Long-Term Evaluation of Diesel Particulate Filter Systems at Inco

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MDEC 2004

Introduction

- **Project background – a quick review**
- **Project status – experience to date**
- **Conclusions to date**
- **Path forward**

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Project Background – Quick Review

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•Government Regulation

•The current Ontario RCD standard is 1.5 mg/m3

•Typical range of RCD at Inco 0.1- 0.5 mg/m^3

•US Interim MSHA M/NM standard, measured as total carbon (TC), is 0.4 mg/m^3 to be reduced to 0.16 mg/m^3 in 5 years

•There was, over the last 6 years, "pressure" from the ACGIH on the Notice of Intended Change list. The proposed DPM TLV went from 0.15 to 0.02 mg/m^3, measured as elemental carbon (EC)

•In 2003, ACGIH removed DPM from the list, indicating further consultation was required before a TLV could be recommended.

•The concentration of RCD > TC > EC, thus factors in determining compliance are the material measured and the method of measurement.

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Health Debate and Pronouncement on Diesel Exhaust

- 1988 NIOSH: Potential Occupational Carcinogen
- 1999 IARC : Probably Carcinogenic to Humans
- 1995 HEI : No Quantitative Risk Estimate is Possible. Questions Validity of Rat to Human
- 1995ACGIH : Suspected Human Carcinogen
- 1996 WHO : No Human Data Suitable for Estimating Unit Risk
- 1998ACGIH : Suspected Human Carcinogen

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The Challenge

- It would not be economically or technically feasible to achieve the forecasted regulation *(reduction of DPM by one order of magnitude 1.5 to 0.16 mg/m3)* by increasing the ventilation rate
- The effective, DPM reduction strategy (at the source of "soot" generation) appears to be Diesel Particulate Filter system - DPF coupled with:

  good ventilation practices

  committed adherence to well planned maintenance program

  use of low emission engine technology

  improved fuel quality

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DPF Selection Point of Reference

- Modern diesel – exhaust DPF technology provides filtration efficiency above 95 % with respect to solid carbonaceous particles
- Filtration of sub-micron particles is no longer a problem for the industry
- The bigger 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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Data - Collection Methodology for Trap Selection

- One of the targets of this study was to collect sufficient information on operating load cycles on five selected units, and to find out and demonstrate
- A method which could be used as a standard procedure for trap selection in other mines

To this end data loggers were installed to monitor backpressure and temperature trend on the selected vehicles over a period of several months

Mean average exhaust temperature of the selected vehicles over 6 months period

Vehicle	Deutz ST8B	Kubota	DDEC 60	Kubota	DDEC 60
Tem deg C 1 sec measuring sequence	312.9	158.6	340.9	No data	366.2
Temp deg C 1 min measuring sequence	329.4	192.3	382.5	203.2	369.6
DPF system	On-board elec & ad Active **JMC**	On–board electric Active **DCL**	Catalytic coating Passive **Engelhar**	Of-board electric Active **ECS/Com**	On-board electric Active **ECS/Com**

Conclusions:

The soot combustion temperature of 600 deg C required to auto regenerate DPFs is not available on the selected vehicles

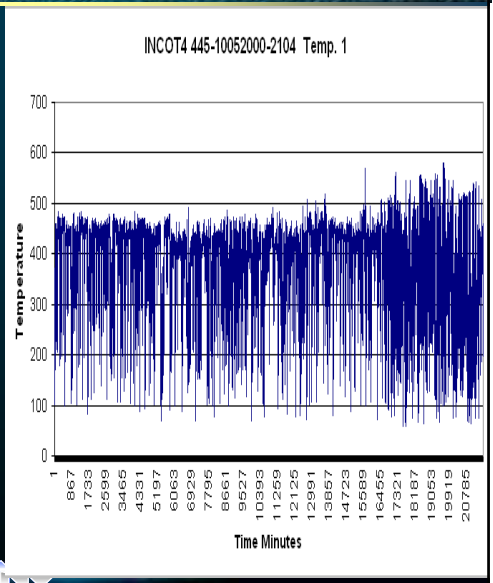
DPF Selection Challenges

The Issue:

- **The following is a temperature trend of 6 months of data logging of exhaust temperature 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 and/or**
- **use of fuel additives – is required to lower the temperature needed to ignite the collected soot, or**
- **off shift regeneration/fuel burner are necessary**



Data evaluation for DPF selection: Example - DDEC 60

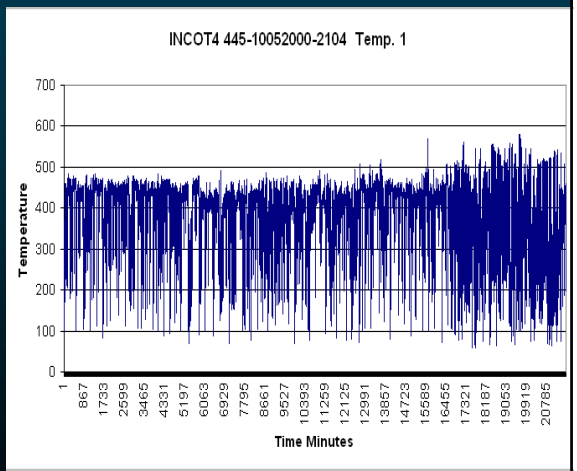
The overall "picture" Indicates a few interesting elements:

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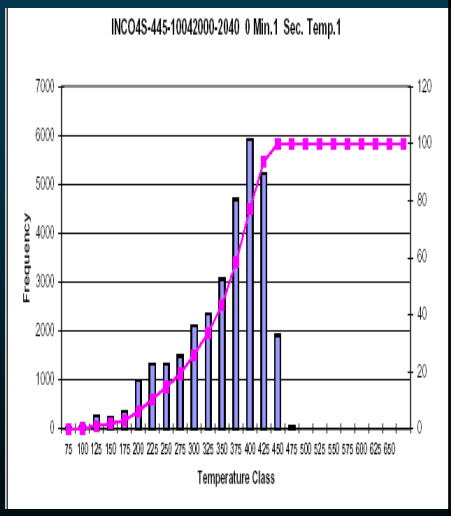
DPFs Selection Methodology – Data Logging: Process and Results - DDEC 60 Engine

- 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.)
- 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
- 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.
- 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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DPFs Used in the Inco Project

Vehicle	Supplier	EC redn	Hrs	Regeneration
Deutz L.H.D.	JMC – Germany	99.9%	2138	on-board in-use +add
DDEC L.H.D.	ECS/Unikat /Comb	92 - 95%	873	on-board plug-in
			1,935	
DDEC L.H.D.	Engelhard	99.9%	2,221	passive catalyzed
Kubota Tractor	ECS/3M Omega	91%	430	plug-in on-board
	ECS/ Combifilter	99.9%	463	on-board plug-in
Kubota Tractor	DCL Titan	99.9%	732	off-board electrical
DDEC LHD	ArvinMeritor	99.0 %	117	fuel burner system

NOTES:

a) Silicon carbide filters are used in the ECS/Unikat & DCL Titan systems (cordierite filter in Engelhard)

b) Elemental Carbon reductions (EC redn) – NIOSH 5040 are similar results to the PAS 2000 EC surface area reductions

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INCO DPF Specifications

These are adapted from the VERT specifications by Team of Inco/DEEP members, Drs Schnakenberg and Bugarski of NIOSH, and Andreas Mayer, Inco/DEEP Primary Technical Consultant

- **Efficiency - 95% removal, both for particulate numbers and elemental carbon mass (NIOSH 5040)**
- **Regeneration – must provide for adequate regeneration for a vehicle running 50% of the time in excess of 350 Celsius**
- **Backpressure – must meet vehicle/engine warranty 100 mbar**
  - **New trap** **50 mbar**
  - **Regenerated trap** **60 mbar**

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INCO DPF Specifications (cont'd)

- **Secondary emissions** (catalyzed traps are the concern)
  - **NO2** – preferably no increase of NO2, but in the limit must not exceed the equivalent of 0.8 ppm at a ventilation rate of 100 CFM/HP
  - **Copper** – is not permitted in any catalyst formulation (fuel or filter) due to the potential for increases in dioxin**
- **Robustness –** harsh environment (water, mud, cold & heat..) and shock & impact design considerations.
- **Risk** – CSA & CEC approved, fire suppression systems
- **Useful life** - 3 years or 9000 hours

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Project Status

…experience to date…

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Heavy Duty Vehicles

- #362 L.H.D. ST8B Detroit Diesel – Series 60, 11.1litre 285 H.P.
- # 820 L.H.D. 12FLW Deutz 277H.P.ST8B
- #445 L.H.D. ST8B Detroit Diesel – Series 60, 11.1litre 325 H.P.
- # 213 L.H.D. ST8 B Detroit Diesel – Series 60 11.1 litre 285 H.P
- #111 L.H.D. Toro1400, Detroit Diesel- Series 60, 11.1litre 285 H.P.

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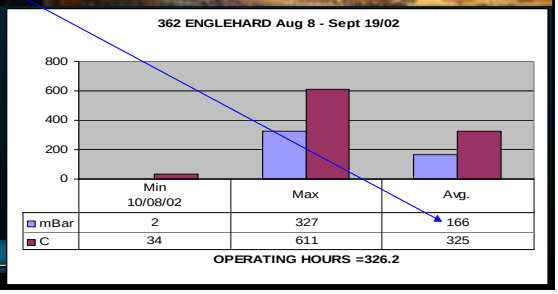
DDEC L.H.D.tram
Engelhard Passive Catalyzed System

- The DPF accumulated 2221 hours on the system with no operational difficulties **
- The average back-pressure, and temp. for two month (Aug - Sept/02) period amounts to 166 mbar, and 326 deg. C
- The maximum back-pressure, and temperature for the same period reaches 327 mbar, and 611 deg. C
- ** A fire incident occurred and the trap system was de-installed



DDEC L.H.D.tram
Engelhard Passive Catalyzed System

Concluding Remarks

- Passive system with wash coated platinum filter can be an excellent low-complexity and cost effective solution for production L.H.D.
- The filter survived an accident when mud penetrated into the cells from below (the discharge side) - proof of robustness
- Backpressure remains very high reaching at times above 300 mbar for extended periods
- Measurable increase in NO2 from two to five times in tailpipe
- Filter had to be cleaned from ash at least 3 times. This is too often over 2200-hour operating period

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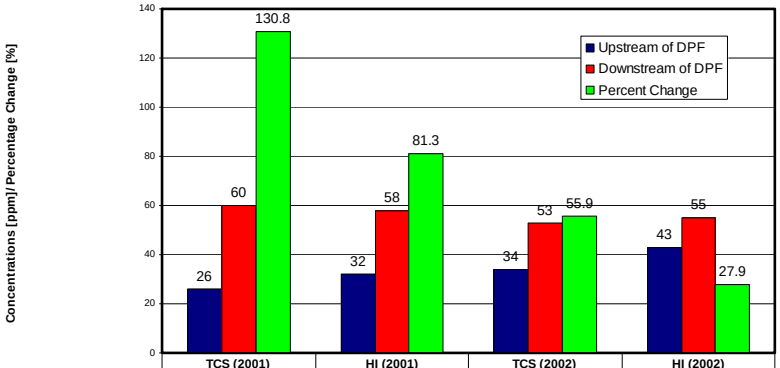
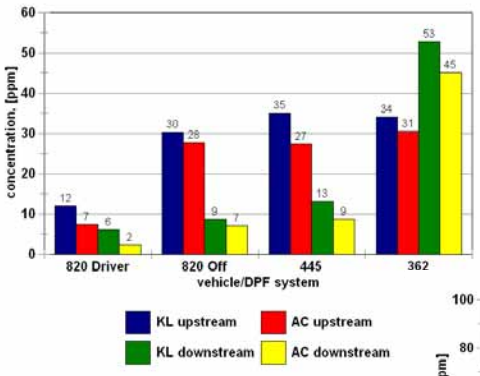
Effects of Engelhard DPF system on Concentration of NO_2 in Exhaust of LHD #362

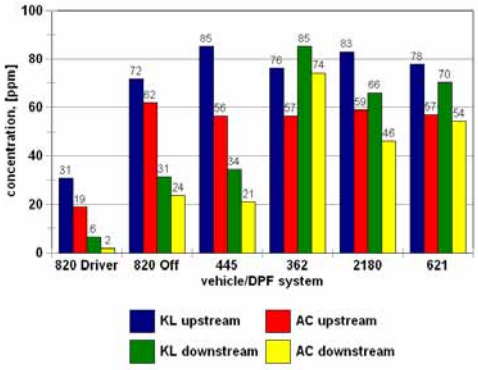


	TCS (2001)	HI (2001)	TCS (2002)	HI (2002)
Upstream of DPF	26	32	34	43
Downstream of DPF	60	58	53	55
Percent Change	130.8	81.3	55.9	27.9

Gaseous emissions

-Nitrogen dioxide NO2





- The Engelhard filter increased NO_2 emissions from the #362 for app. 48 to 55% at TCS conditions.
- The concentrations of NO_2 downstream of the other filters generally were lower than those upstream of the filters.

Deutz ST8 L.H.D.

JMC On Board Fuel Additive Dosing & Electric Regeneration System

- Total accumulated hours on trap is over 2138
- Since Deutz engine has a dual exhaust system, two sets of filters are installed
- These heater elements allow for onboard regeneration

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Deutz ST8 L.H.D.

JMC Electric On-Board Fuel Additive & Electric Regeneration System

- The trap efficiency test conducted by NIOSH, June, 2002 shows 99.9% EC reduction

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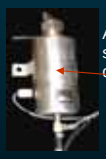
Deutz ST 8 L.H.D.

JMC On Board Fuel Additive & Electric Regeneration System

- **Concluding Remarks**
- The L.H.D. on which this trap is installed is not a production unit. The duty cycle can vary a lot from high load to relatively light loads over extended periods
- The selected system of passive (by fuel additive RHODIA Ecolys Cerium Oxide) and active back-up provides the chance that plug-in active regeneration might not be necessary for a 'long time'
- Possibly , not on a regular shift to shift basis, since the additive can cope with short light load period quite well
- This is a robust system
- Filter had to be cleaned four times from ash.

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

Deutz ST8 L.H.D.

JMC Electric On-Board Fuel Additive & Electric Regeneration System

•In March of 2004 the Silicone Carbide Filters were shown to have some separation from the container - the decision was made to install the spare set of Cordierite Filters

DDEC L.H.D.
ECS/Unikat Dual S18 Combifilter

The installation of the Combifilter were completed in Mar/02

The system consists of **dual filter assembly** vertically mounted & on board electrical regeneration

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DDEC L.H.D.
ECS/Unikat Dual S18 Combifilter

- The Swedish made Regeneration Control Panel, etc **was not CSA approved**

Subsequently the Control Panel was, upgraded, CSA approved and re-installed 06May02

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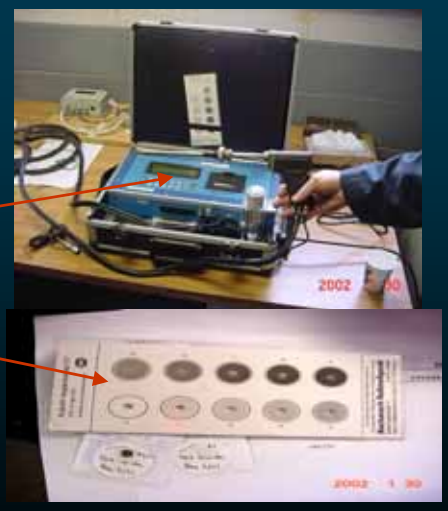
DDEC Scoop

ECS/Unikat Dual S18 Combifilter

- The dual Combifilter had accumulated **873 hours**
- During a regular P.M. while carrying out ECOM test it was determined that the filter had failed as the "smoke number" up stream and down stream were equal.
- Failure was due to operating **the unit without regeneration**



•The spots on the filter paper are compared with the smoke chart in the upper half of the picture

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DDEC L.H.D.

ECS/Unikat Dual Combifilter

- The Combifilter system was de installed from the unit October, 2002
- Re-installation of the Combifilter with a new set of filters was completed in May, 2003
- **The DPF system is now protected through a back pressure sensor and an interface with the DDEC electronic control module. If the backpressure exceeds set values (150mbar) the engine is ramped down to a low idle.**
- The system has accumulated 1935 hours and has had to be cleaned five times

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DDEC L.H.D.
ECS/Unikat Dual Combifilter

Concluding Remarks

- Concept - An active non-catalyzed filter large enough to collect soot over 2 working shifts, followed by on board electric regeneration
- Robust system and no secondary emissions
- The single biggest challenge was the operators acceptance – It was 'difficult', not a normal task for operators to carry out the requirement of routine regeneration (45 – 60 min) at the end of each shift – " to plug it in " – This is no longer the case, through education and training it has now become a routine task

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ArvinMeritor ActiveClean™ Thermal Regenerator
DDEC LHD

- The system uses diesel fuel to burn off soot
- The system is electronically controlled and does not require operator's involvement
- Diesel engine will continue to operate during regeneration
- The regeneration process typically lasts 4 – 8 minutes

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ArvinMeritor Pre – Installation and PHA, April 2004

- In partnership with Sandvik and at their Sudbury site a new R-1400 LHD was used to pre-install, test and carry out PHA on the system
- Process Hazard Analysis was conducted by:
  - Inco J.S.H.C
  - Ministry of Labour
  - Inco Stobie Worker Rep
  - Inco Operation & Ventilation
  - Hatch Associated
  - Sandvik
  - ArvinMeritor

Bob Coupal INCO DEEP, Jon Baurley and Dr. Bruce Conard discuss the challenges of the installation of the unit

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ArvinMeritor Pre – Installation and PHA, April 2004

Two TRU. During Installation of Test unit. (Thermal-Regenerator Unit)

Greg Nault and Rick Mayotte of Inco review the pre-installation

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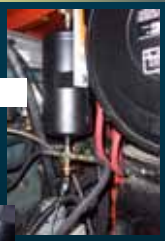
ArvinMeritor ActiveClean™ Thermal Regenerator
DDEC LHD

Required support component

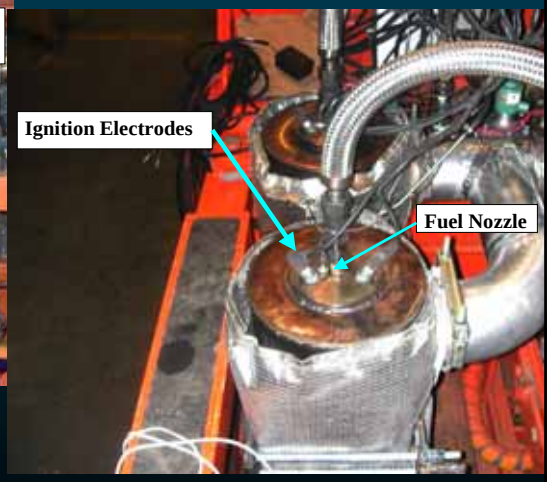
•Air tank top supply air for combustion and atomization

•Air compressor to supply air for combustion and atomization at the correct flow rate

•Air dryer to prevent condensation in the control system



ArvinMeritor ActiveClean™ Thermal Regenerator
DDEC LHD



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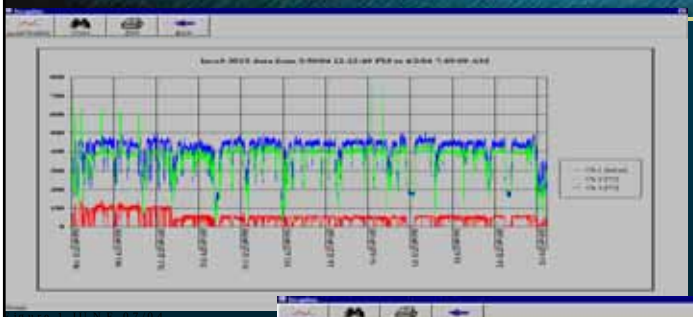
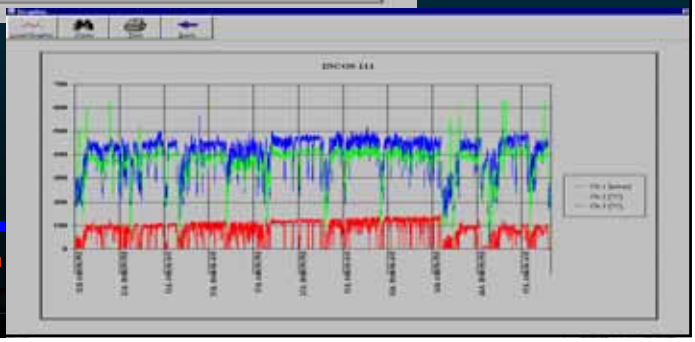
ArvinMeritor Operation – Backpressure and Temperature Data



June 7, 2004
111 Toro LHD
12 hours operating data
•Averages:
Temp. 1 = 361 deg C
Temp. 2 = 394
Backpressure 48 mbar

Aug. 19, 2004
111 Toro LHD
64 hours operating data
•Averages:
Temp. 1 = 365 deg C
Temp. 2 = 400 deg C
Backpressure 82 mbar



ArvinMeritor ActiveClean™ Thermal Regenerator
DDEC LHD

Concluding remarks

•**Concluding remarks**

- –Active regeneration system for diesel particulate filters
- –System automatically activates regeneration based on time
- –Does not require intervention from the operator

•**Status:**

- –117 hours have been logged since installation in May
- –ArvinMeritor technicians have been onsite in July and September for system service
- –In October, INCO mechanics will be trained at ArvinMeritor technical center in Columbus, Indiana to increase system knowledge
- –A second generation ACU will be installed in October to upgrade control software
- –Testing will continue until the end of December

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Light Duty Vehicles

2 Kubota Tractors

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Kubota Tractor

ECS/Unikat/Combifilter On Board Electric Regeneration

- Combifilter installed in May 10/02 upon arrival from Sweden
- This tractor is a personnel transportation vehicle with low utilization
- Combifilter requires regeneration station

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Kubota Tractor

ECS/Unikat/Combifilter On Board Electric Regeneration

- Total hours on the DPF is 463
- Test conducted by NIOSH in June, 2002 found the DPF to be 99.9 % efficient EC
- The unit is to be regenerated at the end of the shift

Kubota Tractor

ECS/Unikat/Combifilter On Board Electric Regeneration

- The model S5 is regenerated over 50 - 60 minutes when the vehicle is not in operation
- The DPF is functioning well.

Kubota Tractor

DCL Titan Off-Board Electric Regeneration

- The system was installed Feb/02 and comprises two interchangeable filters
- The "loaded" filters with soot are removed from the vehicle and placed on the off - board regeneration station
- The regeneration station provides automatic control of combustion

•Quick Release Clamps

•Regeneration "Cooker"

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Kubota Tractor

DCL Titan Off-Board Electric Regeneration

- The system has accumulated 732 hours
- Test conducted by NIOSH, May/02 indicates 99.9 % filter efficiency
- The challenge may be associated with daily replacement of filter
- The average engine back-pressure since installation is 58 mbar

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Preliminary Review of Operating Backpressure and Temperature

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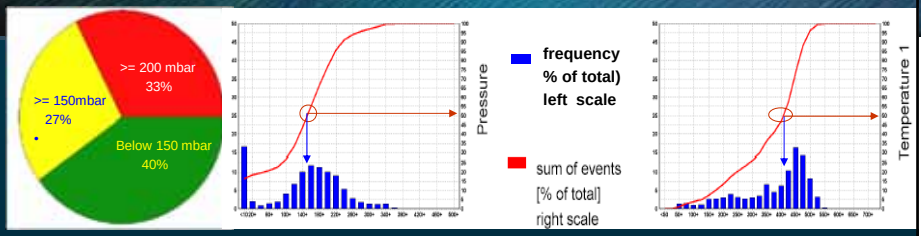
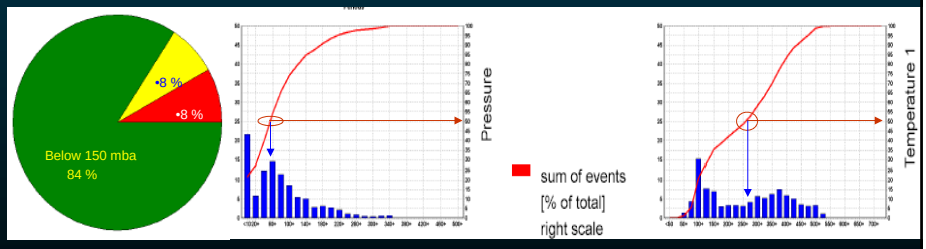
"Snap-shot" of Statistical Analysis – Temperature and Backpressure of DDED and Deutz LHDs Equipped with Engelhard and JMC DPF System



Engelhard DPF w/DDEC–1800 hrs

Cumulative curve shows that 50 % of the time pressure was above 160 mbar and temperature above 400 deg C



JMC w/DEUTZ – 750 hours

Cumulative curve shows that 50 % of the time pressure was above 60 mbar and temperature above 250 deg C

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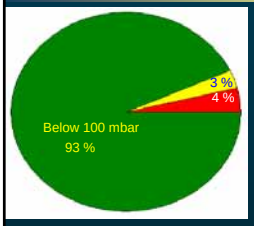
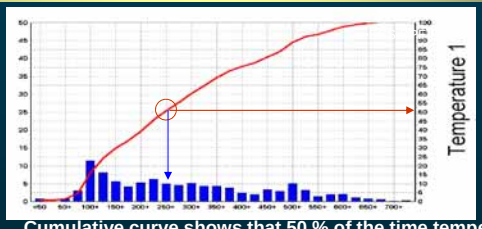
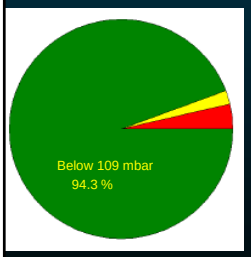
"Snap-shot" of Statistical Analysis – Temperature and Backpressure of Kubota, Light Duty Vehicles Equipped with ECS/Combifilter and DCL DPF System



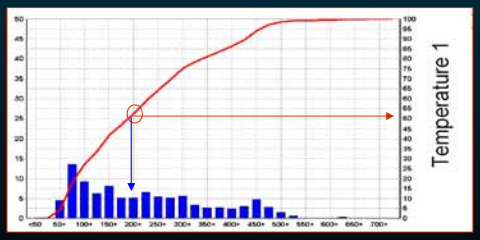
•ECS/Combifilter w/Kubota



Cumulative curve shows that 50 % of the time temperature was above 250 deg C – The most frequent temperature was 100 deg C



•DCL DPF w/Kubota



Cumulative curve shows that 50 % of the time temperature was above 200 deg C

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Exhaust Over Heating…

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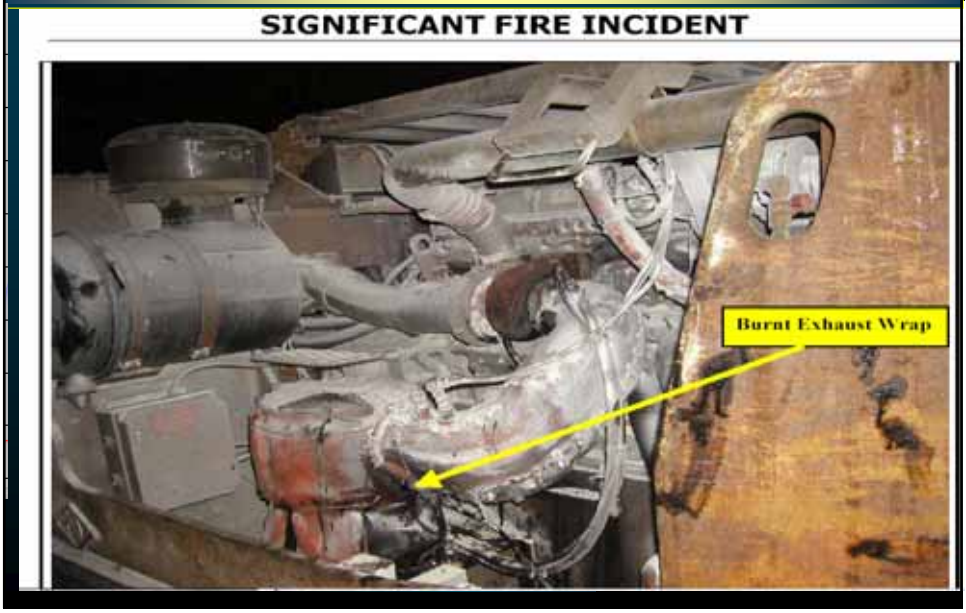
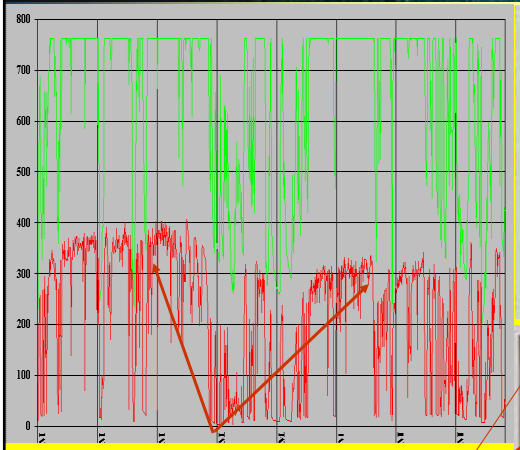
Exhaust over-heating

- **DPFs** can become plugged and give rise to excessive back-pressures, and temperatures,
- **Two unexpected incidents at INCO**
  - Fire on the DDEC L.H.D. with Engelhard passive filter – oil sprayed from failed turbocharger
  - ECS/Unikat/Combifilter trap system failed due to scheduled regeneration not being performed

Fire Incident (the week of Sept 23/02) on DDEC L.H.D., Engelhard DPF Total Hours = 2221



Failure of Combifilter on DDEC Scoop Total Hours = 873



This Swedish system failed last year at Stobie because of inexperience with the system - the importance of regeneration at the end of each shift

Conclusions to Date…

- Operator acceptance is encouraging – even though there is a reluctance to loose any time for trap systems (..or anything else..)
- The systems are all very effective at reducing DPM in properly operating engines
- The operating and maintenance costs seem to be within the acceptable range. Regeneration at the end of shift at a plug-in station is workable for 3 tested vehicles at Stobie Mine .
- The premature-break down of a filter media occurred due to not performing the required regeneration
- There are problems with catalyzed filters – as NO2 level can increase

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Path Foreword…..

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What is INCO doing with the results of this projects?

Pursues new innovative DPF technologies – CRT w/NO2 optimization, fuel burner systems

Evaluating the overall effectiveness of currently available DPF systems, ie: durability, maintainability, no secondary emissions, and implementation logistics/challenges

Developing in house expertise with various DPF systems and their diagnostic/monitoring capabilities

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What is INCO doing with the results of this projects?

Equip several units of mobile equipment with DPF system

Make DPF systems a standard piece of equipment

Ensure that engines are warranted when vehicles are equipped with the DPF

Things to look out for

Strong on road market growth for DPF will provide attractive opportunities regarding better availability and costs for users

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Acknowledgements….

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Acknowledgements

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