ECP	Cordierite	Platinum washcoat + Ce-Pt fuel borne catalyst
92506	MTI LT-350 LHD	Deutz BF4M 1013C	Silicon carbide	Catalyzed + on-board electrical regeneration
92506	MTI LT-350 LHD	Deutz BF4M 1013C	High temp. disposable	Disposable and washable
92526	Elphinstone R1300 LHD	CAT 3306 DITA (165 hp)	Cordierite	Base metal washcoat + off-board electrical regeneration
99942	Elphinstone R1500 LHD	CAT 3306 DITA (220 hp)	Cordierite	Platinum washcoat

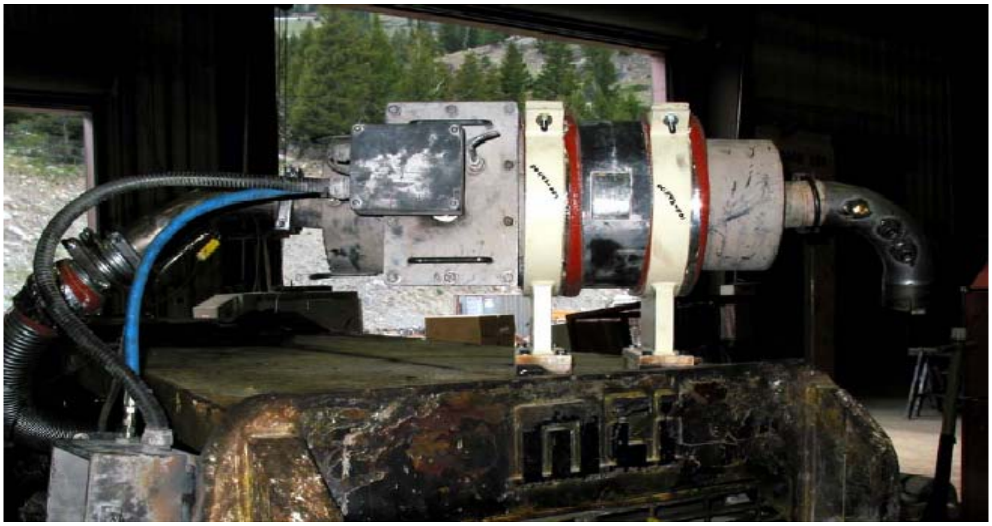


Figure 1: SiC DPF Installed on LHD

Figure 2: Pt Catalyzed Cordierite DPF Installed on Truck

Fuel:

All the diesel-powered vehicles used in underground operations at Stillwater Nye mine are fueled with #1 diesel supplied by local refinery, although this particular fuel exceeds MSHA requirements for diesel fuels used in underground mines. Using #1 diesel 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. Below is a table summary of the fuel used in the study:

Vehicle	Test	Exhaust System Configuration	Fuel
#92128	Baseline	Muffler	#1 (27.5%)/#2 (72.5%) diesel
	DPF	DPF #1	#1 (47.3%)/#2 (72.5%) diesel
#92133	Baseline	Muffler	#1 (19.1%)/#2 (80.9%) diesel
	DPF	DPF #2	#1 (31.4%)/#2 (68.6%) diesel
#92506	Baseline #1 diesel	Muffler	#1 (10.4%)/#2 (89.6%) diesel
	Baseline #2 diesel	Muffler	#2 (100%) diesel
	DPF	DPF #3	#1 (75.0%)/#2 (25.0%) diesel
	Disposable DPF	DPF #4	#1 (14.7%)/#2 (85.3%) diesel
#92526	Baseline #1 diesel	Muffler	#1 (74.1%)/#2 (25.9%) diesel
	Baseline/DOC	DOC and muffler	#1 (52.2%)/#2 (47.8%) diesel
	DPF	DPF #5	#1 (94.8%)/#2 (5.2%) diesel
	Biodiesel B20	DOC and muffler	#2 (80%)/bio (20%) diesel
	Biodiesel B50	DOC and muffler	#2 (50%)/bio (50%) diesel
#99942	Baseline #1 diesel	Muffler	#1 (100%) diesel
	Baseline #2 diesel	Muffler	#2 (100%) diesel
	DPF	DPF #6	#1 (100%) diesel

Results:

Effects of control technologies on elemental carbon:

Test Type	Percent Reduction
#92128 Haul Truck	
Baseline	--
DPF #1	96
#92133 Haul Truck	
Baseline	--
DPF #2	99
#92506 LHD	
Baseline, #1 diesel	--
Baseline, #2 diesel	-12
#92526 LHD	
Baseline	--
Baseline/DOC	-3
Biodiesel B20/DOC	26
Biodiesel B50/DOC	48
#9942 LHD	
Baseline, #1 diesel	--
Baseline, #2 diesel	-10
DPF #6	88

*Note that several of the tests were discarded due to unexplainably low CO_2 concentrations.

Effects of control technologies on total PM concentration under 0.8µg:

Test Type	Average % Reduction
#92128 Haul Truck	
Baseline	--
DPF #1	75
#92506 LHD	
Baseline #1 diesel	--

Baseline #2 diesel	--
#92526 LHD	
Baseline	--
Baseline/ DOC	--
Biodiesel B20/DOC	9
Biodiesel B50/DOC	24
#99942 LHD	
Baseline #1 diesel	--
Baseline #2 diesel	-21
DPF #6	74

Effects of control technologies on NO_2 concentrations:

Evaluating the effects of the DPF systems, particularly those that were wash-coated with platinum catalyst, on concentrations of NO_2 in mine air was one of the major objectives of the study. The results of the NO_2 measurements show that the average normalized concentrations of NO_2 increased about two times when haul truck #92128 was equipped with DPF #1 instead of a muffler. Comparable increases in NO_2 concentration was observed for the DPF #6 system and for the DPF #2 system. For these test runs, 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. During the test involving #99942 equipped with DPF #6, the MSHA ventilation rate normalized peak concentrations exceeded 5 ppm, the short term exposure limit for NO_2, on several occasions. 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 DOC and a muffler showed insignificantly higher NO_2 emissions than when only the DOC was fitted to the vehicle.

Test Type	Average NO_2 (ppm)
#92128 Haul Truck	
Baseline	0.6
DPF #1	1.3
#92133 Haul Truck	
Baseline	0.2
DPF #2	0.7
#92526 LHD	
Baseline, #1 diesel	1.3
Baseline, #2 diesel	1.2
#92526 LHD	
Baseline	1.5
Baseline + DOC	1.8
Biodiesel B20 + DOC	1.7
Biodiesel B50 + DOC	1.9
#99942 LHD	
Baseline, #1 diesel	0.9
Baseline, #2 diesel	0.8
DPF #6	2.1

More information on this project is available at: http://0-www.cdc.gov.mill1.sjlibrary.org/niosh/mining/pubs/pdfs/teost.pdf.

2.6 *Study on Size and Concentration of Aerosol Particles from Retrofit Devices in Underground Mining*

A study was conducted comparing aerosol emissions from seven different retrofit PM exhaust control devices and a standard muffler on a diesel engine operating in an underground mine environment. Testing was done using a diesel laboratory developed in an underground experimental mine. The laboratory included an Isuzu C240 diesel engine on a dynamometer and was operated under four steady-state engine operating modes (R50, R100, I50, I100) using diesel fuel with 11 ppm sulfur. The exhaust control devices included in the study consisted of three types of uncatalyzed DPFs (cordierite, SiC, and a sintered metal filter with a fuel additive), three types of high temperature disposable filter elements (DFEs), and one DOC. One of the DFEs was retested after undergoing a typical cleaning process used by some coal operators. The DPFs were degreened and fully regenerated prior to testing using a commercial automatic cleaning station. Measurements were taken after one hour of engine operation to stabilize the level of soot on the filters. PM mass, PM size, and concentration were measured upstream and downstream of the control devices. The size and number concentration of aerosols between 10 and 408 nm was measured using a scanning mobility particle sizer (SMPS).

The DOC showed minor reductions in aerosol number and mass and the reductions were strongly dependent on engine operating mode. The highest reductions were observed in the I100 mode with a 42% reduction in mass and a 24% reduction in number concentration.

All three DPFs reduced minor reductions in aerosol number and mass and the reductions were strongly dependent on engine operating mode. The highest reductions were observed in the I100 mode with a 42% reduction in mass and a 24% reduction in number concentration.

All three DPFs reduced aerosol mass by an order of magnitude at R50 and I50, with a 20-fold in the R100, I50, and I100 modes and 10-fold at R50. The engine operating mode had a more significant effect on PM size. The DFEs reduced total number concentrations by 93-99% for the light loads and 65-75% for the higher loads. The efficiency increased over the test period as they became loaded with soot. The single-cleaning treatment of the DFE did not have substantial effects on performance.

The DPFs exhibited greater variability between the different technologies and reduced aerosol PM number by 34-95% at light loads and 58-95% at higher loads, with the sintered metal filter increasing aerosol number slightly at the R100 mode.

For both the DPFs and DFEs, the study found a substantial increase of nucleation mode aerosols for the higher engine operating modes. The DPFs exhibited bimodal size distributions weighted toward accumulation mode (>50 nm) particles at low loads and nucleation mode (<50 nm) at high loads. Although similar trends in higher nucleation mode particles at higher loads were observed for the DFEs, their relative numbers were lower due to lower exhaust temperatures due to the use of heat exchangers used to cool the exhaust.

The complete reference for this study is: A.D. Bugarski, et al., "Effects of Diesel Exhaust Aftertreatment Devices on Concentrations and Size Distribution of Aerosols in Underground Mine Air," *Environ. Sci. Technol.*, Vol. 43, No. 17, pp. 6737-6743, 2009.

3.0 Conclusion

As shown by the above case studies, experiences with retrofitting mining equipment diesel engines with emission control devices are growing. The majority of the retrofit experience in mining equipment diesel engine projects has been focused on demonstrating the feasibility of applying available or verified, on-road retrofit emissions control technology on mining equipment and quantifying the diesel emission reductions achieved. Compared to other nonroad diesel engines, there are relatively more examples of the application of diesel particulate filters in the mining sector due to health concerns associated with the exposure of diesel particulate in the confined work areas found in mines. The availability of ultra-low sulfur diesel (ULSD) fuel for non-road diesel engines expanded significantly as the rollout of ULSD for highway applications expands nationwide in the second half of 2006. Emerging on-road verified retrofit technologies such as actively regenerated DPFs and flow-through particulate filters should also find applications in non-road diesel engines and provide more options for significant reductions in diesel particulate emissions from mining equipment engines. New tighter MSHA standards for miners' exposure levels to diesel PM that became effective in 2008 will put more emphasis on reducing PM levels from diesel engines used in mining operations through the use of proven diesel retrofit technologies like diesel particulate filters.