Impact of Stobie Testing on Inco's Research Program

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DEEP Projects on Long-Term Evaluation of DPF Systems

- Inco Stobie mine - May 2001 – April 2006;
  - Nine state-of-the-art DPF systems on five heavy-duty and two light-duty underground mining vehicles;
  - Joint effort of Inco Limited, NIOSH-PRL, and CANMET

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Inco Stobie Mine DPF Project

- Long-term (4 years) evaluation of nine state-of-the-art diesel particulate filter (DPF) systems retrofitted to heavy-duty and light-duty underground mining vehicles used in normal production cycle.
- The emphasis was given to:
  - Assessment of in-use efficiency of selected DPF systems for controlling emissions of diesel particulate matter (DPM);
  - Development of criteria for selection of DPF system and regeneration concept for underground mining applications;
  - Identifying technical and feasibility aspects of maintenance and operation of DPF systems in demanding and harsh underground environment.

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Chronology of Inco DPF Project

- Stage 1: Planning, site preparations and training
- Stage 2: Selection of candidate vehicles
- Stage 3: Duty cycle monitoring of vehicles
- Stage 4: DPF selection
- Stage 5: Installation of DPF
- Stage 6: Production use and regeneration logging
- Stage 7: Periodic monitoring by maintenance personnel
- Stage 8: Industrial hygiene monitoring of mine air
- Stage 9: Detailed efficiency measurements
- Stage 10: DPF post-use analysis
- Stage 11: Integrate results and form conclusions
- Stage 12: Technology Transfer
- Stage 13: Writing Final Report

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Inco DPF Project - Stages of Work

- Planning, site preparations and training
  - The core team from Stobie conducted weekly status meetings throughout the project life
- Selection of candidate vehicles
  - Discussions were held with mine management to select vehicles most representative of heavy duty and light duty diesel horsepower in underground mining.
- Duty cycle monitoring of vehicles
  - Software for controlling the dataloggers was provided by the datalogger manufacturer and training in hardware operation and maintenance and in software for downloading data was carried out by the manufacturer in association with Inco's Mine Training Department. E-mail-ings of these data to the Principal Technical Consultant (A.Mayer) were done about weekly.

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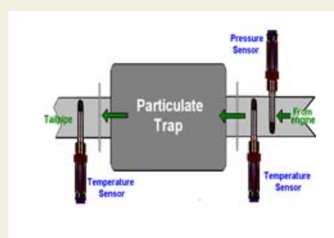
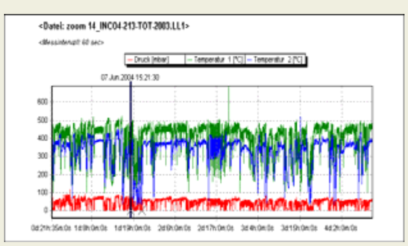
Duty Cycle Monitoring

Temperatursensor



Position of the sensor. The particulate trap occupies the space normally taken by the muffler



The five I/O ports left to right are for pressure, Temperatures, rpm and power alarm

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Inco DPF Project - Stages of Work

- DPFs selection
  - In November 2000 a duty cycle review session was held at Stobie and engine manufacturers, emission control equipment manufacturers, Inco and non-Inco technical personnel and consultants participated. The outcome of this meeting was the selection of DPFs for the six test vehicles
- Installation of PFSs
  - With guidance supplied by the manufacturers and technical consultants, installation of each DPF was carried out by Inco personnel. Equipment manufacturers were invited to Stobie to assist in installation and to train maintenance personnel in specific requirements of each DPF.
- Production use and regeneration logging
  - Vehicles were put into normal operation except that vehicle operators were trained to keep a log of operational performance for each shift. Each use of an active regeneration system was recorded in a log book.

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Inco DPF Project - Stages of Work

- Periodic monitoring by maintenance personnel

  After every 250 hours of vehicle operation, a preventive maintenance procedure was carried out on the vehicle, its engine, its datalogger-sensors and its DPFs. Measurement of undiluted tailpipe gases and opacity/smoke were carried out by Inco maintenance personnel.

- Industrial hygiene monitoring of mine air

  Even though the vehicles being used were not in an isolated area of the mine away from non-DPF-equipped vehicles, attempts were made to determine if the air in the mine in the immediate area around the test vehicle was improved with respect to DPM content.

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Inco DPF Project - Stages of Work

- Detailed efficiency measurements

  Three times during the four year project special sessions of efficiency measurements were conducted in conjunction with U.S. NIOSH scientists. These measurements included particulate concentrations upstream and downstream of a filter; filter efficiencies for removing diesel exhaust components; particle size distributions; gaseous components (NO, NO_2, CO, CO_2, and O_2) upstream and downstream of a filter; exhaust opacity; and smoke numbers.

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Inco DPF Project - Stages of Work

- DPF post-use analysis

  Efficiency measurements at the end of the project were carried out on selected filters by Natural Resources Canada (CANMET) engineers. The original DPF manufacturers had the opportunity to examine the internal states of their filters to determine either the mode of failure (for those that failed during the project) or to determine the internal status of a filter (for those exhibiting a good efficiency at the end of the project).

- Technology Transfer

  Near the end of the project- experimental phase, in July 2004, interested parties were invited to attend a workshop to review the results of the Stobie testing.

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Test Vehicles

- **Five** heavy-duty and **two** light-duty underground mining vehicles.
- Vehicles are representative of the underground mining diesel fleet at Stobie mine.

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 12L413FW	DDEC Series 60	DDEC Series 60	DDEC Series 60	Kubota 2803B	Kubota F2803B
Engine Displacement [liters]	19.1	11.1	11.1	11.1	2.7	2.7
Engine rated Output [kW/hp]	207/277	242/325	213/285	213/285	40.3/50	40.3/50

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DPF Selection Methodology

- Modern diesel exhaust DPF technology was shown in laboratory studies to provide filtration efficiency above 95% with respect to solid carbonaceous particles.
- The challenge is the periodic cleaning of such filters by combustion of the deposited soot (regeneration).
- Unassisted soot combustion for regeneration requires temperatures above 600 ºC – not available under the typical mine vehicle operating conditions.
- The proper selection of the DPF system with respect to functionality, cost and risk of failure requires information on the operation conditions of the target vehicle -- in particular the load cycle, and associated exhaust temperature.

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DPF Selection Criteria

- Modified VERT selection criteria:
  - The system should have efficiency of 95% (particle number and EC);
  - The system should provide adequate regeneration over mining cycle;
  - Backpressure must not exceed:
    - New DPF 50 mbar
    - Regenerated DPF 60 mbar
    - Before cleaning 150 mbar
  - Exhaust temperature and engine backpressure monitoring
  - No increase in emissions - NO2, NO, CO, chained hydrocarbons, dioxin, furans, poly-aromatic hydrocarbons during DPF operation and/or regeneration
  - The system should be ruggedized for underground mining applications;
  - CSA and CEC approved;
  - Useful life of the system should be 3 years or 9000 hours.

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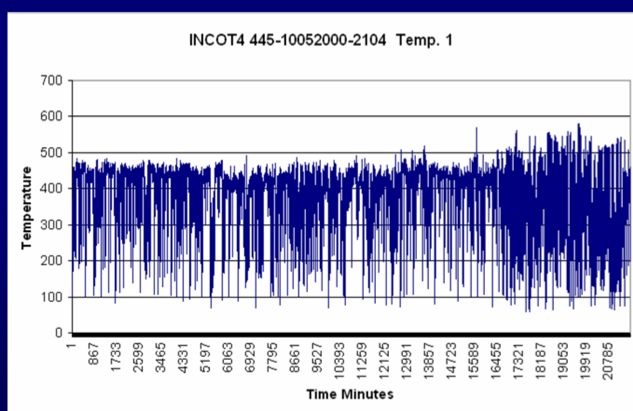
The Issue

- Here is the 6-month exhaust temperature trend for typical LHD powered by DDEC 60 Engine.
- The average temperature is about **380 °C** therefore “auto-regeneration” will not take place in uncatalyzed DPF.

Potential Solutions

- Catalytic coating of the filter element;
- Use of fuel additives;
- Electrical regeneration/fuel burner;



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Tested DPF Systems

DPF Brand	Johnson Matthey	Oberland Mangold	ECS Unikat	ECS Unikat	Arvin Meritor	Engelhard	ECS-3M	ECS-Unikat	DCL Internat.
DPF Model	DPF 201		Combifilter S18	Combifilter S18		DPX 2	Omega	Combifilter S	Titan
Vehicle	#820	#445		#213	#111	#362	#2180		#621
Filter Media	silicon carbide /cordierite	knitted glass filter cartridges	silicon carbide	silicon carbide	Cordierite	cordierite with pre-catalyst	ceramic fibres cartridges	silicon carbide	silicon carbide
Number of Filter Units	two, vertical	single, horizontal	double, in parallel, vertical	double, in parallel, vertical	double, vertical	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)	fuel borne catalyst (cerium /platinum)	wash coat (base metal)	wash coat (base metal)	n/a	wash coat (precious metal)	n/a	n/a	n/a
Type of Active Regeneration	**on-board electrical**	**n/a**	**on-board electrical**	**on-board electrical**	**on-board, fuel burners**	**n/a**	**on-board, electrical**	**on-board, electrical**	**off-board electrical**
DOC	n/a	n/a	n/a	n/a	Pt form. on metal substrate	n/a	n/a	n/a	n/a
Number of Hours Accumulated	2138/2391	n/a	940	2084	117	2221	453	577	864
Emissions Tests	July 2001 May 2002 June 2004	July 2001	May 2002	June 2004	June 2004	July 2001 May 2002	July 2001	May 2002 June 2004	May 2002 June 2004

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Highlights of Emissions Measurements Results

- Elemental Carbon Concentrations reduced as much as 99.8% according to PAS 2000 measurements.
- Elemental Carbon Concentrations reduced as much as 98.2% according to NIOSH 5040 analysis.
- Size distribution and number concentration measurements showed that engine de-rating from 325 to 285 hp reduces DPM concentration up to 2 orders of magnitude at torque converter stall conditions.
- Platinum catalyzed DPF system increased NO_2 emission by a factor of two
- Tested catalyzed DPF systems reduced CO emissions.

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Concluding Observations

- The Stobie study demonstrated that both heavy-duty and light-duty underground diesel vehicles can be fitted with functional DPF systems –… but
- The main challenge remaining to be resolved in implementing DPF system technology is to eliminate the human parameter from their operation (ie. Catalytic converter in your car).
- The study showed that tested DPF systems were efficient in removing DPM, elemental carbon and generally particles from the diesel exhaust.
- But, the study also showed that the effects of the DPF systems on secondary emissions should be closely investigated and assessed.

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Concluding Observations

- The successes of the DPF installations were found to be warranted only in the case of careful and educated selection of the DPF system for the particular application
- The study showed that the installation of DPF system should be preceded and supported with thorough emissions based maintenance
- The DPF systems should be operated strictly according to the manufacture recommendations and under close supervision of operators and mechanics
- Controlling exposure of underground miners to DPM and implementation of DPF systems in underground mines was found to be complex multifaceted task that requires concerted effort from several mine departments and considerable support from mine management

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Review

(Red – challenges, Yellow – some minor issue, Green – OK)

DPF Brand	Johnson Matthey	Oberland Mangold	ECS Unikat	ECS Unikat	Arvin Meritor	Engelhard	ECS-3M	ECS-Unikat	DCL Internat.
DPF Model	DPF 201		Combifilter S18	Combifilter S18		DPX 2	Omega	Combifilter S	Titan
Vehicle	#820	#445		#213	#111	#362	#2180		#621
Purchase Price							Not Available		
Pre-installation preparation									
Ease of Installation									
Operational Maintenance	Plug in back up		Daily plug in	Daily plug in	On line burner			Daily plug in	“Take and bake”
Operator acceptance									
Durability									
Soot Removal									
Back-Pressure									
Minimal NO2									

Final Report on Inco DPF Project

- Conard B.R. et al. (2006). Evaluation of Diesel Particulate Filters at Stobie Mine (http://www.deep.org/reports/stobiedpf.pdf).

Summary

- DEEP has shown that reducing emissions of DPM from the tailpipes of diesel vehicles is not a simple task:

a) Use of biodiesel fuel as a complete replacement fuel for normal diesel fuel will not achieve the target levels of DPM in underground air, although reductions of about 50% can be obtained.

b) Improved maintenance practices can assist in reducing DPM emissions and also result in significant cost savings in operating diesel equipment. By itself, however, maintenance is only a partial solution.

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Summary

c) Older diesel engines, particularly heavy duty engines, are the primary generators of DPM. Newer engines, which are electronically controlled, are better, **but most probably the proposed DPM levels could not be met by exclusively replacing dirty for low-emitting engines.**

d) The proportion of light duty vehicles is increasing steadily in most mining operations. A successful implementation of DPM control must be found for both heavy duty and light duty vehicles.

e) Diesel particulate filter (DPF) systems are able to remove DPM with high efficiencies and durability provided that each DPF system is carefully matched to the duty cycle of the engine it is to service.

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Summary

- The main challenge remaining to be overcome in implementing DPF system technology on underground vehicles is to **eliminate the human parameter from their operation.**
- Current DPF systems still require human interaction to ensure proper periodic filter regeneration, without which DPF failure is inevitable. **Human attention to regeneration, however, is unreliable and this makes the DPF system unreliable as well.**
- What is needed is a **DPF system that works in a fashion similar to an automotive catalytic converter, that is, the operator of a vehicle does not need to interact with the system under normal operating conditions**. The system itself performs reliable regeneration without human prompting or knowledge it is occurring.

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CONCLUSIONS AND RECOMMENDATIONS

- Inco tested eight state-of-the-art particulate filter systems on a total of nine vehicles operating in underground production mode.
- Both heavy duty and light duty vehicles were used in the tests.
- Extensive duty cycle monitoring was conducted so that filter system characteristics could be chosen to properly match engine performance.
- In a number of the systems operational time with high filtration efficiencies exceeded 2000 hours.
- Exhaust analyses were carried out routinely on all systems and special high intensity analyses were carried out three times.
- Industrial hygiene measurements were obtained with and without trap installments.
- Post-test analyses were conducted on certain filters.

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What We Learned

1. Both heavy duty and light duty vehicles in underground mining operations can be retrofitted with high efficiency Diesel Particulate Filter Systems (DPFSs) for DPM removal.
2. However, all of the systems tested in the Stobie Project required more close attention than was desired, although there existed a wide variation in the amount of attention needed.
3. Ideally, a DPFS would be invisible to a vehicle's operator and almost invisible to the maintenance department. That is, people would go about their jobs in a conventional manner and would not need to pay attention to the filter or its regeneration.
4. This was clearly NOT the case for any of the filters being tested in the Stobie Project and this remains a critical issue in any successful program for retrofitting or for installing PFSs as OEMs.

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Path Forward/ What Is Needed

- The main challenge remaining to be resolved in implementing DPF system technology is to eliminate the human parameter from their operation
- Therefore we need to engage in exploring/test-advanced technology, which will yield mine worthy filters that can regenerate at low exhaust temperatures without the production of excessive NO2. The lower the exhaust temperature for filter regeneration, the more widely applicable and tolerant of unpredictable low duty cycles the filter system becomes.
- Inco has undertaken steps to close this gap…..(approval to test/evaluate advanced systems)

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Acknowledgements

- Diesel Emissions Evaluation Program (DEEP) Consortium and for financial support and DEEP Technical Committee for technical support and advice
- NIOSH, CANMET, VERT/Switzerland, Kali und Salz Mines/Germany, LKAB Mines, Sweden
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- Manufacturers of DPF systems for in-kind contributions and technical support
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- Noranda Brunswick Mining and Smelting

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