Long-Term Evaluation of Diesel Particulate Filter Systems 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 selected diesel particulate filter (DPF) systems, available to the underground mining industry. Nine state-of-the-art DPF systems were retrofitted to heavy-duty and light-duty vehicles and were subjected to extensive long-term in-mine evaluation.

Periodic efficiency tests were conducted at various stages of the study (in 2001, 2002 and 2004) to establish in-use efficiencies and durabilities of the tested DPF systems. During efficiency tests, the vehicles/engines were operated over several steady-state operating conditions. Various instruments were used to measure particulate and gaseous emissions upstream and downstream of the filter systems. The results were used to assess the effects of the filter systems on the concentrations of diesel particulate matter (DPM), nitric oxide, nitrogen dioxide and carbon monoxide in the vehicle exhaust.

Experience with the operational issues related to deployment of the filter systems on underground mining vehicles, coupled with the assessment of the filtration efficiencies, were the primary objectives of the study. The variety of filtration systems and regeneration concepts used in this study offered the opportunity to investigate the advantages and disadvantages of the various types. Some of the major issues studied were criteria for selecting the filter media, means of regeneration, the long-term operational reliability, and the occurrence of unwanted secondary emissions.

INTRODUCTION

Ever since the first diesel-powered machine, a Wagner Scooptram™ load-haul-dump vehicle, was introduced into mining operations at Inco in March 1966, the popularity of diesel-powered vehicles has grown. Today Inco's Ontario underground mining operations employ over 800 diesel-powered vehicles.

As potential adverse health effects from exposure to DPM have been reported in recent years, the Canadian mining industry has seen the necessity of improving underground air quality (Stachulak and Conard, 1998, 2001). Emissions-assisted engine maintenance, use of modern low emitting engines, better quality fuels, and exhaust control technology are some of the techniques Inco pursues in order to control particulate matter and gaseous emissions of diesel powered vehicles. Coupling these techniques with good ventilation practices remains the best strategy to reduce DPM in Inco mines.

One of the more attractive technologies to accomplish this goal involves the use of exhaust treatment devices, such as filters. Particulate traps (filters) have been commercially available since the mid-1980s and have found some success in on-road applications. The experience in mining, however, has been mixed. In some mines, filters were expected to be the panacea and were put into service, without much technical care. We now know that was a mistake. We now know that much care must be taken in matching a filter to an engine. Without such care, endless maintenance problems and poor performance will eventually lead to abandoning the technology and this is exactly what has happened in many Ontario mines.

Beginning in 1982, Inco embarked on an underground evaluation of diesel particulate filters (DPF)s by installing three pairs of ceramic filter units on heavy-duty diesel equipment. These filter sets accumulated 267 hours, 850 and 396 hours of vehicle operation, before unacceptable increases in backpressures were experienced (Dainty *et al*, 1985), due to insufficient exhaust temperatures to burn off the accumulating soot (a process called regeneration).

One of the chief problems encountered in prior implementation of particulate filters underground was not having reliable regeneration methods. Because the filters involved in filtering relatively high temperature diesel exhaust are expensive and labour-intensive to install and remove, methods for *in situ* regeneration have been sought. The best advances have been made by igniting the solids built up on the filter. This can be most effective because DPM consists predominantly of elemental carbon particles, the surfaces of which contain adsorbed hydrocarbons. Thus, burning the mass on the filter to form carbon dioxide removes more than 99 per cent of the mass and regenerates the filter for continued use. The primary challenge, however, is associated with attaining a temperature of about 600°C that is required to ignite the accumulated soot/DPM and to sustain this high temperature long enough to complete soot combustion. It was initially hoped that an engine's loading experienced during normal use would be sufficient to reach and sustain the necessary regeneration temperature, for a filter located in the exhaust manifold, but it is now known that these conditions may exist for very few underground vehicles, particularly now that many are using modern engines. Therefore, regeneration technology has evolved into 'assisted' regeneration (regeneration achieved by add-ons). Those systems can use various catalyst formulations, washcoated or fuel borne, to lower the ignition temperature or/and external source of energy, diesel fuel burner or electric heaters, to increase exhaust temperature and that way promote regeneration of the filters. Most of these technologies have seen significant improvements in recent years.

In 1997 members of the Canadian mining industry, together with labour unions and government agencies, formed the Diesel Emissions Evaluation Program (DEEP) with the objective of conducting research on controlling emissions from diesel-powered vehicles and reducing exposure of underground miners to particulate matter and gases from those vehicles. In 1999 DEEP initiated two comprehensive long-term studies, one of which was conducted at Inco's Stobie mine and is the subject of the present paper, to investigate the potential of using available DPF technologies to control diesel particulate matter emissions from underground mining vehicles.

OBJECTIVE

Nine state-of-the-art DPF systems were retrofitted to underground mining heavy-duty and light-duty vehicles at the Stobie mine and tested in normal production. The objective of the study was to address issues such as:

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1. criteria for selection of the filter medium and a vehicle- and use-specific DPF regeneration concept for underground mining applications;
2. technical and feasibility aspects of maintenance and operation of DPF systems in 'demanding/harsh' underground environments; and
3. in-use efficiency of the selected systems for controlling DPM emissions.

METHODOLOGY

Vehicles

The vehicles chosen to best represent the most critical components of underground mining diesel fleets consisted of four heavy-duty and two-light duty vehicles. The Wagner STB8 Scooptram™ and Toro 1400, powered by Detroit Diesel (DDEC) Series 60 engines, were selected because they represent the fleet of heavy-duty production load-haul-dump (LHD) vehicles. The Wagner STB8 Scooptram™ powered with a Deutz F12L413 engine is an older heavy-duty LHD unit, primarily used to carry out a broad range of support tasks. The Kubota M5400 is a typical light-duty vehicle, used for transport of personnel and materials throughout the mine. The technical specifications for vehicles and engines used in this study are summarised in Table 1.

Prior to the DPF installations, one of the targets of this study was to collect sufficient information on operating cycles from each of the selected vehicles and establish a method that could be used as a standard procedure for DPF selection in other mines. To this end, data loggers were installed on each of the test vehicles and data collected over a period of six months on backpressure and temperature trends. The mean average temperature for the logged one-minute averages was in the range of 380°C for DDEC 60 engines, 330°C for Deutz F12L413FW engines, and 200°C for light duty Kubota vehicles. Because of these low exhaust temperatures, reliable regeneration of DPF was confirmed to be a major challenge.

Diesel particulate filter systems

The DPF systems tested in this study were carefully selected so that various DPF designs and regeneration concepts, representative of those available on market, could be assessed. The important technical specifications for selected DPF systems are given in Table 2.

Four types of filtration media were tested in this study (see Table 2). Seven out of the nine DPF systems were designed around wall flow filter elements made of cordierite or silicon carbide ceramic monoliths. The two other used deep bed filters made with knitted or woven glass fibre. The DPF systems selected also represent two different regeneration categories, active and passive. Active regeneration requires a person to actively perform some task to regenerate the DPF. The task either involves exchanging a loaded filter with one regenerated in a special regenerating unit, or connecting the DPF system which contains an electric heating element to a regeneration station, when the vehicle is between shifts. Passive regeneration occurs during the normal operation of the vehicle, due to sufficient exhaust temperatures to promote the oxidation of the accumulated soot.

Two active regeneration DPF systems were installed on Kubota tractors. The silicon carbide filter elements in both systems were sized with sufficient capacity to collect soot generated by Kubota engines, during eight hours of operation, without creating unacceptable exhaust back pressure. The regeneration of both systems depended on heat generated by electrical heaters, provided with the systems. In the case of systems from ECS installed on vehicle #2180, the electrical heaters were integrated into the DPF system. For this vehicle, the regeneration of the DPF was done, by taking it to a designated regeneration station, where the DPF system was connected to power and a compressed air supply. The system was designed to be regenerated in a period of 60 minutes. In the case of the system from DCL on vehicle #621, the electrical heaters were in a special regeneration unit, located off-board the vehicle. The filter element needed to be removed from the vehicle in order to be regenerated. The regeneration took approximately 60 minutes.

Two of the five DPF systems installed on heavy-duty vehicles were fully passive. Two types of catalysts were used in these systems to lower regeneration temperatures. The Oberland Mangold system was designed to be used in conjunction with a bimetallic fuel-borne catalyst. The Engelhard DPF system contained a proprietary platinum-based catalyst wash coated on the cordierite filter medium.

The ECS/Unikat and Arvin Meritor DPF system, which were installed on a heavy-duty vehicle, operated in an fully active regeneration mode. The ECS/Unikat system was equipped with an on-board electric regeneration system, and required daily 90-minute regeneration. The Arvin Meritor system used a diesel fuel burner, which was activated by an on-board control unit based on either predetermined time intervals or a selected backpressure. The burner would fire for approximately ten minutes.

The last unit used a combination of active and passive regeneration. This Johnson Matthey DPF system had an integrated on-board electrical heater to support regeneration which was performed at the end of the shift. An on-board dosing of a fuel-borne (cerium) catalyst was incorporated in the vehicle fuelling system and was found to provide partial regeneration that allowed operation for several shifts when regeneration was not possible.

Emissions tests

Vehicle/engine operating conditions

Efficiency tests were carried out periodically. The objective of these tests was to establish in-use efficiency and durability of the

TABLE 1

Vehicles used.

Inco vehicle designation	#820	#445/#213	#111	#362	#2180	#621
Vehicle brand and model	Wagner STB8	Wagner STB8	Toro 1400	Wagner STB8	Kubota M5400	Kubota M5400
Vehicle type	LHD	LHD	LHD	LHD	Tractor	Tractor
Vehicle classification	heavy duty, non production	heavy-duty, production	heavy-duty, production	heavy-duty, production	light-duty, personnel transporter	light-duty, personnel transporter
Engine make and model	Deutz F12L413FW	DDEC Series 60	DDEC Series 60	DDEC Series 60	Kubota F2803B	Kubota F2803B
Engine displacement (litres)	19.1	11.1	11.1	11.1	2.7	2.7
Engine rated output (kW)	207	213	213	213	40.3	40.3

tested DPF systems. The first tests were conducted between 16 and 19 July 2001, the second round of tests between 25 and 31 May 2002, and final set of tests from 7 to 11 June 2004.

Emission measurements were taken in the exhaust system of stationary vehicles, with engines operated at selected, repeatable steady state and transient conditions. All engines, including those in the vehicles with automatic (heavy-duty LHDs) and manual (light-duty tractors) transmission, were tested at low and high idle conditions. The LHD engines, which were coupled to a torque converter and automatic transmission, were also operated under a torque converter stall (TCS) condition. During the TCS test the vehicle was parked, wheels chocked, service brake engaged, and transmission placed in the highest gear, thereby loading the engine against the torque converter. Energy produced by an engine under such conditions is mostly dissipated as heat in the torque converter, and the test was limited to about two minutes to avoid overheating the converter fluid. The TCS test is generally recognised to be the most reliable and repeatable way to substantially load an engine (approximately 75 per cent of maximum torque), of a vehicle equipped with a torque converter under stationary conditions.

Measurement methods and instrumentation

Various methods and instruments were used to measure concentrations of particulate matter and gases in the exhaust of the tested vehicles.

Concentrations of polycyclic aromatic hydrocarbons/ elemental carbon (PAH/EC) particles

Real-time concentrations of elemental carbon particles upstream and downstream of each filter were measured in diluted exhaust using a Photoelectric Aerosol Sensor, the PAS 2000, developed by Matter Engineering AG (Wohlen, Switzerland) and marketed in North America by EcoChem Analytics (League City, Texas). The PAS 2000 is a real time particle analyser based upon the detection of carbon particles ionised by the adsorption of ultraviolet energy, by the polycyclic aromatic hydrocarbons attached to the particles. The PAS 2000 can be used to estimate elemental carbon concentrations. Since the concentrations of particles in raw exhaust exceeded the maximum concentrations measurable by the instrument, the exhaust was diluted using a spinning disk dilution system (MD19-2E) from Matter Engineering AG. The diluter was integrated in a sampling train that allowed quick switching between the sampling ports located upstream and downstream of the filter element. In order to avoid condensation of volatile and semi-volatile compounds in the sampling lines, the exhaust stream sampling lines and dilution system were heated and maintained at 80°C. The dilution ratio was occasionally adjusted between tests to accommodate for differences in aerosol concentrations produced at the different engine operating conditions. The results were adjusted for the prevailing dilution rate and were averaged over several measurements to calculate the efficiencies of the DPF systems.

Elemental carbon concentrations

Samples of DPM, collected on tissue quartz media for elemental carbon analysis, were obtained from the exhaust system upstream and downstream of the filters during the July 2001 tests. The custom sampling method and equipment were developed in order to collect a sufficient DPM sample for carbon analysis, in a relative short period during torque converter tests. Three samples were collected at each sampling location for each of the tested configurations. The filter samples were shipped to

TABLE 2

Diesel particulate filter systems – vehicle combinations tested.

Vehicle	#820	#445		#213	#111	#362	#2180		#621
DPF brand	Johnson Matthey UK/Germany	Oberland Mangold Germany	ECS Unikat Canada/ Sweden	ECS Unikat Canada/ Sweden	Arvin Meritor USA	Engelhard USA	ECS-3M Canada	ECS-Unikat Canada/ Sweden	DCL International Canada
DPF model	DPF 201		combi-filter S18	combi-filter S18		DPX 2	Omega	combi-filter S	Titan
Filter media	silicon carbide/ cordierite	knitted glass filter cartridges	silicon carbide	silicon carbide	cordierite	cordierite with pre-catalyst	Nextel ceramic fibre cartridges	silicon carbide	silicon carbide
Number of filter units	two, vertical	single, horizontal	double, in parallel, vertical	double, in parallel, vertical	double	single, vertical	single, horizontal	single, horizontal	single, horizontal
Regeneration type	passive + active	passive	active	active	active	passive	active	active	active
Type of catalyst	fuel borne catalyst (cerium-Eolys)	fuel borne catalyst (cerium/ platinum, CDT Platinum Plus)	n/a	n/a	n/a	wash coat (precious metal - propriet.)	n/a	n/a	n/a
Type of active regeneration	on-board electrical	n/a	on-board electrical	on-board electrical	on-board, fuel burner	n/a	on-board, electrical	on-board, electrical	off-board electrical
DOC	n/a	n/a	n/a	n/a	Pt formulation on metal substrate	n/a	n/a	n/a	n/a
No. hours accumulated	2138	n/a	873	>1935	117	2221	430	463	732
Emission tests	July 2001 May 2002 June 2004	July 2001	May 2002	June 2004	June 2004	July 2001 May 2002	July 2001	May 2002 June 2002	May 2002 June 2004

the NIOSH Pittsburgh Research Laboratory and analysed for elemental carbon content, using NIOSH Analytical Method 5040 (Birch and Cary, 1996; NIOSH, 1999).

Number concentrations and size distribution of aerosols

The size distribution and number of particles with geometric mean between 10 and 392 nm in the diluted exhaust were measured during the tests conducted in May 2002 and June 2004, using a Scanning Mobility Particle Sizer (SMPS) Model 3926, from TSI Inc (St Paul, MN). Since the exhaust particle concentration in the raw exhaust exceeded the range of the SMPS, the exhaust was diluted using the Model MD19-2E spinning disk dilution system. The results were adjusted for the applied dilutions and averaged over several measurements. The filter efficiencies were determined for the abovementioned three steady state engine operating conditions, using dilution-adjusted average total number concentrations of aerosols upstream and downstream of the DPF systems.

Exhaust opacity

The exhaust opacities were measured upstream and downstream of the filters using an AVL (Gratz, Austria) DiSmoke 4000 instrument. The DiSmoke reports the maximum exhaust opacity and engine speed over a snap acceleration test. During this test the engine was aggressively accelerated from low idle to its rated speed, with only engine and flywheel inertia providing a load to the engine. The results were averaged over several measurements.

Smoke number

The filter samples for Bacharach smoke number analysis were collected using ECOM America, Ltd (Norcross, GA) KL and AC Plus instruments. The smoke samples were collected while vehicles/engines were operated at torque converter stall conditions. Bacharach combustion smoke spot samples were collected by flowing 1.6 litres of exhaust through a filter paper clamped in the sampling probe which confined the flow to a spot approximately 6 mm in diameter. A Bacharach smoke number was assigned to the spot obtained by comparing its 'greyness' on the ECOM-supplied scale with ten spots running from zero (white) to nine (very dark grey/black). The results were reported as the average of several measurements.

Gaseous emissions

The concentrations of carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO_2), and oxygen (O_2) in the raw exhaust of the tested vehicles were measured upstream and downstream of the filters using ECOM KL and ECOM AC Plus portable emission analysers. Both instruments use electrochemical cells to measure the aforementioned gases. The measurements were performed simultaneously at the same location (upstream or downstream), with both instruments. The concentrations were determined for three steady-state engine-operating conditions (see above). The results of measurements obtained with each of the instruments were averaged over several readings and used to calculate the effects of DPF systems on concentrations of CO, NO, and NO_2 in the exhaust.

RESULTS AND DISCUSSION

Efficiency of DPF systems

The results of efficiency measurements are shown in Table 3.

The results show that a majority of systems offered reductions exceeding 95 per cent in elemental carbon and number of particles. The exception was the Oberland Mangold (OM) DPF system installed on #445. The results of the tests, performed in July 2001, indicated substantial internal leaks within the filter. Subsequently it was thoroughly inspected by Catalytic Exhaust, the representative of OM for North America. The inspection revealed structural problems that resulted in having exhaust bypass the filter cartridges and further testing of this filter design was aborted.

In March 2002, vehicle #445 was fitted with an ECS-Unikat DPF system. The results of tests conducted in May 2002 on this system showed that the unit was performing less efficiently than expected. A visual inspection of the filter element revealed physical damage at the downstream end of the filter element. Additional analyses were performed on this engine's backpressure history. This revealed that the system had been operated at elevated backpressures for extended periods of time, and this was linked with inattention to making sure the electrical regeneration process was being followed. As a result, after 873 hours in operation, the damaged ECS-Unikat filter was removed from vehicle #445. In order to confirm the acceptable efficiency of an undamaged ECS/Unikat system, an identical unit was installed on LHD #213. The results of the test performed on that unit in June 2004 showed 99.9 per cent efficiency measured by PAS2000. The same system reduced number of the particles by 91 per cent.

The ECS Omega DPF system with 3M glass fibre cartridges exhibited somewhat lower filtration efficiencies than DPF systems with silicon-carbide (SiC) and cordierite monolith elements. Several months into study the filter media supplier, 3M, decided to terminate production of the cartridges. As a consequence, this 3M-based DPF system was replaced with an ECS Combi-filter in April 2002.

The results of opacity and smoke number measurements are summarised in Table 4. Of these two relatively simple methods, the smoke number appears to be the more reliable of the two methods as evidenced by the May 2002 test of ECS, in which the opacity of 1.6 per cent was not indicative of the low filter efficiency, yet for the May 2002 test of the Engelhard on #362 appeared to indicate a similar value (two per cent) for a filter determined highly efficient by other methods. Although the smoke number method lacks the accuracy to quantify the effects of DPF systems on DPM emissions, it can be successfully used by mine operators to diagnose potential problems with DPF systems.

It should be noted that the results of smoke number measurements performed in May 2002 revealed the aforementioned problems with ECS/Unikat DPF system on #445. The smoke number measurements were also good enough to indicate a difference between the efficiencies of glass fibre cartridges and ceramic monolith elements.

The effects of DPF systems on concentrations of NO_2 and CO

The results of measurements of NO_2 and CO concentrations upstream and downstream of the tested DPF systems are presented in Tables 5 and 6. A substantial increase in NO_2 concentrations was observed for one of the systems. The Engelhard DPF system on vehicle #362 was catalysed with a proprietary platinum-based catalyst, in order to lower regeneration temperature, and it is expected that the formation of NO_2 may have been increased by this system. For the JM system on #820, using a fuel-borne catalyst, and for the system from ECS/Unikat on #213, catalysed with a proprietary base metal catalyst, the NO_2 concentrations were found however, to be lower downstream than upstream of the filter elements. The concentrations of NO_2 were also found to be lower downstream than upstream, for the active systems on light duty vehicles. This may be attributed to the reaction between NO_2 and particulate matter accumulated in the filter.

TABLE 3
Efficiencies of the DPF systems.

DPF system	Test	PAS 2000 (%)			EC NIOSH 5040 (%)	Total particulate number (%)		
		TCS	High idle	Low idle	TCS	TCS	High idle	Low idle
JM SiC Right on #820	July 2001	99.9	-	-	98.3	-	-	-
JM SiC Right on #820	May 2002	100.0	99.9	99.9	-	99.1	98.8	97.2
JM Cord Right on #820	June 2004	99.9	99.8	-	-	97.8	98.1	96.9
JM SiC Left on #820	July 2001	100.0	99.9	-	97.6	-	-	-
JM SiC Left on #820	May 2002	99.5	99.9	99.9	-	98.1	98.7	97.2
JM SiC Left on #820	June 2004	99.4	99.3	-	-	98.7	96.3	84.5
Oberland Mangold on #445	July 2001	2.8	13.6	-	43.6	-	-	-
ECS SiC 1 on #445	May 2002	94.8	93.0	92.9	-	99.6	93.6	-
ECS SiC 2 on #213	June 2004	99.9	99.8	-	-	91.2	98.9	-
ArvinMeritor on #111	Data not available at this time							
Engelhard on #362	July 2001	99.6	99.7	-	99.4	-	-	-
Engelhard on #362	May 2002	100.0	99.6	100.0	-	97.0	95.1	-
ECS 3M on #2180	July 2001	-	83.3	-	94.4	-	-	-
ECS SiC on #2180	May 2002	-	100.0	100.0	-	-	99.7	99.7
ECS SiC on #2180	June 2004	-	99.9	-	-	-	99.9	-
DCL SiC on #621	May 2002	-	99.8	99.9	-	-	99.9	99.3
DCL SiC on #621	June 2004	-	99.9	-	-	-	97.5	-

TABLE 4
Results of opacity and smoke number measurements.

DPF system	Test	Opacity		Smoke number			
		Snap acceleration		TCS		High idle	
		Upstream	Downstream	Upstream	Downstream	Upstream	Downstream
JM SiC Right on #820	July 2001	-	-	6.0	0.0	-	-
JM SiC Right on #820	May 2002	7.8	0.1	8.8	0.0	-	-
JM Cord Right on #820	June 2004	-	-	-	0.5	-	-
JM SiC Left on #820	July 2001	-	-	6.5	0.0	-	-
JM SiC Left on #820	May 2002	2.9	0.3	7.0	0.0	-	-
ECS SiC 1 on #445	May 2002	35.3	1.6	7.8	5.7	-	-
ECS SiC 2 #213	June 2004	45.0	0.4	8.5	0.0	-	-
ArvinMeritor on #111	Data not available at this time						
Engelhard on #362	May 2002	35.9	2.0	9.0	0.0	-	-
ECS 3M on #2180	July 2001	-	-	-	-	9.0	3.5
ECS SiC on #2180	May 2002	39.8	0.2	-	-	6.5	0.0
ECS SiC on #2180	June 2004	44.7	0.0	-	-	8.5	0.0
DCL SiC on #621	May 2002	33.5	0.3	-	-	6.0	0.0
DCL SiC on #621	June 2004	37.9	0.0	-	-	5.5	1.0

The platinum catalyst in the DPF system from Engelhard was also found to efficiently oxidise (reduce) CO and hydrocarbons (see Table 6). The concentrations of CO were found to be unexpectedly higher downstream than upstream of some of the uncatalysed filters (#820 on June 2004, #445 on May 2002, #2180 on July 2001 and May 2002).

Comments on the systems tested

The filter medium, together with its regeneration system, defines the DPF. Several of the DPF systems tested at Stobie mine have demonstrated good robustness and reliability during some 2000 hours of operation for heavy-duty vehicles and, to date, 700 hours of light duty units. Long-term verification of in excess of 99 per cent soot removal was shown for both heavy duty and light duty vehicles.

- The Johnson Matthey system, installed on an LHD powered by Deutz F12L413FW engine, proved to be robust. The system had an added complexity of requiring a fuel additive, but also had an active regeneration backup using electric heaters, if needed. It did not produce increased NO_2, and operated within the engine manufacturer's recommended backpressure limit.

TABLE 5

Average concentrations of NO_2.

DPF system	Test	NO_2 (ppm)					
		TCS		High idle		Low idle	
		Upstream	Downstream	Upstream	Downstream	Upstream	Downstream
JM SiC Right on #820	July 2001	22.0	10.0	26.0	3.0	26.0	2.0
JM SiC Right on #820	May 2002	12.0	6.0	17.3	6.0	30.8	6.4
JM Cord Right on #820	June 2004	15.0	6.7	21.7	7.7	29.7	9.7
JM SiC Left on #820	July 2001	15.0	10.0	20.0	5.0	15.0	8.0
JM SiC Left on #820	May 2002	30.3	8.7	46.7	8.3	71.7	31.4
Oberland Mangold on #445	July 2001	-	41.0	-	20.0	-	-
ECS SiC 1 on #445	May 2002	35.0	13.0	48.0	12.0	85.0	34.4
ECS SiC 2 on #213	June 2004	8.3	5.3	17.3	6.7	36.3	7.0
ArvinMeritor on #111	Data not available at this time						
Engelhard on #362	July 2001	26.0	60.0	32.0	58.0	53.0	-
Engelhard on #362	May 2002	34.0	52.7	50.7	50.3	76.2	85.0
ECS 3M on #2180	July 2001	-	-	44.0	30.0	-	-
ECS SiC on #2180	May 2002	-	-	89.0	79.7	83.0	66.0
ECS SiC on #2180	June 2004	-	-	72.3	38.0	66.3	17.7
DCL SiC on #621	May 2002	-	-	90.3	83.7	77.7	70.3
DCL SiC on #621	June 2004	-	-	59.0	48.0	61.0	43.3

TABLE 6

Average concentrations of CO.

DPF system	Test	CO (ppm)					
		TCS		High idle		Low idle	
		Upstream	Downstream	Upstream	Downstream	Upstream	Downstream
JM SiC Right on #820	July 2001	133.0	130.0	132.0	110.0	85.0	75.0
JM SiC Right on #820	May 2002	373.0	185.0	71.3	50.0	60.4	5.0
JM Cord Right on #820	June 2004	142.0	177.7	92.0	84.0	58.7	56.3
JM SiC Left on #820	July 2001	115.0	115.0	99.0	99.0	71.0	62.0
JM SiC Left on #820	May 2002	99.0	91.7	140.0	119.7	163.0	137.0
Oberland Mangold on #445	July 2001	-	473.0	-	143.0	-	-
ECS SiC 1 on #445	May 2002	110.0	224.3	90.0	98.0	119.4	93.4
ECS SiC 2 on #213	June 2004	136.7	169.0	115.7	112.3	120.7	116.0
ArvinMeritor on #111	Data not available at this time						
Engelhard on #362	July 2001	82.0	10.0	88.0	2.0	165.0	-
Engelhard on #362	May 2002	117.0	12.3	101.3	8.7	146.8	25.0
ECS 3M on #2180	July 2001	-	-	193.0	233.0	-	-
ECS SiC on #2180	May 2002	-	-	349.3	370.0	138.7	135.5
ECS SiC on #2180	June 2004	-	-	438.0	375.0	147.7	153.3
DCL SiC on #621	May 2002	-	-	309.3	312.0	127.0	122.0
DCL SiC on #621	June 2004	-	-	296.0	266.7	132.0	132.3

- The ECS/Combi-filter system, installed on an LHD with a DDEC Series 60 engine, also showed good results as long as operators were attentive to the need to regenerate the system at the end of each shift. It did not produce an increase in NO_2 emissions and it was operated within the recommended engine backpressure limit.
- The Engelhard DPF system, installed on a heavy duty LHD powered by DDEC Series 60 engine, provided a low complexity, fully passive system at reasonable cost. The filter showed its ruggedness when it survived an accident during which mud penetrate into filter cells. This system provided a 'business as usual' mode of operation that required negligible attention from the vehicle operator, but the system did show a measurable increase in NO_2 concentrations in the tailpipe and the engine back-pressure routinely was above the manufacturer's recommended maximum.
- The DPF systems requiring active regeneration were shown to be also well adapted to the light duty vehicles. In one system, the DPF was small and easily replaced with a regenerated one. The other system required only a short time for regeneration (60 minutes), which easily fit into the vehicle's schedule. This is a promising result in light of the increased presence and usage of light duty vehicles in modern mining operations.

CONCLUDING REMARKS

The proper selection of particulate trap/regeneration systems require information, specifically exhaust temperature logs, on the duty cycle of the candidate vehicles. Duty cycles depend not only on the typical operating conditions but also on individual driving patterns, engine power setting, engine age and maintenance status and many other parameters. These parameters not only change from one application case to another, but they also vary for a given application as a function of time, season, driver and other factors and are in many cases unpredictable. Modern DPF system technologies offer high temperature filter media, such as ceramic wall flow filters, metallic sinter structures and fibre structures, which provide good trapping efficiency, with respect to solid carbonaceous particles in the size range above 10 nm. For passive systems, it is essential, however, to match the correct DPF system to the vehicle, engine and duty cycle. While active systems may not require as much 'matching' attention, the challenge shifts to one of communicating system requirements to the vehicle operators, who must give attention for proper regeneration to occur.

The Stobie tests demonstrate that both heavy duty and light duty underground diesel vehicles can be fitted with functional DPF systems, but only when preceded by careful planning and careful attention to matching the specific requirements of the DPF system with the specific operational characteristics of the vehicle onto which it is placed, and, most importantly, only when followed up by strict attention to the operational requirements of the DPF system. While the former requirement can be attained by those with proper technical knowledge, the latter requirement falls to and burdens the vehicle operators and maintenance personnel. A guide for the selection and use of DPF systems is available from both the MSHA and NIOSH web sites (Schnakenberg, 2003).

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REFERENCES

Birch, M E and Cary, R A, 1996. Elemental carbon-based method for monitoring occupational exposures to particulate diesel exhaust, *Aerosol Science and Technology*, 25:221-241.

Dainty, E D, Mogan, J P, Lawson, A and Mitchell, E W, 1985. The status of total diesel exhaust filter development for underground mines, in *Proceedings XXI International Conference of Safety in Mines Research Institutes* (ed: A R Green), pp 453-461 (A A Balkema: Rotterdam).

National Institute for Safety and Health (NIOSH), 1999. Elemental carbon (diesel particulate): Method 5040, Issue 3 (Interim), in *NIOSH Manual of Analytical Methods*, fourth revised edition, Cincinnati. Available from: <http://www.cdc.gov/niosh/nmam/pdfs/5040f3.pdf>.

Schnakenberg, G H, 2003. Diesel particulate filter selection guide for diesel-powered equipment in metal and non-metal mines. Available from: <http://www.cdc.gov/niosh/mining/topics/diesel/diesel.html>.

Schnakenberg, G H and Bugarski, A D, 2002. Review of technology available to the underground mining industry for control of diesel emissions, US Department of Health and Human Services Information Circular IC 9262. Available from: <http://www.cdc.gov/niosh/mining/pubs/pdfs/ic9462.pdf>.

Stachulak, J S and Conard, B R, 1998. Diesel exhaust: control strategy and measurements at INCO mines, *CIM Bulletin*, 91(1022):82-87.

Stachulak, J S and Conard, B R, 2001. Diesel emission control strategy: underground evaluation of particulate filter systems at Inco's Stobie Mine, in *Proceedings Seventh International Mine Ventilation Congress*, pp 929-932 (The Research and Development Center for Electrical Engineering and Automation in Mining EMAG: Cracow).