DEEP project on evaluation of diesel particulate filters at Inco's Stobie Mine

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ABSTRACT: The objective of the Diesel Emissions Evaluation Program (DEEP)-sponsored project at Inco's Stobie mine was to conduct a long term field evaluation of diesel particulate filter (DPF) systems available to the underground mining industry. Some of the major issues studied were criteria for selecting the filter media, means of DPF regeneration, efficiency of DPF systems and the occurrence of unwanted secondary emissions, and reliability and durability of DPF systems. Nine state-of-the-art diesel particulate matter (DPM) filtration systems have been retrofitted to heavy-duty and light-duty vehicles and have been subjected to extensive long-term in-mine evaluation. Periodic efficiency tests were conducted at various stages of the study (2001, 2002 and 2004) to establish in-use efficiencies and durability of the tested DPF systems. The results were used to assess the effects of the filter systems on the concentrations of particulate matter, nitric oxide, nitrogen dioxide and carbon monoxide in the vehicle exhaust. The variety of filtration systems and regeneration concepts used in this study offered the opportunity to investigate their advantages and disadvantages. This paper also offers a review of selected experiences with the installation and operation of the DPF systems on underground mining vehicles at the Inco Stobie Mine.

1 INTRODUCTION

Since their introduction into underground mining operations in the mid-1960s, diesel powered equipment has become increasingly employed and recognized as the workhorse in mining. Diesel engines proved to be relatively durable, easy to maintain and generally to have relatively low operating costs. Inco Limited employs over 800 diesel-powered units at its Ontario mining operations in the Sudbury basin. Although the use of alternative sources of power (e.g., electricity, fuel cells) is being explored, Inco and most other Canadian deep-rock mining companies realize that diesel engines will continue to be a very important source of power for growing fleet of heavy- and light-duty vehicles for many years to come. In view of this, it is imperative to lessen adverse effects of diesel emissions on quality of the air in underground mines.

A Canadian industry/labor/government consortium, Diesel Emissions Evaluation Program (DEEP), was formed in 1999 to address issues related to exposure of underground miners to diesel particulate matter (DPM). One of the major objectives of this program was to identify strategies and controls that will attain a tenfold reduction in miners' exposure to DPM. DEEP sponsored two projects, one hosted by Noranda's Brunswick mine (McGinn 2004) and the other hosted by Inco's Stobie mine (Stachulak et al. 2005a) that tested existing diesel particulate filter (DPF) technologies in operating mines. The long-term study, conducted under DEEP auspices at Inco's Stobie mine from April 2000 to December 2004, assessed the suitability and effectiveness of selected DPF systems for control DPM emissions from heavy- and light-duty underground diesel mining equipment.

Diesel exhaust is complex mixture of gases, liquids, and solids. The gaseous phase includes carbon monoxide (CO), carbon dioxide (CO_2), nitric oxide (NO) and nitrogen dioxide (NO_2) (in combination termed NO_x), sulfur dioxide (SO_2) and sulfur trioxide (SO_3) and a number of low molecular weight hydrocarbons (HC). The liquid or vapor phase includes condensed hydrocarbons of varying molecular structures and sulfuric acid aerosols, which are formed by the combination of sulfur trioxide with water. The solid phase, commonly known diesel particulate matter, is predominantly made of elemental carbon (that arises from partially burned fuel), ash and sulfate aerosols (see Figure 1). The metals contained in these compounds originate from lubricating oil and impurities in the fuel. The majority of these diesel-produced particles are submicron in size and therefore respirable. Due to

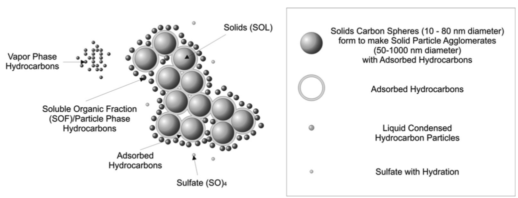

Figure 1. Schematic of diesel exhaust particulate.

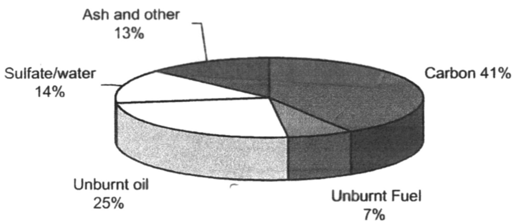

Figure 2. Typical constitution of diesel exhaust (after Burtscher, 2005).

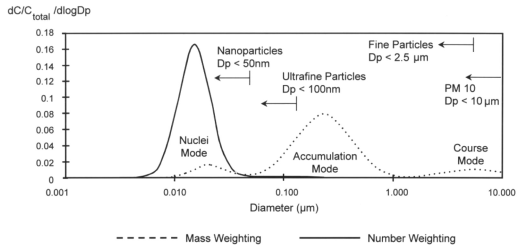

Figure 3. Typical particle size distribution of DPM (after Kittelson, 1998).

the small particle sizes, the elemental carbon particles provide a large surface area suitable for adsorption and absorption of volatile and semi-volatile hydrocarbons. These hydrocarbons constitute the soluble organic fraction of diesel particulate matter. Typical chemical composition of diesel particulate matter is shown in a pie chart in Figure 2 and a typical particle size distribution, summed over the operating modes of a diesel engine, is shown in Figure 3.

Physical properties and chemical composition of a diesel engine's exhaust were found to vary as a function of a number of parameters including engine design, age, operating conditions, maintenance, type of fuel, etc. It is important to recognize that there are certain limitations and trade-offs in controlling these parameters in an effort to minimize potentially harmful emissions from diesel engines. It is apparent that substantial reduction in emissions of a number of components of diesel exhaust are achievable only by various combinations of exhaust after-treatment technologies such as diesel oxidation converters (DOCs), diesel particulate filter (DPF) systems, selective catalyst reduction (SCR) systems, etc.

DOCs are widely deployed by the underground mining industry for control of CO and HC emissions from diesel engines (Stachulak 2003). Those devices were found to be relatively easy to operate and maintain. On the contrary, controlling DPM emissions was found to be substantially more challenging (Schnakenberg and Bugarski 2002). Improvements in fuel quality (Watts et al. 1998) and maintenance, as well as improvements in engine design, operation and ventilation, were shown to be insufficient to accomplish a desired 90% reduction in DPM. It became apparent that removal of DPM from the exhaust stream using diesel particulate filter systems was likely to be an integral part of the strategy to achieve dramatic reductions in DPM emissions (Conard and Stachulak 2000).

The first ceramic monolith DPF for use in underground applications was developed by Corning Glass in collaboration with Natural Resources Canada (CANMET) scientists. In the early 1980s prototype systems were laboratory-tested and then taken underground for field trials (McKinnon 1989). Inco was involved in testing a prototype at Little Stobie Mine (Stachulak and Conard 2001) and in implementing what was then considered to be a successful technology via the National Research Council's Program for Industry/Laboratory Projects (PILP) run under the auspices of the Collaborative Diesel Research Advisory Panel. However, initial success was afterward impeded by long-term implementation issues. Frequent problems with filter regeneration – burning-off of the collected DPM – often resulted in unacceptable engine backpressures. As a result, many of these systems were eventually rejected by vehicle operators. Mine management, as well as workers, became skeptical of the technology. It is now recognized that the performance of a filter is intimately associated with successful periodic regeneration of the filter. The early implementation of filters on underground equipment relied on this removal being done by the heat in the engine exhaust itself and, as now realized, sufficient temperatures were not achieved for many DPF systems because of a combination of lower than expected exhaust temperatures and/or a lack of sufficient time at high exhaust temperature to complete regeneration.

VERT, a European project, evaluated the best technology to curtail DPM emissions from engines used in construction and tunneling operations (Mayer et al. 1998). Both laboratory testing and field evaluations of various control technologies were conducted under auspices of this project (Mayer et al. 1999, 2002). Discussions between DEEP and Andreas Mayer, VERT's technical director, assisted greatly in developing the Stobie project's scope of work. VERT's list of tested and approved DPFs for retrofitting diesel engines (SAEFL 2003) was extensively used during the DPF selection process for the Stobie project. The knowledge gained by VERT in successfully matching engine and DPF system characteristics was particularly valuable to the DEEP researchers.

As a result of the high demand for after-treatment systems to control diesel particulate emissions from on-road and off-road vehicles, DPF technology rapidly advanced in recent years. Some of these technologies are in wide use in on-road applications, but have not yet been tested and proven for underground mining applications. Therefore, in light of the increased concern on the effects of DPM on human health and recent developments in control technology, DEEP decided to sponsor long-term evaluation of six DPF systems retrofitted on production and support vehicles in the Inco Stobie mine fleet. The specific objectives of the project were to:

1 develop methods for selecting DPF systems for underground mining vehicles;
2 determine the ability of tested DPF systems to reduce DPM emissions without significantly increasing secondary emissions of other noxious substances;
3 evaluate the long-term durability and reliability of the tested DPF systems;
4 establish operational and maintenance costs for such systems;
5 develop Canadian expertise on the DPF technology and DPM measurement methods.

The project was initiated in early 1998 with the generation of a proposal for conducting the study. The proposal was peer reviewed by DEEP's Technical Committee and outside reviewers, and the project was officially approved in mid-1999. Originally planned to be conducted over roughly 2.5 years, the testing was extended to December 2004 primarily to enable reasonable operating hours to be accumulated by the systems so that an assessment of long-term reliability and durability was possible.

2 METHODOLOGY

2.1 *Test vehicles*

Five heavy-duty load/haul/dump (LHD) vehicles were selected as representing the primary heavy-duty workhorse in underground mining. One of these units had a dual exhaust Deutz engine and the other four had Detroit Diesel Series 60 engines. The engines spanned a range of age and service use.

Two Kubota tractors powered by Kubota F2803B engines were selected as being representative of light duty vehicles, which are increasingly being used in transporting underground personnel. DPF service on light-duty underground mining vehicles had not been studied anywhere at the time the Stobie Project was

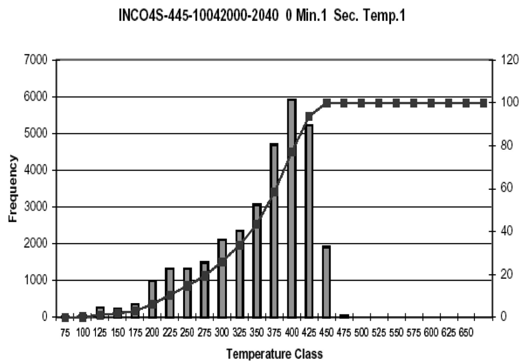

Figure 4. Exhaust temperature histogram for production LHD vehicle.

started. Their inclusion in the Stobie testing was considered important, because the contribution of light-duty vehicles to concentrations of diesel pollutants in underground mines is increasing (Rubeli 2003).

Temperature and pressure sensors were installed upstream of the muffler on the each candidate vehicle and data were collected at 1 Hz frequency using on-board data acquisition systems. The temperature and engine backpressure data were collected for six months prior to the final selection the DPF systems for testing. The temperature traces were used to generate exhaust temperature histograms. Temperature traces and histograms were needed in DPF system selection to assess whether the engine-produced exhaust temperatures and heat were sufficient to sustain partial or even complete passive regeneration of filters. These data were found to be absolutely essential for selection, installation and optimization of DPF systems (Mayer 2000).

As illustrated on the example histogram shown in Figure 4, the engines in heavy-duty LHD vehicles did not routinely achieve high enough exhaust temperatures (~600°C) for long enough periods to support complete regeneration of uncatalyzed DPF systems. This meant that DPF systems retrofitted to LHDs needed to be catalyzed to support passive regeneration at relatively lower exhaust temperatures. The alternative to those systems were active systems regenerated with help of external sources of energy. Similarly, data on light-duty vehicles clearly showed the need for active regeneration. The data on all vehicles indicated that engine backpressure would be an important diagnostic tool for monitoring the status of the DPF systems.

2.2 *Selection of DPF systems*

The temperature traces and other information relevant to the selection and optimization of the DPF systems were supplied to potential DPF system suppliers. The

DPF systems were required to meet criteria developed by VERT (SAEFL 2003). The resulting proposals from suppliers were thoroughly reviewed by DEEP Technical Committee, Inco's Stobie team and external reviewers.

Two of the LHD vehicles powered by Detroit Diesel Series 60 engines were retrofitted with completely passive systems: an Oberland-Mangold DPF system with a knitted glass fiber filter and a dosing system for fuel-borne catalyst on one, and an Engelhard DPX2 DPF system with a catalyzed cordierite monolith on the other. One of the remaining LHDs, also powered by Detroit Diesel Series 60, was retrofitted with a completely active system from ECS/Unikat with a SiC monolith filter and an on-board electrical heater for off-duty regeneration. A Johnson Matthey passive/active system DPF 201 with a SiC (or cordierite) monolith was retrofitted to the dual exhaust Deutz engine. This system was partially regenerated passively with help of a fuel-borne catalyst. The complete regeneration of these filters was secured with on-board electrical heaters. Two light-duty Kubota tractors were retrofitted with active DPF systems: one with an ECS/3M with a ceramic fiber filter and an on-board electrical heater; the other with a DCL system with a removable SiC monolith that was regenerated using an off-board electrical heater.

At a later stage of the project the Oberland-Mangold DPF system was replaced, due to technical problems, with an ECS/Unikat DPF system with a SiC monolith filter and an on-board electrical heater. Similarly, the ECS/3M DPF system was replaced with an ECS/Unikat with a SiC monolith filter and an on-board electrical heater. In the third year of the project one additional LHD powered by a Detroit Diesel Series 60 engine was fitted with a prototype active DPF system from Arvin Meritor. This system was designed around a cordierite monolith filter and an on-board diesel fuel burner for regeneration during normal vehicle operation.

More detailed descriptions of the evaluated DPF systems, test vehicles, and DPF installations are available in Stachulak et al. 2005a.

2.3 *Measurement of emissions and other relevant parameters*

Each vehicle was brought in for general maintenance at least every 250 hours of operation. The effects of DPF systems on the emissions were measured at torque converter stall steady-state engine operating conditions. Emissions of NO, NO_2, CO, and CO_2 were examined using an ECOM AC portable gas analyzer. That analyzer was also used to determine the Bacharach smoke number upstream and downstream of each system.

More extensive emission tests were conducted in July 2001, May 2002, and June 2004 under three reproducible steady-state engine operating conditions: (1) torque converter stall, (2) high idle, and (3) low idle. The concentrations of NO, NO_2, CO, and O_2 were measured upstream and downstream of the systems using ECOM KL and AC portable gas analyzers. Particulate concentrations were measured upstream and downstream of the systems using a photoelectric aerosol sensor (PAS 2000 from EcoChem Analytics) and an opacity meter (DiSmoke from AVL). Particle size distributions and concentrations were measured using a Scanning Mobility Particle Sizer (Model 3926 from TSI Inc.).

Industrial hygiene (workplace) measurements were conducted for "with filter" and "without filter" conditions while selected test vehicles were performing normal production duties. Ten particulate samples were collected for each test: three samples for RCD analyses and three samples for elemental carbon (EC) analyses were collected on the test vehicle just behind the driver; two samples for EC analyses were collected at the fresh air supply; and two EC samples were collected at the exhaust air outtake. Air flow measurements were performed during each test period.

All test vehicles were equipped with temperature (TS-200 EGTS from Heraeus) and pressure (Series BT8000 from Sensor Technics) sensors and data acquisition systems (Model FCD-001 from Paul Nöthiger Electronics). The exhaust temperature upstream and downstream of the DPF systems and engine back pressure data were collected throughout study at 1 Hz frequency.

3 RESULTS AND DISCUSSION

3.1 *Selection of DPF systems*

The process of critically evaluating DPF system design with a vehicle's duty cycle was found to be essential for selecting the optimum DPF system. Gathering adequate information specific to each individual application was found particularly important for making educated decisions on selection and optimization of each DPF system with regard to both its regeneration method and the filter's proper sizing. Actual exhaust temperature profiles and good estimates of in-use DPM emissions are critical inputs for selecting DPF systems.

The experience gathered during this project was used to complement VERT filter selection criteria (SAEFL 2003) to cover specifics of underground mining applications:

1 The system should have efficiency of 95% in removal of both particulate number and elemental carbon mass (NIOSH 5040);
2 The system should provide adequate regeneration over mining cycle;

3 Backpressure must meet vehicle/engine warranty:
New DPF 50 mbar
Regenerated DPF 60 mbar
Before cleaning <150 mbar.
4 The system should be supplied with adequate temperature and engine backpressure monitoring transducers, data acquisition system, and appropriate displays;
5 Secondary emissions (catalyzed traps are the concern):
6 preferably no increase of NO_2, but in any event the system should not increase ambient NO_2 concentrations above 0.8 ppm at a ventilation rate of 100 ft^3/hp;
7 Copper is not permitted in any catalyst formulation (fuel or filter) due to the potential for increases in formation of dioxins;
8 The system should be rugged enough for underground mining applications;
9 The system should be CSA & CEC approved and equipped with fire suppression systems;
10 Useful life of the system should be 3 years or 9000 hours.

3.2 *DPF sizing*

Elevated engine backpressures, substantially exceeding the manufacturer's recommended maximum values, were recorded during operation of several tested systems. For example, the backpressure on the engine equipped with Engelhard DPX2 DPF system frequently exceeded its manufacturer-recommended values, periodically exceeding 300 mbar for extended periods. The turbocharger on that engine eventually failed and caused an oil fire. At this time is not clear what role the DPF system and elevated engine backpressure may have played in the turbo failure. In general, the effects of prolonged elevated backpressure on performance and durability of a diesel engine are not very well established and more research is needed to address this issue. It is clear, however, that failure to regularly regenerate an filter and maintain engine backpressure within recommended limits eventually resulted in failure of the filter element.

DPF sizing was found to be particularly important for active systems in which an inadequately sized filter could potentially impact vehicle usability and productivity. It is important to consider the limitations imposed by restricted space on the vehicle, together with safety and maintenance issues.

3.3 *Effects of DPF systems on particulate and gaseous emissions*

The emissions tests showed that the evaluated DPF systems, if properly installed and maintained, can provide reductions in DPM emissions targeted by DEEP. The majority of tested DPF systems provided reductions in tailpipe DPM concentrations measured by PAS 2000 in excess of 90%. Similarly, elemental carbon analysis showed twenty-fold reductions for several tested systems. Size distribution and concentration measurements in the exhaust systems showed reductions in total number of diesel aerosols in excess of 95%. The effects of DPF systems on gaseous emissions were also closely investigated. The uncatalyzed DPF systems were found to have minor effect on tailpipe concentrations of CO, NO, and NO_2. Very low concentrations of CO downstream of the filter and a two-fold increase in NO_2 emission were observed for the platinum-catalyzed DPF system from Engelhard. Consequently, personal exposures to NO_2 should be closely monitored. More details on the results of emissions measurements are available in Stachulak et al. 2005a.

3.4 *Durability and reliability of DPF systems*

One of the DPF systems from ECS, and the systems from Johnson Matthey and Engelhard accumulated over 2000 hours of operation. Tailpipe emissions measurements verified their durability. The other system from ECS failed after approximately 870 hours of operation due to human error. The initial round of emissions testing revealed deficiencies in the Oberland Mangold system design, and it was consequently removed from the vehicle. The DPF systems installed on the Kubota tractors accumulated somewhat less operating time due to lower utilization of those vehicles. The active systems from DCL (~730 hours) and ECS/Unikat (~460 hours) proved to be durable and reliable. The ECS/3M system (~430 hours) was replaced with ECS/Unikat systems after 3M decided to stop supplying their wound fiber filter media. It is crucial to have equipment suppliers committed to an on-going maintenance and service issues.

Close attention should be given to the design, specifications, and installation of auxiliary equipment for the DPF systems. Such equipment including electrical circuits, fuses, heating elements, timers, air flow controllers, fuel-borne catalyst dosing systems and diesel burner and other special equipment often required special attention to ensure that Canadian standards for safety were met, that consumables could be purchased easily, and that maintenance was straight-forward.

The reliability of vehicle-mounted air compressors and air pumps on active systems was found to be poor. When possible, compressors and pumps on a vehicle should be replaced by compressed mine air with the moisture removed using conventional moisture separators. Flow rates of the air supply during active regeneration using electric heating elements were found to play an important role in regeneration process. Excessive air flow can reduce the temperatures being attained and adversely affect the regeneration process. Therefore, air flows should be periodically verified and adjusted if needed.

3.5 *Installation of DPF systems*

The project offered an opportunity to investigate several issues related to the installation of DPF systems on underground mining equipment. Ideally, the operation of DPF systems should be transparent to the vehicle's operator and should require minimum additional maintenance effort. The DPF systems evaluated in this study did not meet this ideal situation. In general, tested systems required a relatively high level of operator attention and engagement from maintenance personnel. Some of the systems proved to be particularly complex and demanding. Some of the technical problems with those systems can be attributed to the fact that manufacturers had limited experience with deploying their products to underground applications and used this study as a platform for development and optimization of their systems.

All of the DPF systems tested on the relatively large LHD vehicles were successfully installed in the engine compartments of those vehicles. It was important to consider all potential problems associated with installation and engine maintenance. Installation of DPF systems on Kubota tractors was somewhat more challenging. The systems on the tractors were installed on the front fenders outside of the engine compartment.

Continuous monitoring and recording temperature and engine backpressure was found to be a very useful tool. The continuous and instantaneous information on engine backpressure proved to be valuable for diagnostics of regeneration and overall performance of DPF system. A redundant system with simple, but effective, dashboard alarm signal is needed in order to give information to the vehicle operator about the engine backpressure. Operators must be attentive to non-conventional alerts and alarms for high backpressure or else serious harm could be done to the engine. Analyzing temperature and engine backpressure data requires expertise and time. For proven DPF systems, the data need only be collected at a minimum frequency so as to minimize the time spent processing and analyzing data.

Thermal insulation of exhaust pipes and filters, where possible, was found to be effective in improving DPF performances. The length of exhaust manifolds and number of bends were minimized for optimum performance.

Using shock absorbing mounts on the DPF assembly was found to improve the durability of the systems.

Mounting DPF system high on a vehicle was found to reduce potential damage from the intrusion of mud and water in the DPF housing. An incident with an LHD which was used for cleaning sumps showed that mud and water can compromise performance of the filter element and electrical connections. An alternative to elevating the complete system is designing an enclosure or redesigning the DPF system so that the electrical heater is not part of the system, but can be quickly installed when regeneration is needed.

It is important to install the DPF system components and associated exhaust manifolds at a safe distance from fire suppression actuators on the vehicle. A fire suppression system on one of the evaluated vehicles was actuated as a result of temperatures generated from an exhaust manifold that was routed too close to the actuator by mistake.

The operation of the engine with an overloaded DPF system might cause serious damage to the DPF system and engine. The ideal solution would be integration of the DPF system sensors into an electronic control module (ECM) of electronically-controlled engines and thus would allow engine output to be limited when excessive engine backpressure is sensed. This option needs to be explored with engine manufacturers.

The use of metal electrical connector housings instead of the often supplied plastic housings was found to improve their ruggedness, resulting in fewer maintenance problems.

3.6 *Operation of DPF systems*

This project showed that an emissions/maintenance program is essential for implementation and operation of DPF systems. The performance of DPF systems should be evaluated as part of routine preventive maintenance (Stachulak et al. 2005b). The portable gas analyzers, such as those from ECOM America used in this study, were found to be helpful in performing diagnostics on DPF systems. These measurements are most effectively carried out by skilled mechanics during scheduled vehicle maintenance, and it is relatively easy to include this in routine vehicle servicing. Education and training of maintenance personnel in the specifics of each DPF system plays an important role in the process.

Proper education of vehicle operators, mechanics and others involved with DPF systems implementation and operation is essential for their successful, long-term use.

ACKNOWLEDGMENTS

The authors would like to express their gratitude to the DEEP consortium for funding the project, and particularly to the members of its Technical Committee. Also, recognition is due to the Ontario Workers Safety and Insurance Board and the New Brunswick Workplace Health, Safety and Compensation Commission for their funding support of the project. An enormous number of people assisted the project, including

Andreas Mayer and Paul Nothinger of Switzerland, Sean McGinn, Win Watts, Michel Grenier, Bill Howell and DPF system/diesel engine manufacturers. A very large team of employees at Inco contributed to the success of the project including vehicle operators, maintenance and instrumentation personnel, along with shift supervisors and foremen. Acknowledgement is also given to the Stobie Mine manager, Mike McFarlane, to senior mine personnel Greg Nault and Rick Mayotte. Special thanks to Giles Bedard, Bob Coupal and the other members of Stobie DEEP Team as well as to the Ontario Division of Inco for their support and encouragement.

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