The Effects of a Diesel Particulate Filter and Fuel Borne Catalyst on Engine Emissions

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ABSTRACT

CANMET has been involved in an industry-government program to assess the quality of mine air and to improve the working environment. One aspect of the program is to reduce diesel particulate matter (DPM) generated by heavy-duty diesel vehicles having low exhaust temperature duty cycles. The low exhaust gas temperatures that are common in modern engines lead to insufficient regeneration of diesel particulate filters (DPF). A study was undertaken in partnership with DCL International to examine additive assisted regeneration. This study uses a cerium based fuel-borne catalyst to complete the regeneration of a DPF. Regeneration of a DPF occurs when the accumulated DPM in a filter combusts in a controlled manner. Cerium based fuel-borne catalysts have been used in many other applications worldwide but this is perhaps the first application in an underground mine.

The paper describes the results of an underground mine study involving two heavy-duty vehicles, one equipped with a mechanical fuel injected engine and the other equipped with a modern electronic fuel injected engine. In each case, diesel exhaust gas emissions (regulated gases and DPM) were measured during mine production duty cycles with and without the filters and fuel catalyst. Engine exhaust back-pressure and temperatures were also measured to study filter regeneration. The results indicate a substantial reduction in CO, NO_2, DPM and EQI (Exhaust Quality Index). The ashes from filters were also analyzed for various chemicals in order to develop a methodology to clean the filters. The reduction in DPM is currently a major concern for the mining industry.

KEYWORDS

Emissions, Diesel Engine, Sootfilter, Catalyst, Exhaust Aftertreatment, Cerium, Particulate Matter, DPM, and Regeneration.

INTRODUCTION

Diesel exhaust is considered to have adverse effects on the health of workers and the environment. There have been numerous reports dealing with the effect of diesel exhaust exposure on worker's health. Since the 1970's, laboratory research and a number of epidemiological studies have indicated that exposure to diesel exhaust must be minimized. In 1978, CANMET contract research concluded that DPM is the pollutant of gr25eatest health concern among all the major diesel exhaust constituents (French & Mildon, 1978, 1984 & 1990). Until such time as evidence to the contrary becomes available, all approaches should be taken to reduce exposure to as low a level as is practical. In 1988, NIOSH (National Institute for Occupational Safety and Health) recommended that whole diesel exhaust be regarded as a "potential occupational carcinogen" and that reductions in workplace exposure be implemented to reduce cancer risks (NIOSH, 1988), while the IARC (International Agency for Research on Cancer) declared in 1989 that enough data existed to conclude that diesel emissions are a probable carcinogenic element for humans (IARC, 1989).

In 1995, ACGIH (American Conference of Governmental Industrial Hygienists) added DPM to the notice of intended changes for 1995-96 at "Level A2 – suspected human carcinogen" (ACGIH, 1995). Since then, there has been an increased trend in lowering DPM levels by regulators and operators. In 1998, MSHA (Mine Safety and Health Administration) proposed a rule to reduce the risks to underground coal miners from the serious health hazards that are associated with the exposure to high concentrations of DPM (MSHA, 1998a). The proposed rule requires the installation of DPM filters on diesel powered equipment to trap diesel particles before they enter the mine environment. In the same year, MSHA proposed a new rule to control DPM levels in metal/non-metal mines by setting a maximum exposure interim limit of 0.4 mg/m^3 to be phased in over a period of five years to a final limit value of 0.16 mg/m^3 (MSHA, 1998b).

In October 1998, ACGIH proposed a notice of intended changes for 1999 and included TLV (threshold limit value) for DPM at 0.05 mg/m^3 level much lower than the 1995 proposed value of 0.15 mg/m^3 (ACGIH, 1998). The DPM was proposed at A2 level – suspected human carcinogen. These exposure limits are much lower than usually found in the mine environment and, although ACGIH has no jurisdiction in the area of regulation, its proposals usually have a great deal of influence.

These proposed limits on DPM levels for underground mines suggest that new technologies be adopted to reduce DPM levels. While modern clean engine technology has greatly reduced DPM emissions, a further reduction is required to meet new proposed DPM levels. The amount of ventilation alone required to dilute DPM to the new levels in underground mines could be very expensive and is not a practical choice. Hence, all possible attempts should be made to reduce DPM at the source, before it enters the mine environment. A suitable approach to reduce DPM by up to 90% is the application of diesel particulate filters.

Diesel particulate filters (DPF) are extremely efficient in removing diesel particulate matter (DPM) with typical trapping efficiencies around 90% (HEI, 1995; Dainty *et al.*, 1986; Gangal *et al.,* 1985). However, the biggest difficulty when using them is to maintain an acceptable pressure drop over a long period of time. In many underground mine applications, there is insufficient regeneration of the diesel particulate filters because of too low exhaust gas temperatures. Hence, there is a need to enhance or assist the regeneration of the diesel particulate filters by some method.

There are various ways to increase the regeneration rate. It can be done with an electrical resistance heater or with a diesel fuel burner. The use of diesel-fuel additives or fuel-borne catalysts such as iron, copper and cerium is another alternative to enhance regeneration. In this study a cerium additive was used in the fuel to regenerate the filter at low engine exhaust temperatures. A recent paper on the effects induced by the accumulation of additives on diesel particulate filters indicates that the cerium additive does not react with commonly used filters (Montanaro and Negro, 1998).

IN-MINE FIELD STUDY

In this study, a cerium based fuel-borne catalyst was used to complete the regeneration of the DPF. Cerium based fuel-borne catalysts have been used in many other applications worldwide (Pattas *et. al.*, 1996; Lepperhoff *et. al.*, 1995) but this is believed to be the first application in underground mines. The application of this fuel additive with a DPF is registered with the US-EPA and is on MSHA's list of registered fuel additives for use in diesel-powered equipment. The combination of the DPF technology and a fuel-borne catalyst makes it possible to continuously trap up to 90% of the raw exhaust DPM at lower engine exhaust temperatures (250°C – 400°C) than are normally required for unassisted filter regeneration.

For this study, at the Bousquet underground mine in Val d'Or (Québec), three catalysed DPFs were installed on two production vehicles in late August 1997. The filters were installed in place of the original muffler silencer and fume diluter. Table 1 shows the characteristics of the vehicles and filters. One of the initial concerns of the operators was the noise level after the mufflers were replaced. Noise level data was monitored at the vehicle operator's cab with the DPF in place, even though these measurements are usually difficult to make accurately. However, after a week of study, according to the operators, the diesel particulate filters were quieter than the original exhaust system with mufflers. The diesel fuel used at the mine was a low sulphur fuel (340 ppm).

Table 1. Characteristics of the equipment.

	Haulage Truck	**LHD**
Vehicle	Haulage Truck	Load Haul Dump
Engine	Turbo, Inline 6 cyl.	NA, V-10 cyl.
Fuel Injection	Electronically controlled injection	Mechanically controlled injection
Power	340 kW	170 kW
DPF Size	38 cm x 38 cm	28.6 cm x 30.5 cm (2 req'd)
Material	Corning EX80	Corning EX80
Catalyst	MX-2004	MX-2004
Cerium	100 ppm Then 50 ppm	100 ppm

Both vehicles were equipped with electronic data-loggers that continuously recorded the backpressure caused by the filters in order to determine whether regeneration was continuous. Periodically, the data files were transferred from the data loggers to a laptop computer before being sent via Internet to DCL in Toronto for analysis.

In order to determine the performance of the filter/additive system on engine exhaust emissions, the concentrations of gases and DPM in undiluted exhaust during the normal mine production duty cycle, were measured for both vehicles. The measurements were made in the exhaust gas stream before and after the filter. The gases and DPM sampling were performed using heated sample lines to avoid any water condensation in the lines. The exhaust gases were measured using a commercially available multi-gas monitor and data were continuously recorded on a RAM card. The DPM samples from the exhaust gas were collected on a glass fibre filter and analysed gravimetrically.

The monitored gases included oxygen (O_2), carbon monoxide (CO), nitric oxide (NO) and nitrogen dioxide (NO_2). Carbon dioxide (CO_2) and sulphur dioxide (SO_2) were calculated. The temperature and pressure of the engine exhaust gas before the DPFs was also continuously monitored and recorded.

The emissions performance of the DPFs was calculated using the Exhaust Quality Index (EQI). The EQI expression was developed (French & Mildon, 1978, 1984 & 1990) as a tool to estimate the relative potential for diesel exhaust emissions. This is a very useful tool to compare the emissions effects of various devices. For this reason an EQI based testing protocol called 'MAPTEST' is used in Canada for evaluating the emissions performance of addon systems including, fuel variations, additives, catalytic converters, DPF, and other treatment technologies (CANMET, 1997).

The EQI equation is expressed as (gases measured in ppm and DPM measured in mg/m^3);

$$EQI = \frac{CO}{50} + \frac{NO}{25} + \frac{DPM}{2} + 1.5\left(\frac{SO_2}{3} + \frac{DPM}{2}\right) + 1.2\left(\frac{NO_2}{3} + \frac{DPM}{2}\right)$$

RESULTS

Figure 1 shows the real-time trace of CO concentration in the undiluted exhaust gas, before and after the filter, during a complete duty cycle of the haulage truck. The reduction in CO due to the filter/Cerium system, is clearly shown. The average CO reduction efficiency was measured at 61%. Similarly, Figure 2 shows reduction for NO_2 due to the filter/additive system. The average NO_2 reduction during a duty cycle was measured at 65%.

Table 2 summarizes reductions in the undiluted exhaust concentrations of CO, NO_2, DPM and EQI for both vehicles during a typical production cycle. It should be mentioned that other measured gases did not change significantly, hence they are not shown here. There is a significant reduction in NO_2 while the value of NOx (NO+NO_2) remains about the same.

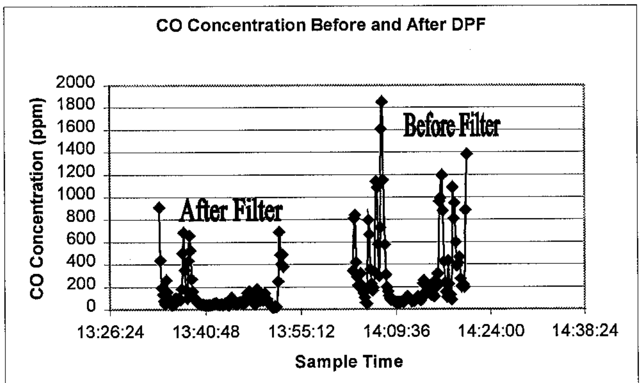

Figure 1. Real-time trace of undiluted exhaust CO concentration for haulage truck.

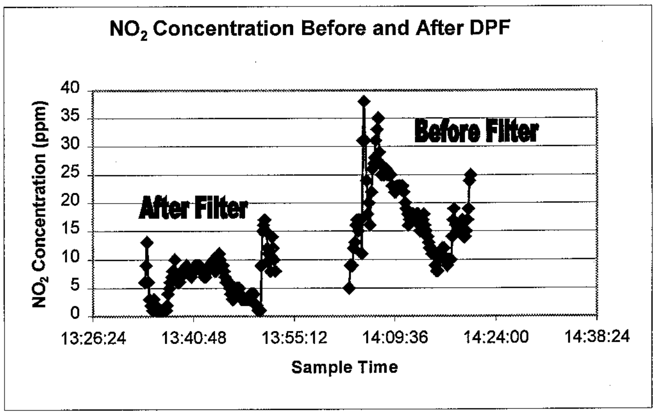

Figure 2. Real-time trace of undiluted exhaust NO_2 concentration for haulage truck.

Table 2. Percent reduction of exhaust emissions due to DPF/additive system.

	CO	NO_2	DPM	EQI
Haulage Truck	61%	65%	92%	64%
LHD	13%	83%	84%	59%

A sample of the DPM in the undiluted exhaust gas, before and after the DPF, was collected on glass fibre filters. Figure 3 shows the photograph of these filters for both vehicles. The reduction in DPM is very clear from this figure.

Diesel Particulate Filter / Cerium Based Fuel Additive - Field Study

Undiluted DPM Sampling System Test Filters

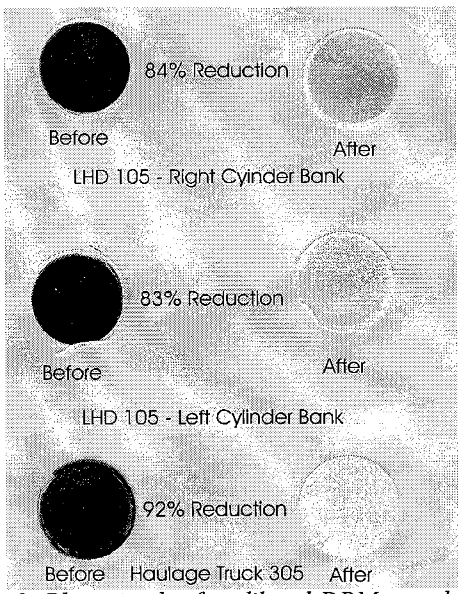

Figure 3. Photograph of undiluted DPM samples collected on glass fibre filters.

EXHAUST BACKPRESSURE

Figures 4 & 5 below show a comparison between the exhaust back-pressure observed with fume diluters and with clean filters for a initial duration of four hours. The back-pressure with a fume diluter was taken the day before the installation of the filters and the back-pressure with a filter was taken after their installation. The measurements were taken with the same equipment in both cases. On Figure 4 (Haulage Truck), the maximum back-pressure (around full load) with fume diluters is much higher than the back-pressure with the diesel particulate filters.

The installation of the DPF reduced the maximum back-pressure at least during the initial trial hours of operation. The maximum allowable back-pressure during the trial period was targeted to be below 40 inches of water column.

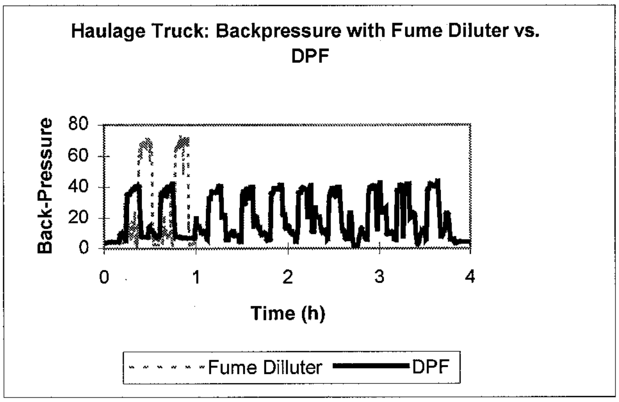

Figure 4. Initial exhaust backpressure for fume diluter and DPF on the haulage truck.

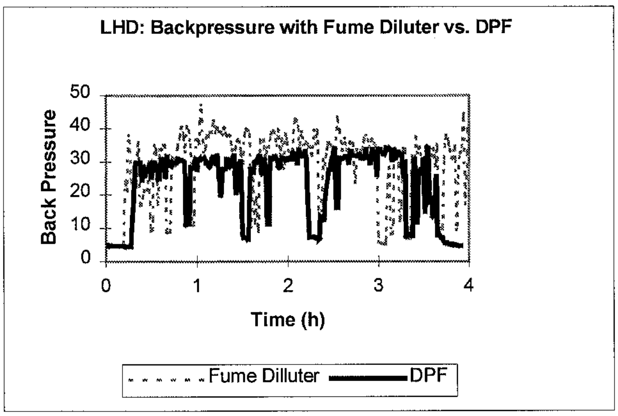

Figure 5. Initial exhaust backpressure for fume diluter and DPF on the LHD.

In figure 5, there is a smaller difference in back-pressure between fume diluter and DPF. The results shown in Figure 5 are for the left cylinder bank of the engine but are similar to the results on the right bank (not shown).

These results are useful to determine the initial back-pressure but one has to keep in mind that they only show short-term variations. Figure 6 shows the long-term trend of the back-pressure on the LHD. The back-pressure Occasionally increased above 40 inches of water column over a two-month period. It must be noted that the two banks are very similar despite the fact that one of the bank emits twice as much particulate as the other one. This seems to indicate that the regeneration of DPF is almost complete and that the increase in maximum back-pressure can be mostly attributed to the cerium ash trapped in the filter, which was confirmed later during chemical analysis of ashes trapped in the PDF. Unfortunately because of problems with the data logger, the data for August 28th and September 20th was lost.

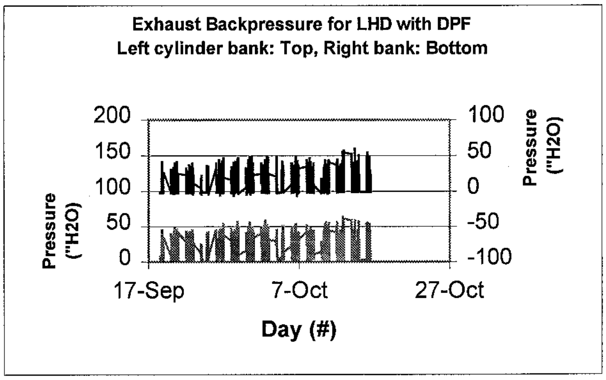

Figure 6. Exhaust back-pressure trend for LHD.

Figure 7 illustrates the back-pressure trend for the haulage truck. Here again, some data was lost in September due to problems with the data logger. The DPF was removed on October 1st for cleaning and chemical analysis of ashes.

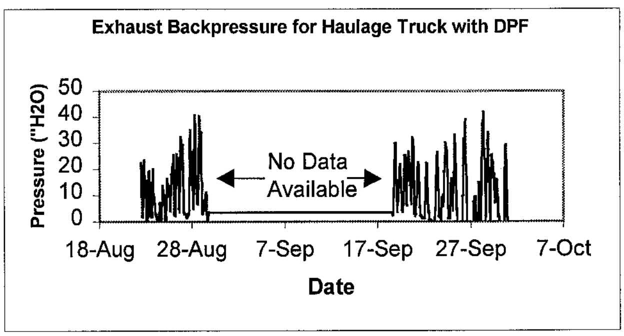

Figure 7. Exhaust back-pressure trend for haulage truck.

ADDITIVE ISSUES

During this field study, the vehicle operator added the cerium catalyst to the fuel. At the beginning of the shift, the operator would add a measured quantity of cerium solution to the diesel fuel in the vehicle tank. The amount of additive dispensed by the operator was based on a full tank of fuel to give a concentration of approximately 100 ppm of cerium in the fuel.

While this dosing procedure was deemed suitable for R&D tests, a more sophisticated method would be required for long term trials. Several techniques were discussed including on-vehicle automated dosing, refuelling station dosing and premixing of the entire fuel depot at the surface. Before this third option was explored, it was decided to test a light-duty vehicle using the cerium additive but without a DPF. The purpose was to get an estimate on the concentration of emissions in the absence of a DPF. For this purpose the test was run on a mine tractor equipped with a 31.3 kW, 3.1 L, naturally aspirated, three cylinder diesel engine. The tractor fuel tank had a volume of 65 liters. The tractor's exhaust system was composed of a catalyst, muffler and a fume diluter. The tractor was operated for several hours on a typical duty cycle and this duty cycle was kept the same during the entire test. The duty cycle took about 14 minutes to complete.

Gas and particulate sampling equipment was installed on the tractor at the mine. The exhaust gas and DPM sampling line drew a sample from a point in the exhaust stream just before the fume diluter. The exhaust gases and DPM were measured in a similar fashion to the filter study described earlier. Initially, the vehicle was monitored over two typical duty cycles, then the cerium additive was dosed to the fuel tank. The concentration of cerium in the diesel fuel was analyzed at 135 ppm by the laboratory XRD method. After several trial runs to assure adequate mixing, the exhaust emissions were monitored again over the same two duty cycles. The average data for typical vehicle duty cycles with and without cerium additive are given in Table 3.

Table 3. Summary of exhaust emission data with and without cerium additive for light-duty vehicle.

Exhaust Component	**Without Additive**	**With Additive**	**Change (%)**
O_2 (%)	15.5	15.4	***-0.6***
CO_2 (%)	4	4.05	***1.3***
CO (ppm)	396.2	367.9	***-7.1***
NO (ppm)	362.9	409	***12.7***
NO_2 (ppm)	40.7	33.5	***-17.7***
NOx (ppm)	403.6	442.5	***9.6***
SO_2 (ppm)	5.85	5.95	***1.7***
DPM (mg/m^3)	54.5	47.2	***-13.4***
EQI	142.5	127.4	***-10.6***

The close correlation for O_2 and CO_2 allows us to conclude that the duty cycles with and without cerium additive were very similar. Table 3 shows that the concentration of CO, NO_2, DPM, and EQI decreased with the use of the additive, while NO, and total NOx increased. It appears that cerium additive alone without a DPF has some effect on vehicle exhaust emissions. However, the use of cerium without a DPF is not recommended due to the release of fine cerium particles into the mine environment (Mayer *et al.*, 1998).

Table 3 shows that NOx concentration increased by 9.6% while DPM decreased by 13.4% due to the cerium additive. These changes in NOx and DPM are similar to those found in a European study (Mayer *et al.*, 1998). That study tested a Liebherr engine and cerium additive without a filter and showed similar results; 10% increase in NOx and 13% reduction in DPM.

DPF CLEANING ISSUES FOR CERIUM ASHES

During this study some difficulties were encountered in establishing a cleaning procedure for the particulate filters. When exhaust back-pressure had risen above acceptable limits the DPFs were removed and shipped to DCL for cleaning. It was initially thought that the increase in back-pressure was caused by soot accumulation. The usual procedure for soot removal is to blow out the filter with compressed air, followed by oven heating to combust any remaining soot. When this procedure was not entirely successful, residue from the filter was analysed to determine the cause of the high back-pressure.

Thermogravimetric laboratory analysis (TGA) showed that approximately 75% of the residue was composed of cerium with only small quantities (5%) of lube oil ash present. Small amounts of calcium may have been acting as binding agents, fixing the cerium in the filter structure. This was confirmed when X-ray powder diffraction (XRD) revealed that the residue contained between 66 - 70% cerium oxide and 16 – 17% calcium sulphate.

The filter cleaning procedure was modified to include a 30 minute hot water soak followed by pressurised water cleaning. This dissolved enough calcium to unplug the filter sufficiently to return it to service. The filter was then blown out with compressed air and dried in an oven for 3-4 hours at 150°C.

The chemical analysis of the DPF residue also revealed that some contamination occurred during washdown of the LHD. The placement of the DPF outlet pipe allowed ore dust from the mine to be forced into the DPF. This left a pinkish-orange residue that could not be easily cleaned. Hence care should be taken not to allow mine ore material into the DPF during vehicle washing.

This study ran from late August 1997 to April 1998 with some problems. Catalyst-assisted regeneration appeared to take place but cerium ashes increased the back-pressure.

All the monitoring experiments were conducted during actual production periods with only minor interruptions for installation and removal of instrumentation and periodic swapping of filters done during regular maintenance.

RECOMMENDATIONS

It is believed that lower cerium concentrations would allow for extended cleaning intervals with little effect on particulate reductions.

Further work needs to be done to develop an automated additive dosing system acceptable to ensure adequate concentration of cerium in the fuel.

More laboratory testing should be performed to fine tune the additive concentration levels and to confirm the field data on the simultaneous reduction of DPM and NO_2. The significant reduction of NO_2 along with DPM is very encouraging and desirable in the underground mine environment but the principle of NO_2 reduction is not yet clear.

FILTER ECONOMICS

The cost of these filters is approximately $10,000 to $12,000 depending on the engine size and configuration. The operating costs (excluding maintenance costs) are estimated at about $10 per day for the LHD and $20 per day for the haulage truck.

There is a cost for the periodic cleaning and maintenance of the filters. Beside these costs, the gains from using DPFs are enormous since no other commercially available technology can provide such a reduction in DPM to improve the mine air quality. In this study EQI was reduced by 59 - 64% along with a simultaneous reduction in DPM (84 – 92%) and NO_2 (65 – 83%).

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