Evaluation and Experience with Diesel Particulate Filter Systems at Inco

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DPM Regulations

- The current Ontario RCD standard is 1.5 mg/m^3
- Typical range of RCD at Inco 0.1- 0.5 mg/m^3
- MSHA interim M/NM standard: 0.308 mg/m^3 of elemental carbon (EC) to be reduced to 0.16 mg/m^3 of total carbon in May 2006, subject to a proposed revision of the rule

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Challenges

- It would not be economical to achieve the substantial DPM reductions by increasing the ventilation rate
- DPM needs to be controlled at the source
- The effective DPM reduction strategy appears to be Diesel Particulate Filter system - DPF coupled with
  - good ventilation practices
  - adherence to well planned maintenance program
  - use of low emission engine technology
  - improved fuel quality

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Objective

- Long-term 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 DEEP 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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Methodology – 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 deg. C – not available under the typical mine vehicle operating conditions
- The proper selection of the filter 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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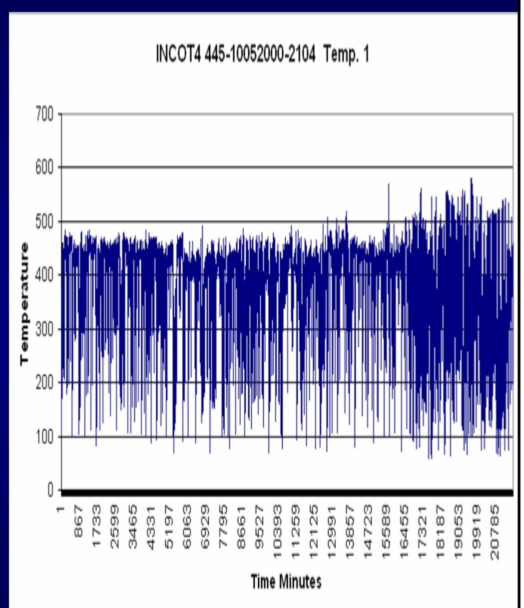
The Issue

- Here is the 6-month exhaust temperature trend for DDEC 60 Engine
- The average temperature is 380 deg. C therefore filter “auto-regeneration” will not take place



Solution

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

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Data evaluation for DPF selection: Example - DDEC 60

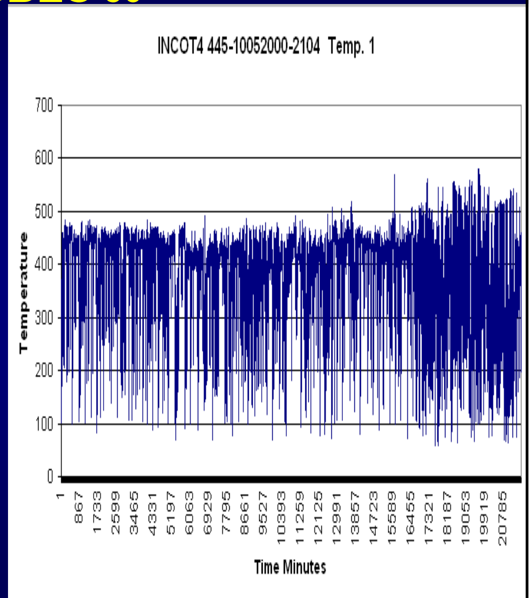
The overall "picture" indicates a few interesting elements:

The temperature trace is not uniform showing wide variation due to the nature of vehicle activity

The full power peaks can be so short that the filter media does not attain the temperature measured

Amount of time spent at temperatures necessary for DPF regeneration is hard to determine

(Analysis needs to include the durations that the temperatures stay above a certain value)



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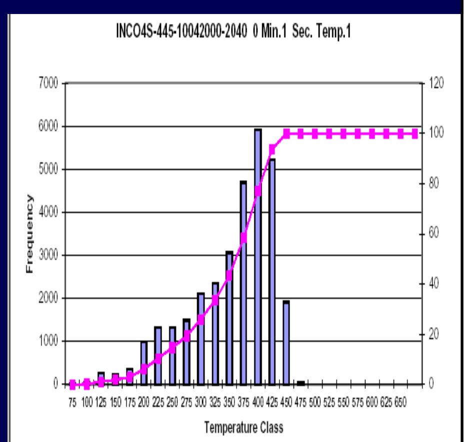
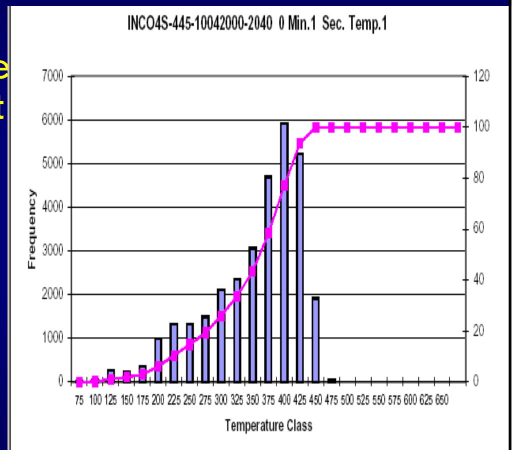
DPFs Selection Methodology – Data Logging: Process and Results - DDEC 60 Engine

- *The next step of the evaluation was the calculation of the temperature frequency distributions*
- (Frequency means the number of observations during the test period per temperature class - the columns in steps of 25 deg C) summed up by the dotted line Since the time per observation in this case is just one second – the number of observations is equal to the cumulative residence time in this class in seconds.)



DPFs Selection Methodology – Data Logging: Process and Results - DDEC 60 Engine

- From this histogram one gets the impression that a quite extended residence time can be expected above 400 deg. C which would lead to the conclusion that simple regeneration methods like catalytic coating can be applied



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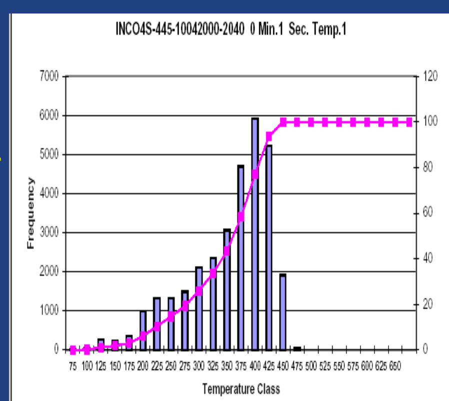
DPFs Selection Methodology – Data Logging: Process and Results - DDEC 60 Engine

- This histogram does not reflect however the thermal history at all. The largest column could be a single event, an episode or it could represent 4000 spike events of 1 second each, preceded and followed be idle periods at very low temperature levels.



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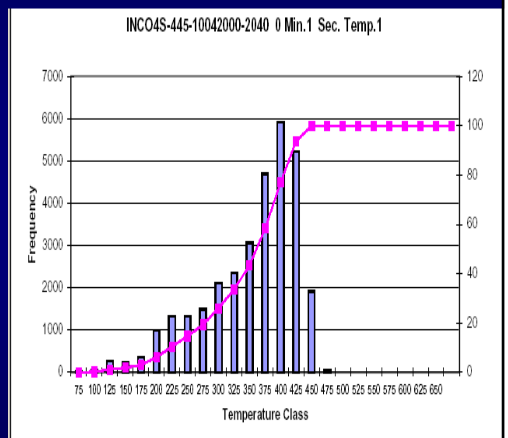
DPFs Selection Methodology – Data Logging: Process and Results - DDEC 60 Engine

- In the first case the time would be sufficient to heat the large mass of the filter to a temperature level sufficient for a smooth regeneration – in the second case the filter would remain cold in spite of the high temperature peaks and no regeneration would happen



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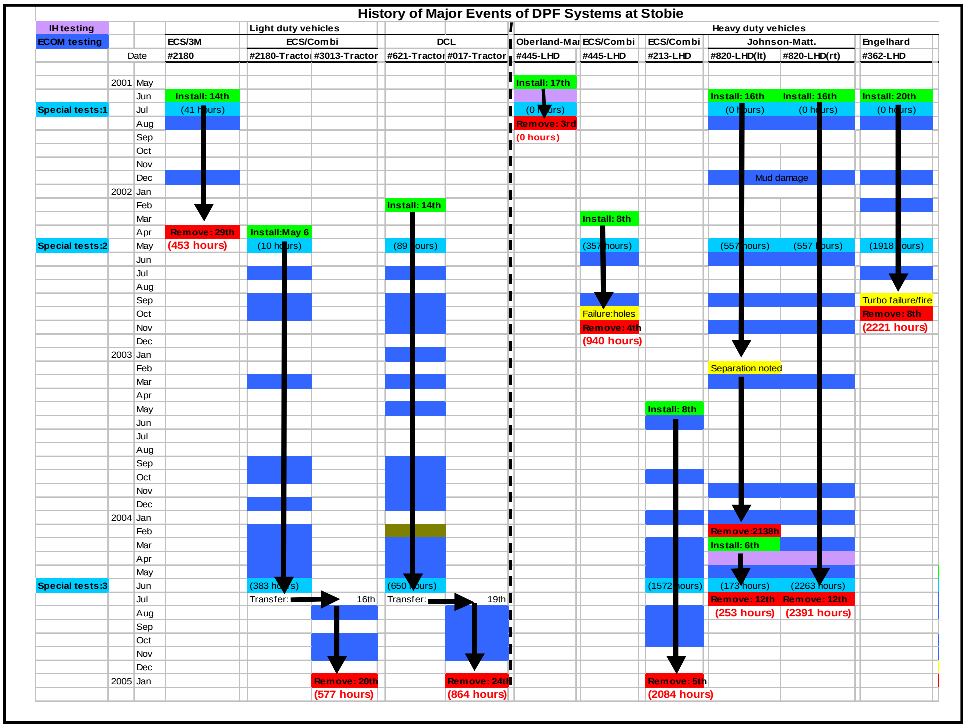
Tested Diesel Particulate Filter Systems

Nine state-of-the-art diesel particulate filter (DPF) systems were tested

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	July 2001	May 2002	June 2004	June 2004	July 2001	July 2001	May 2002	May 2002



Johnson Matthey DPF 201 DPF System on LHD#820

- Consisted of two silicon carbide monolith filters mounted vertically on each side of Deutz V-12 engine
- The system was regenerated with fuel borne catalyst and on-board electrical heaters
- The system accumulated 2138/2391 hours in operation

JMC computerized fuel additive dosing & electric regeneration system

Automatic fuel additive dosing system. Fuel additive is added only during regular maintenance

A build–up of soot will result in the lights on the monitor gradually signalling from left to right. This monitor gauge is installed on the dash allowing the operator to view the build up of particulate in the filter unit

Oberland Mangold DPF System on LHD #445

- **The system used knitted glass fiber cartridges**
- **It was regenerated with cerium/platinum based fuel borne catalyst**

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ECS/Unikat Combifilter S18 DPF Systems on LHD #445 and LHD #213

- **They consisted of two parallel silicon carbide monolith filters vertically mounted and a regeneration station**
- ***The filter was regenerated using heat provided by on-board heaters and compressor***
- **The system accumulated 2084 hours in operation**

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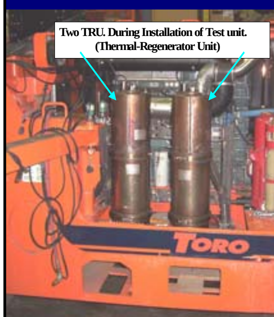
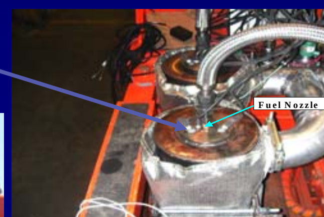
Arvin Meritor Diesel Fuel Burner (Prototype) DPF System with Pt DOC on LHD #111

- Two vertically mounted Cordierite RC monoliths
- The filter was regenerated in predetermined intervals using supplemental heat provided by on-board diesel fuel burner

Ignition Electrodes





ECU

Flameholder & DPF

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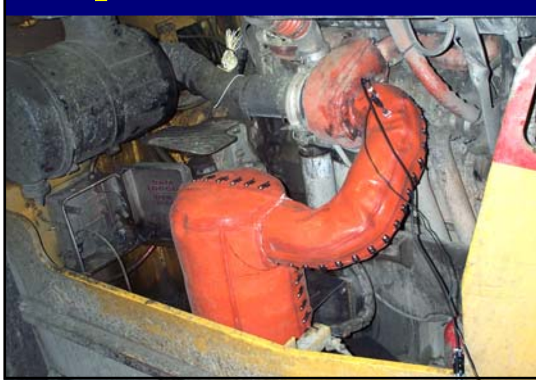
Engelhard DPX2 DPF System on LHD #362

- Vertically mounted Cordierite monoliths
- The filter was regenerated with proprietary platinum based catalyst
- The system accumulated 2221 hours of operation



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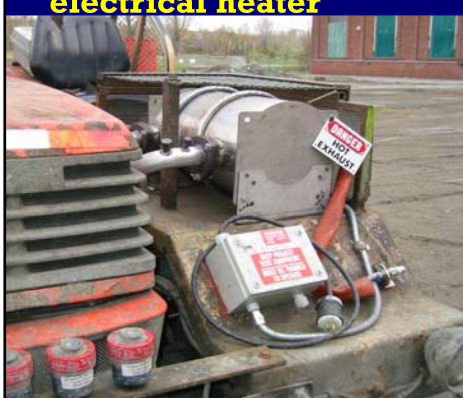
ECS 3M Omega DPF System on Tractor #2180

- 3M Nextel ceramic fiber cartridges
- The filter was regenerated actively with on-board electrical heaters
- DPF accumulated 453 hours of operation

ECS/Unikat Combifilter on Tractor #2180

- Horizontally mounted SiC monolith and a regeneration station
- The filter was regenerated actively with on-board electrical heater



The system accumulated 577 hours in operation

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DCL International Titan DPF on Tractor #621

- Horizontally mounted SiC monolith
- The filter was regenerated with off-board electrical heater

DPF and quick release clamps

Regeneration Cooker

The system accumulated 864 hours in operation

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Tailpipe Emissions Measurements Relative Elemental Carbon Concentrations

- The effects of the systems on concentrations of elemental carbon particles were determined from the measurements performed upstream and downstream of each filter by a Photoelectric Aerosol Sensor, the PAS 2000 (Matter Engineering)
  - Exhaust was diluted using Model MD19-2E spinning disk

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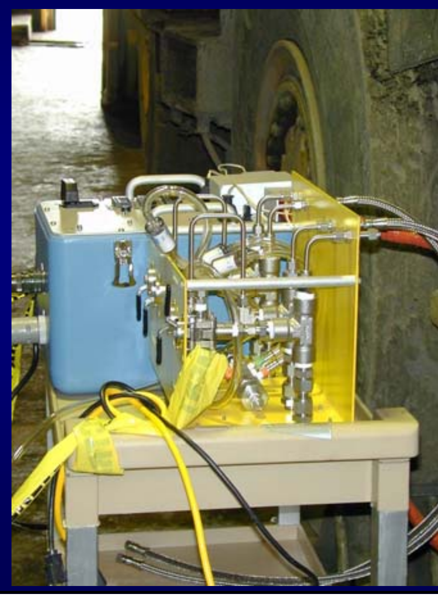
Tailpipe Emissions Measurements
Elemental Carbon Concentrations

- Samples collected from the exhaust system upstream and downstream of DPF systems
- Samples analyzed by NIOSH PRL using NIOSH Analytical Method 5040



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Tailpipe Emissions Measurements
Size Distribution and Number Concentration

- During the tests conducted in May 2002 and June 2004 the size distribution and number of particles with geometric mean between 10 and 392 nm were measured upstream and downstream of DPF systems using a Scanning Mobility Particle Sizer (SMPS) Model 3926 from TSI Inc.
  - Exhaust was diluted using Model MD19-2E spinning disk dilution system (Matter Engineering)

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Tailpipe Emissions Measurements
Opacity

- The exhaust opacities were measured upstream and downstream of the filters using an AVL (Gratz Austria) DiSmoke 4000 instrument

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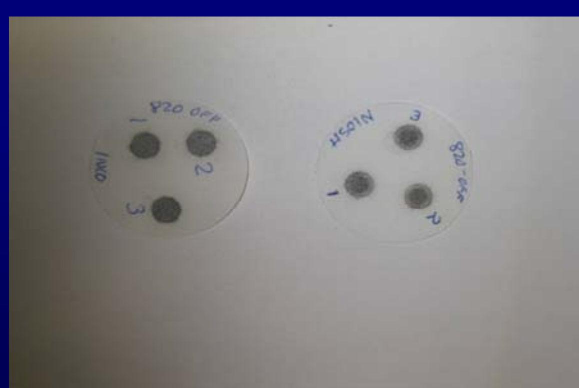
Tailpipe Emissions Measurements
Smoke Number

- The filter samples for Bacharach smoke number analysis were collected using ECOM America, Ltd. Models KL and AC Plus portable emissions analyzers



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Tailpipe Emissions Measurements
CO, NO, NO_2, and O_2 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 analyzers

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Results

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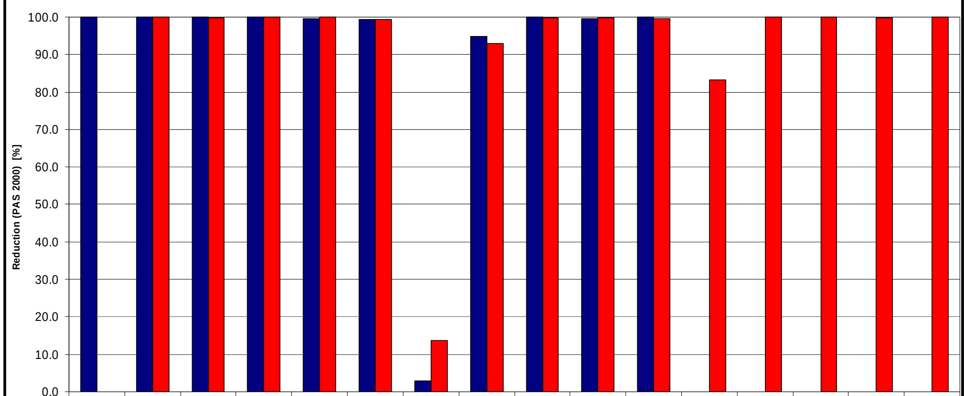
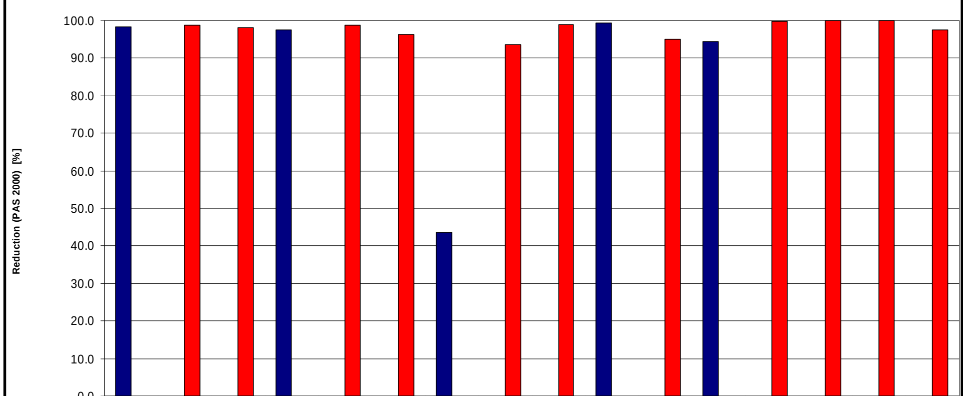
Efficiency of DPF Systems - PAS 2000 Measurements



	Jul-01 JM SiC Right on #820	May-02 JM SiC Right on #820	Jun-04 JM Cord. Right on #820	Jul-01 JM SiC Left on #820	May-02 JM SiC Left on #820	Jun-04 JM SiC Left on #820	Jul-01 OM on #445	May-02 ECS SiC1 on #445	Jun-04 ECS SiC2 on #213	Jul-01 Eng. on #362	May-02 Eng. on #362	Jul-01 ECS 3M on #2180	May-02 ECS SiC on #2180	Jun-04 ECS SiC on #2180	May-02 DCL SiC on #621	Jun-04 DCL SiC on #621
TCS	99.9	100.0	99.9	100.0	99.5	99.4	2.8	94.8	99.9	99.6	100.0					
High Idle		99.9	99.8	99.9	99.9	99.3	13.6	93.0	99.8	99.7	99.6	83.3	100.0	99.9	99.8	99.9

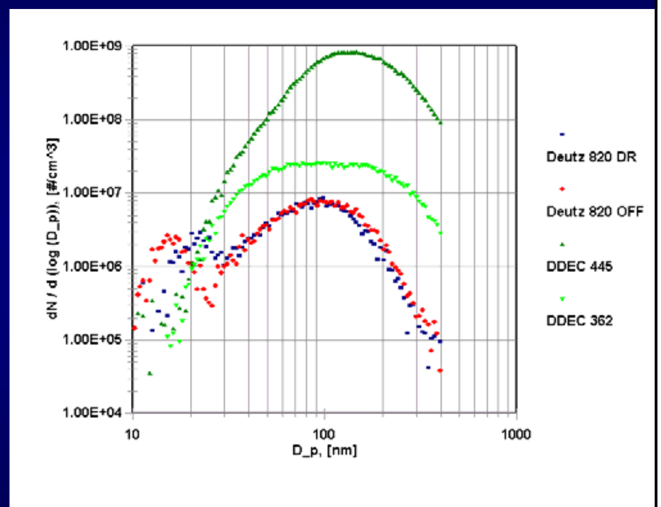
Efficiency of DPF Systems – NIOSH 5040 and SMPS



	Jul-01 JM SiC Right on #820	May-02 JM SiC Right on #820	Jun-04 JM Cord. Right on #820	Jul-01 JM SiC Left on #820	May-02 JM SiC Left on #820	Jun-04 JM SiC Left on #820	Jul-01 OM on #445	May-02 ECS SiC1 on #445	Jun-04 ECS SiC2 on #213	Jul-01 Eng. on #362	May-02 Eng. on #362	Jul-01 ECS 3M on #2180	May-02 ECS SiC on #2180	Jun-04 ECS SiC on #2180	May-02 DCL SiC on #621	Jun-04 DCL SiC on #621
NIOSH 5040 TCS	98.3			97.6			43.6			99.4		94.4				
SMPS HI		98.8	98.1		98.7	96.3		93.6	98.9		95.1		99.7	99.9	99.9	97.5

Size Distribution of Aerosols

- Engine out concentrations much higher for #445 (325 hp) than those for #362 (285 hp)



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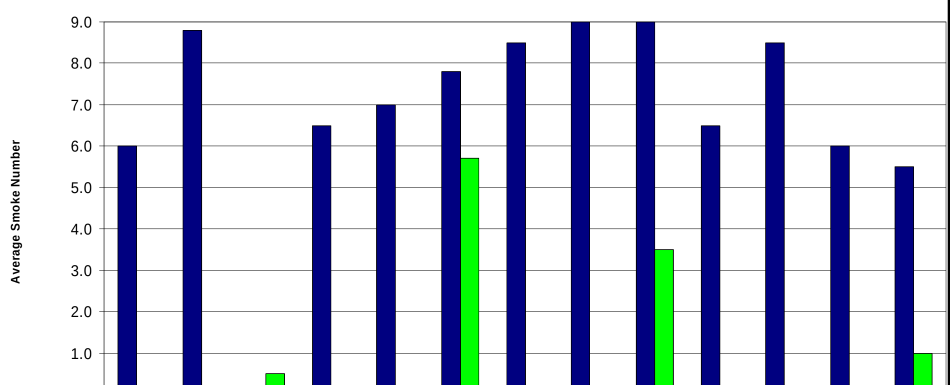
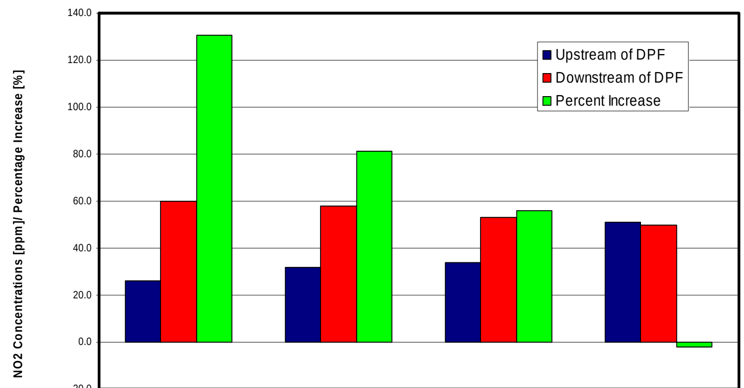
Efficiency of DPF Systems – Smoke Number Measurements



	Jul-01 JM SiC Right on #820	May-02 JM SiC Right on #820	Jun-04 JM Cord. Right on #820	Jul-01 JM SiC Left on #820	May-02 JM SiC Left on #820	May-02 ECS SiC 1 on #445	Jun-04 ECS SiC 2 #213	May-02 Engelhard on #362	Jul-01 ECS 3M on #2180	May-02 ECS SiC on #2180	Jun-04 ECS SiC on #2180	May-02 DCL SiC on #621	Jun-04 DCL SiC on #621
Upstream	6.0	8.8		6.5	7.0	7.8	8.5	9.0	9.0	6.5	8.5	6.0	5.5
Downstream	0.0	0.0	0.5	0.0	0.0	5.7	0.0	0.0	3.5	0.0	0.0	0.0	1.0
	Torque Converter Stall								High Idle				

Effects of DPF Systems on NO_2 Emissions

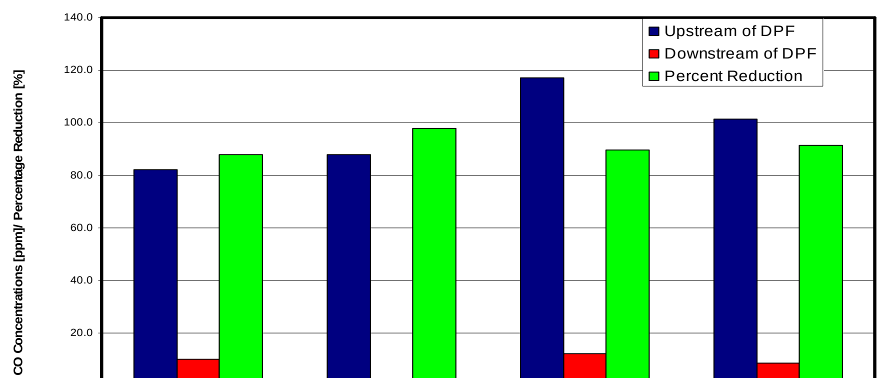
- Pt-catalyzed Engelhard DPF system on #362 promoted NO to NO_2 conversion
- The other tested filters generally reduced NO_2 emissions



	TCS (2001)	HI (2001)	TCS (2002)	HI (2002)
Upstream of DPF	26.0	32.0	34.0	51.0
Downstream of DPF	60.0	58.0	53.0	50.0
Percent Increase	130.8	81.3	55.9	-2.0

Effects of DPF Systems on CO emissions

- Pt-catalyzed Engelhard DPF system on #362 reduced CO emissions
- The other tested filters did not substantially affected CO emissions except during regeneration process



	TCS (2001)	HI (2001)	TCS (2002)	HI (2002)
Upstream of DPF	82.0	88.0	117.0	101.3
Downstream of DPF	10.0	2.0	12.3	8.7
Percent Reduction	87.8	97.7	89.5	91.4

General Observations
Johnson Matthey DPF201 DPF System

- The system was proven to be good solution for the non-production LHD #820 that was operated over the broad range of duty cycle including those causing relatively high and relatively low engine loads
- Using RHODIA Ecolys Cerium Oxide fuel additive eliminated the need for performing frequent active regeneration sessions particularly during periods of high engine load
- The electrical heaters provided needed alternative regeneration mode
- This is a robust system
- The filters had to be cleaned four times from ash during 2138 hours in operation.

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General Observations
ECS/Unikat Combifilter DPF System

- These active systems showed good results as long as operators were attentive to the need to actively regenerate the system at the end of each shift
- The challenges of this DPF concept were found to be its relative complexity, the 60 minute regeneration time and the need for operator discipline
- The first of these systems failed due to human error
- The second system received much more attention and it was operated within the recommended engine backpressure limit most of the time
- Robust system and the secondary emissions of NO_2 were not issue
- The second system had to be cleaned several times from ash

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General Observations
Engelhard DPX2 DPF System

- Passive system with wash coated platinum filter can be an excellent low-complexity and cost effective solution for production LHD
- Observed two fold increase in NO_2 emissions presented a problem
- The filter survived an accident when mud penetrated into the cells from below (the discharge side) - proof of robustness
- Backpressure was rather high exceeding occasionally 300 mbar for extended periods of time
- Filter had to be cleaned from ash 3 times over 2200-hour operating period

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General Observations
ECS/Unikat and DCL Titan Active Regeneration DPF Systems

- The DPF systems requiring electrical regeneration were shown to be suitable for the light-duty vehicles.
- DCL Titan DPF unit is relatively small and easily interchangeable with a regenerated unit.
- The ECS Unikat 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

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Path Foreword…..

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Acknowledgements

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The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the Inco Limited or of the National Institute of Occupational Safety and Health.

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Questions???

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