Development and In-mine Field Trials of a Diesel Particulate Filter System With On-board, Electrical, Partial Flow Regeneration

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ABSTRACT

The need to improve air quality in many North American mines is clear, with stringent new diesel emission regulations being proposed by MSHA. In response to these changing demands from customers, DCL has developed an electrically heated active sootfilter regeneration system for mining vehicles. Mining production vehicles that have often been borderline soot filter applications in the past will benefit from this technology.

The system design is an electrically heated partial flow regeneration concept using a silicon carbide (SiC) wall flow filter and microprocessor-based controls.

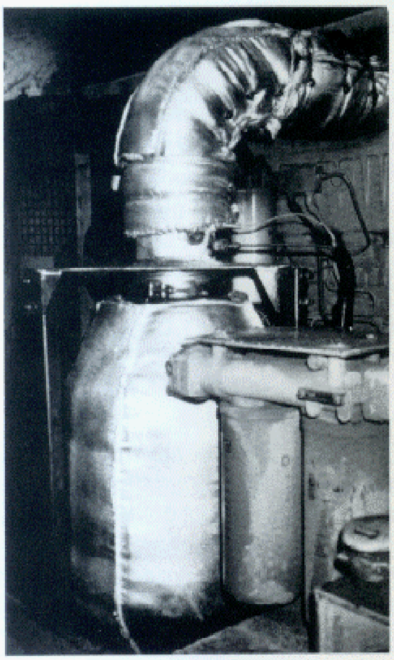
This paper presents the results obtained after six months of experimental system development and four months of in-mine prototype field trials. Backpressure behavior, regeneration time, emissions performance and temperature profiles are among some of the important parameters studied.

KEYWORDS

Emissions, Diesel Engine, Sootfilter, Diesel Particulate Filter, Exhaust Aftertreatment, Particulate Matter, Regeneration

INTRODUCTION

Ceramic, wall-flow particulate filters have been an enabling technology for diesel emission control for over fifteen years. First developed by Corning, diesel particulate filters (DPF) have been used in thousands of applications around the world to reduce worker's exposure to diesel particulate. Properly engineered and applied, a DPF is an extremely effective device. Particulate reductions of over 90% are routinely achievable. There are some drawbacks, however. As diesel particulate is collected in the filter, it must be periodically burned off to prevent filter clogging and the resultant increase in exhaust backpressure on the engine. This happens when the excess oxygen available in diesel engine exhaust combines with the carbon in particulate matter to form CO_2 gas, which can then pass out of the filter. The other components of diesel particulate matter, such as adsorbed hydrocarbons are oxidized also. This is known as passive filter regeneration. In an ideal application, this is achieved automatically when the engine exhaust temperature exceeds the ignition temperature for diesel particulate. Unfortunately, the ignition temperature for diesel particulate is approximately 550°C, an exhaust temperature that is higher than commonly seen with diesel engines. Catalysts and fuel additives can lower this temperature threshold somewhat but it is generally accepted that not all diesel engine applications can achieve sufficient exhaust temperatures to ensure reliable DPF regeneration.



MINE-X SOOTFILTER installed in a Wagner ST8B loader with a Cat 3406 PCTA engine.

REGULATORY DRIVERS

US regulators have cracked down on diesel emissions for both on- and off-road applications. Possible future Tier 3 diesel standards could mandate particulate emission levels as low as 0.2 g/kWh across engine families from 130 to 560 kW starting in 2006. This is targeted right at primary heavy-duty construction equipment such as loaders and haulage trucks.

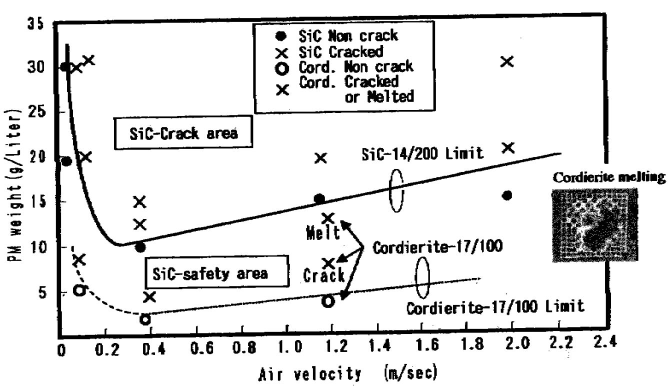
The bar could be raised for the mining industry also. MSHA (Mine Safety and Health Administration) has proposed a new rule for underground coal and metal/non-metal mines (MSHA, 1998a). The proposed rule for coal requires the installation of DPM filters on permissible diesel powered equipment immediately and installations on non-permissible equipment shortly thereafter, effectively a technology standard. The rule for metal/nonmetal mines sets 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, an air quality standard (MSHA, 1998b).

Elsewhere, the effect of diesel particulate emissions on ambient air quality is being monitored also. 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.

The California Air Resources Board (CARB) has labelled diesel exhaust as a "toxic air contaminant" and the US Environmental protection agency is performing extensive studies of the toxicity of diesel particulate and will be releasing a study by the end of this year. Clearly both the original equipment manufacturer and the end user will have to develop diesel particulate control strategies.

SYSTEM OVERVIEW

If passive filter regeneration is not achievable for a particular application, a number of active regeneration strategies are available. Active systems use an additional source of energy to heat the filter element above the particulate ignition temperature. The two most common energy sources are electrical heating and diesel fuel burners. The regeneration strategy can be either full or partial flow. Full flow systems add heat to the total exhaust gas flow passing through the DPF, they require large amounts of energy to heat large amounts of gas and the engine must be operating. Partial flow systems use only enough gas for particulate combustion. This lowers the amount of energy required and allows the engine to be shut off during regeneration if the combustion air is supplied from an external source. After reviewing the feasibility of several concepts, DCL International Inc. decided to focus development on an electrical, partial flow system to best meet the needs of its mining customers.



The DCL DPF is regenerated with an on-board, electrical, partial flow system. This two part hybrid concept allows the filter to remain in the vehicle for large applications while electrical power and combustion air are supplied from an external source. This obviates the need to remove large and heavy filters from the vehicle while ensuring that the system electronics can be stored off the vehicle in a maintenance area for safety.

The electrical heating element is integral with the filter body mounted on the vehicle. No connection is made to the vehicle's electrical system. When the DPF requires regeneration, the vehicle is returned to a staging or maintenance area where power and air connections are made to a portable regeneration unit. The filter is then automatically regenerated, following a pre-programmed schedule. Regeneration can proceed unattended and a system annunciator panel alerts the operator to system status and regeneration completion.

DPF FILTRATION ELEMENT SELECTION

Although traditional ceramic DPF elements made of cordierite have proven to be durable, with some applications exceeding 11,000 hours of operation, there are some disadvantages.

The decomposition temperature for cordierite is 1200°C and temperatures around 1000°C should be avoided during operation. It is possible for filter temperatures to exceed 1000°C during uncontrolled regeneration. The ceramic material has low bending and compressive strength and must be packaged carefully and protected from mechanical shock.

Silicon carbide (SiC), used as a new filter media, has the potential to solve some of the problems presented by cordierite. The decomposition temperature is 2300°C and the maximum safe operational temperature is 1600°C. It is highly unlikely that these temperatures would be reached even in a practical "worst case" regeneration scenario.

Property	SiC	Cordierite
Bulk density g/cm^3	1.6	1
Porosity %	50	46
Surface area m^2/L	0.42	0.63
Compressive(l) MPa	60	0.85
Bending (kg/cmm^2)	3	1.25
T.C. (cal/cms^oC)	0.076	0.0025
Decomposition ^oC	2300	1200
Max Operating ^oC	1600	1000

Silicon carbide has other advantages that increase its utility as DPF media. High compressive and bending strength increases durability and high thermal conductivity lowers heat-up time and smoothes filter regeneration.

The DCL system employs a silicon carbide filter element to ensure durability and reliability in demanding industrial diesel applications.

REGENERATION STRATEGY

Several regeneration strategies were considered for the project including diesel burners, electric hot air blowers and electrical heating elements.

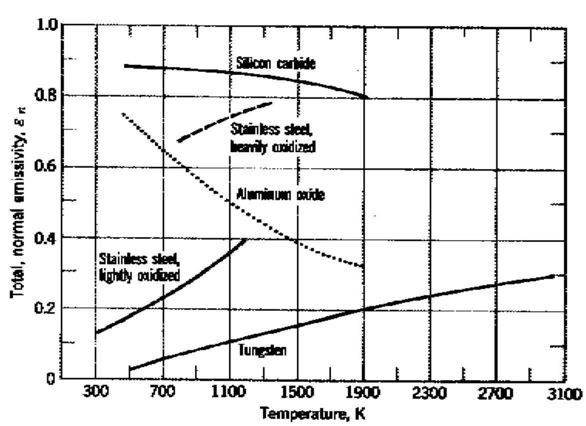
Diesel fuel burner concepts were discarded as complex and unreliable. Burners require modifications to the vehicle fuel system which raise safety issues and prevent system standardisation. It was unlikely that the mining market would allow such a system underground without extensive safety devices.

Electric hot air blowers were also considered. These units can supply air at 600-700^{o}C to the filter. Air blowers were found to be effective for small filters (< 3.0 L volume) but not for larger units. The time required to heat up the larger filters to a point where particulate would combust was too long to be acceptable for the mining industry. The two step process to first heat air and then use that air to heat the filter was found to be too energy intensive. In order to ensure fast heat up of the filter element, large flows of air were required which in turn required a large amount of electrical energy.

It was decided to heat the filter element directly using radiation heat transfer and only supply enough air for combustion. This concept was modelled after work performed at CANMET's Diesel Emissions Laboratory in Ottawa, Canada. By placing an electric heating element close to the filter face, heat can be transferred directly to the filter element, greatly reducing the system electrical power requirements and complexity. The face heater unit can be easily welded into a filter assembly, minimising space requirements and increasing durability.

ELECTRIC POWER REQUIREMENTS

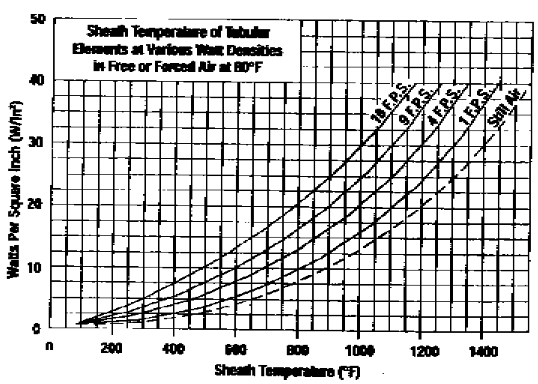
Radiation heat transfer from the heating element to the 15"x12" filter face was simplified and modelled as blackbody radiation exchange between two coaxial, parallel disks. SiC has a high emissivity at system operating temperatures.



System parameters required heating the filter face from room temperature to 600°C. This would initiate a combustion wave at the filter face which would propagate through the filter element, consuming particulate as it went, supported by a small amount of externally supplied combustion air. Regeneration would be completed as the wave reached the filter exit face.

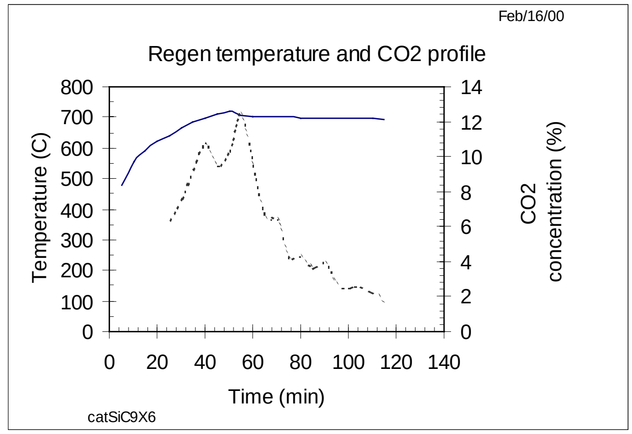
After calculation of the system heat-up requirements, the DEEP system prototype was equipped with an 8 kW spiral element.

Watt density of the heating element was the reviewed to ensure safe operation. It is defined as the heater power divided by the radiation surface area. At a watt density of 40 W/in^2, the sheath temperature would achieve 870°C in still air. This is the maximum safe temperature for the Incoloy® 800 sheath.



SCALE MODEL TRIALS

Several small-scale systems were built and tested. Best results were obtained with a 9"x6" filter element heated by a 2.4 kW electric face heater. Various system parameters such as preheat time, combustion air volume and heater power input were optimised. Complete filter regeneration could be achieved in 1.5 hours.

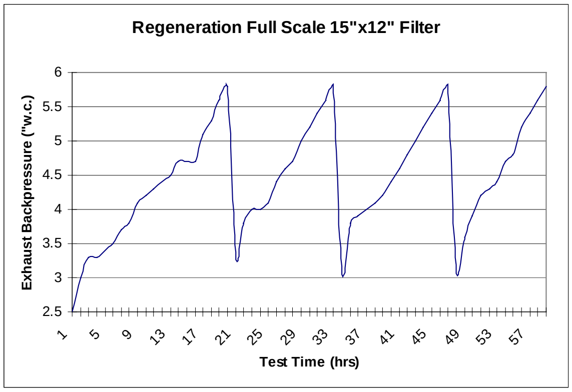


FULL SCALE PROTOTYPE TRIALS

With the success of the 9"x6" unit, it was decided to scale up the concept to simulate a mining vehicle concept. A 15"x12" filter was loaded with DCL's 150 HP Caterpillar 3306 PCNA engine.

After a few weeks of system optimisation, the regeneration time could be held to 1.5 hours as before with a significantly larger filter.

Multiple loading and regeneration cycles were carried out on the DEEP filter system before shipping it to the mine.



INITIAL DEEP FIELD TRIALS

The prototype unit is currently being field tested in an underground mine environment as part of the multi-stakeholder Diesel Emissions Evaluation Program (DEEP). The unit was installed on a Wagner ST8-B loader and placed into active production. Performance is being monitored and reported by DEEP to the mining industry.

Immediately after installation, the system baseline performance was measured using Brunswick Mine's UGAS emission measurement protocol.

Table1: Post Installation Performance

	Upstream Side	*Downstream Side*
Back Pressure	24 iwg – 60 mbar	N/A
Temperature	765ºF - 407ºC	735ºF - 391ºC
(CO)	106 ppm	1 ppm
(CO_2)	8.4%	8.43%
(O_2)	9.52%	9.47%
(NO)	692 ppm	624 ppm
(NO_2)	30 ppm	114 ppm
(NOx)	722 ppm	738 ppm
Smoke Index	7	0

FIRST DEEP TRIAL STATUS REPORT

One month after installation, the system was once again checked for emissions performance. Measurements were repeated using the UGAS system and the NanoMet instrument.

Independent observers from NIOSH and CANMET were on hand. The vehicle had accumulated a total of 174 operating hours.

Table 2: UGAS data at 174 hrs

	Upstream side	Downstream side
CO	172 ppm	18 ppm
NO	460 ppm	471 ppm
NO2	11 ppm	21 ppm
NOx	471 ppm	492 ppm
CO2	7.69%	7.66%
Smoke Test	7	1
Exh Temp	405º C	393º C
BackPressure	80 mbar – 32" wg	Na
RPM	1850	1850

There are 6 test modes used for a complete test on a filter using the new NanoMet instrument. Both sides of the trap are sampled simultaneously in each mode. The test modes are:

❶ Full throttle – Full torque converter stall
❷ Snap acceleration – free no load sets of 3
❸ Snap acceleration – full stall (Sets of 3)
❹ Idle – No Load
❺ Full Throttle – No Load
❻ Full Throttle – Full torque converter stall

Table 3: NanoMet Testing Results

Mode	**Filtration Efficiency**	
	DC (1)	**PAS**
❶	94.6%	99.6%
❷	96.3% 96.8%	99.5% 99.8%
❸	96.8% 93.8%	99.8% 99.6%

❹ (2)	94.4% 95.9%	89.4% 94.5%
❺	95.5% 95.5%	99.9% 99.9%
❻	94.3%	99.9%

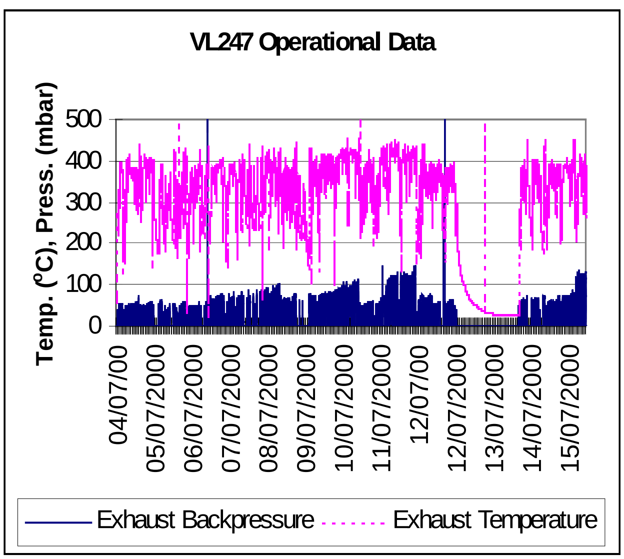
(1) Results from the DC sensor were unstable due to problems that are suspected due to condensation from the mine environment relative humidity and cold spots in the heated sample line. For this reason the best-deduced efficiency values should be taken from the PAS sensor measurement.
(2) Mode 4 – Low Idle produced consistently flawed or suspect data

The DCL system is providing better than 95% particulate matter filtration efficiency below the 100 mbar backpressure target.

VEHICLE OPERATIONAL DATA

The critical system parameters, exhaust temperature and backpressure, are being monitored continuously during this field trial. This data is being analysed to determine long term system performance and durability.

Figure X: PNE Data



The DEEP filter trials are scheduled to continue for at least a year. System performance will continue to be evaluated and reported by DEEP.

CONCLUSIONS

The DCL filter concept provides an effective way to ensure filter regeneration by removing the system dependency on exhaust temperature. As long as 1-2 hour breaks can be tolerated between shifts, the system can load and regenerated in a controlled manner. The vehicle duty cycle can change without affecting regeneration and no additions or modifications to the vehicle's fuel or electrical system are required.

For smaller applications, like forklift trucks and mine tractors, an exchangeable system concept is under development.

REFERENCES

1) ACGIH, 1995, "Notice of intended changes for 1995-1996", *1995 Annual Reports of the Committes on the Threshold Limit Values and Biological Exposure Indices*, May 23, 1995, Kansas City, Missouri.

2) ACGIH, 1998, "Notice of intended changes for 1999", *1998 Annual Reports of the TLV and BEI Committees*, October 25, 1998, Cincinnati, OH.

3) Dainty, E.D., Gangal, M.K., Carlson, D.H., Vergeer, H.C. and Mitchell, E.W., 1986. A summary of underground mine investigations of ceramic particulate filters and catalytic purifiers. *Special Vol. No. 36, Heavy Duty Diesel Emissions Control: a*

Review of Technology, Canadian Institute of Mining and Metallurgy, pp 54-77.

4) HEI, 1995, "Diesel Exhaust: A Critical Analysis of Emissions, Exposure, and Health Effects". *A Special Report of the Institute's Diesel Working Group*, Health Effects Institute, Cambridge, MA.

5) Mayer, A., Czerwinski, J., Matter, U, Wyser,M., Scheidegger, Kieser, D., and Weidhofer, 1998. " VERT: Diesel nano-particulate emissions: Properties and reduction strategies. *SAE Paper 980539*, pp 127-138.

6) MSHA, 1998a, "Diesel particulate matter exposure of underground coal miners; proposed rule", *MSHA, Department of Labour*, 30CFR Parts 72 and 75, April 9, 1998.

7) MSHA, 1998 b, " Diesel particulate matter exposure of underground metal and non metal miners; proposed rule", *MSHA, Department of Labour*, 30 CFR Part 57, October 29, 1998.

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