Development, Optimization, and Long-Term Evaluation of Diesel Emission Control Systems for Heavy-Duty Mining Engines

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Mirarco MINING INNOVATION

VALE

Content

- Review of previous DPF studies and results
- Evaluation of Johnson Matthey (JM) Continuously Regenerating Trap (CRT) **optimized** for underground mining applications:
- Summary

Challenges

Diesel Particulate Matter (DPM) needs to be controlled at the source.

The effective **DPM reduction** strategy is **Diesel Particulate Filter (DPF**) system combined with:

- good ventilation practices
- adherence to well planned maintenance program
- use of low emission engine technology
- use of high quality fuels and lubricants

DPF Technology

- DPF are very efficient > **95%** with respect to **mass** and **number of solid carbonaceous particles.**

- **Unassisted/or uncatalyzed** DPF requires regeneration temperature

  - in the range 500 - 600 **ºC**

  which may not be attainable under the typical mine vehicle operating conditions

DPF Regeneration key challenges

Snapshot of LHD's Mean Exhaust Temperature–deg C

Vehicle #	Description	Accum. Hours	Mean Temp.	Max Temp.
			ºC	ºC
820-Deutz ST8B	LHD	183.3	313	498
362-DDEC 60	LHD	453.2	366	465
445-DDEC 60	LHD	592.1	**341**	468

J. Stachulak, B. Conard et all Evaluation of Diesel Particulate Filter Systems at Stobie Mine
https://mirarco.org/wp-content/uploads/CAMIRO-Archive/MasterStobie-ver2-Sept2012q2.pdf

DPF Regeneration key challenges

This figure shows the entire history of temp upstream of the muffler for LHD prior to installation of a DPF.

The data covers 35,520 min(592 hr) of monitoring,

This record includes many shifts mucking by many operators at mean temp of 341 C

The **variations in temperature** show the essential characteristic of the operation of the scoop, **covering periods of full power** and other periods of extensive idling.

Including in this history are also differences in driving habits of different operators

Interestingly, **the high peak temperatures expected for a fully loaded** engine were not seen by the sensor despite
the fact that this LHD was periodically operating **under peak load conditions.**

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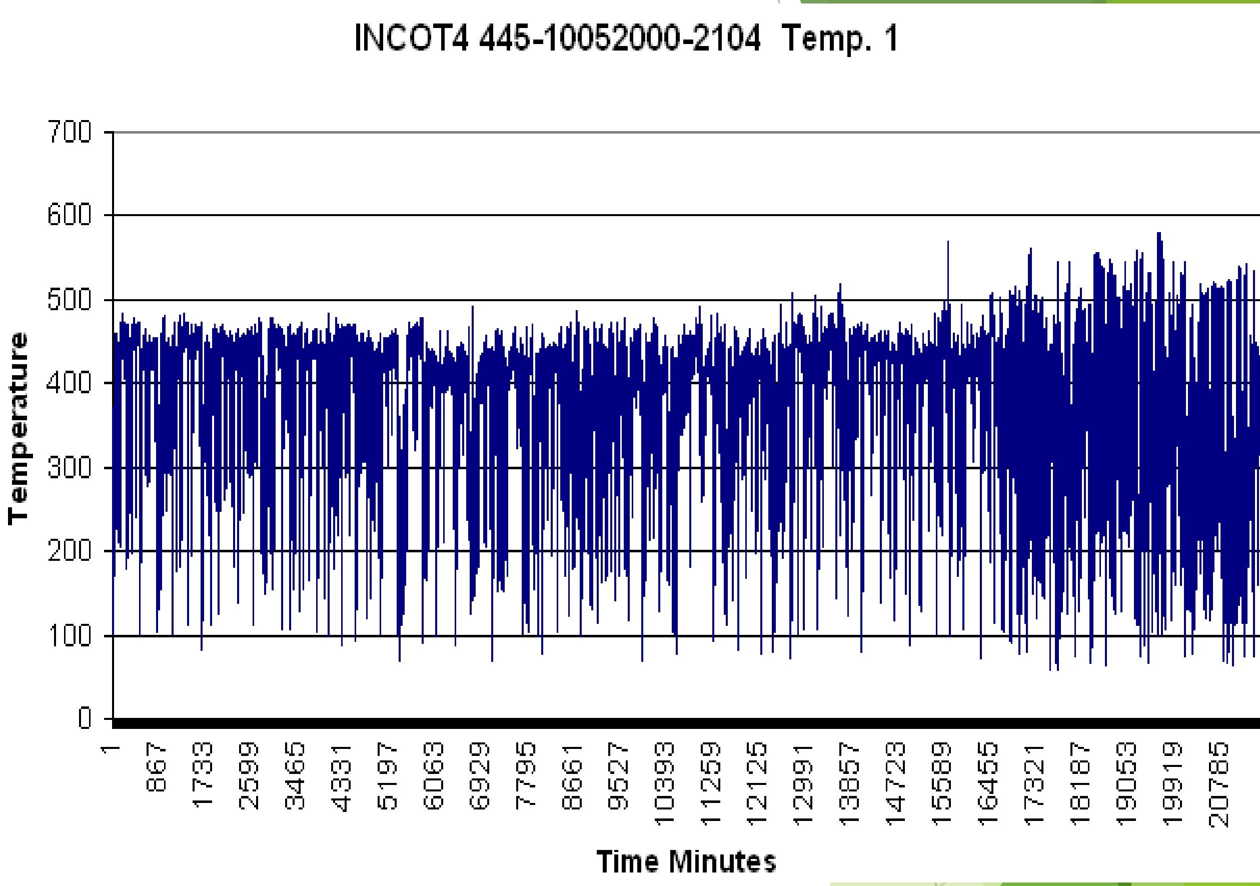


Temperature C history for vehicle LHD #445 **for 592hours** of monitoring, mean temp, 341 C

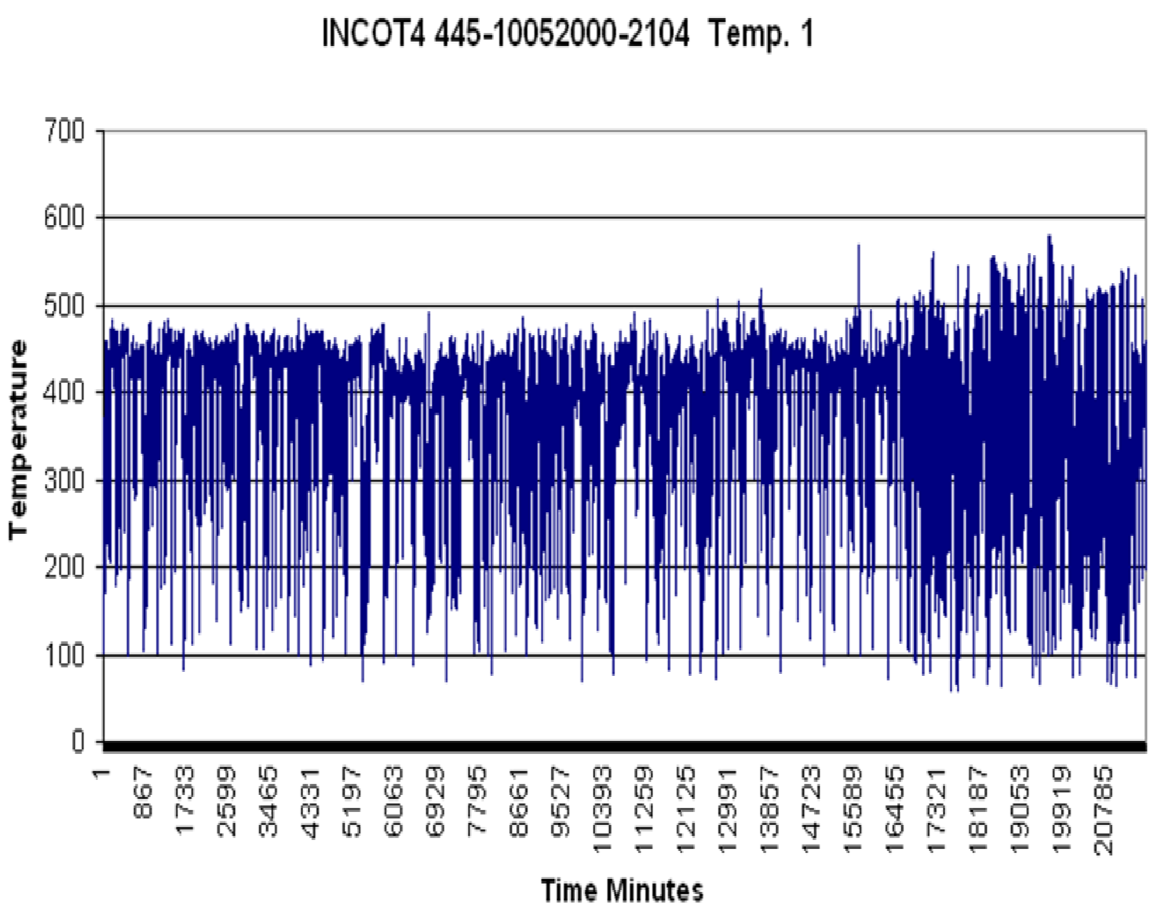
DPF Regeneration key challenges

- The reason for the lower than expected temperatures are that **the high loads lasted only a relatively short** time

- and that the relatively **small volumes** of very hot gases produced are being **cooled by the thermal inertia** of the **exhaust manifold and tailpipe** before the muffler.

- The absence of **high temperatures for a heavy duty LHD** is extremely important in deciding whether **passive DPF systems could** work

- It is known that successful passive regeneration of some DPF require a significantly prolonged episode of exhaust temperatures well above > 500 C



Temperature C history for vehicle LHD #445 **for 592hours** of monitoring, mean temp, 341 C

Formation of DEEP (Diesel Emission Evaluation Program)

INCO/Vale spearheaded DEEP, research consortium, formed by

- Canadian Mining companies,
- Government,
- Labor, unions and
- Team of **international scientists/engineers**.

- Two projects on Diesel Particulate Filters (DPF) were initiated, **one hosted by Noranda's mine (S. McGinn) and the other hosted by Vale's Stobie mine.**

- **This program, investigated the ability of (BAT) best available technology to significantly reduce DPM (Diesel Particulate Matter**

DEEP Evaluation at Vale's Stobie Mine

- **Vale evaluated 9 (nine) DPF systems retrofitted to:**
- Heavy and light-duty underground mining vehicles used in normal production cycle. – project duration 4 years

https://mirarco.org/wp-content/uploads/CAMIRO-Archive/MasterStobie-ver2-Sept2012q2.pdf Evaluation of Diesel Particulate Filter Systems at Stobie Mine

https://mdec.ca/2015/S3P2 History of Diesel Emission Projects at Vale Ontario Mines; J.Stachulak; C. Allen

Nine innovative DPF systems were evaluated

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	n/a	873	>1935	117	2221	430	463	732
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 2002	May 2002 June 2004

Findings of DEEP DPF Evaluation Program

One of the key challenges in implementing DPF system was the need for **extensive human** involvement in their operation.

- **Plugging in for regeneration**
- **Generation of NO_2 in filters with platinum catalyst**

DPF implementation challenges

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	Combifilte r 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									

Solving the Challenge/Breakthrough

- Lessons/experience learned from DEEP provided a platform for further research into innovative DPF systems
- The research/testing program was **sponsored** by
  - Vale Sudbury
  - Vale Thompson,
  - Glencore Sudbury
  - Glencore Timmins,
  - KGHM Sudbury operation.
- **Scientists from NIOSH/USA and CANMET/NRCAN provided technical support**
- Communication and lessons learned at Kali und Salz, mines, Germany and LKAB mines, Sweden

Search for **Continues Reliable DPF System Auto-Regeneration Operation** – For Heavy Duty Application

Objective

Find “business as usual“ DPF system operation, ideally, a DPF system that is “invisible” to the vehicle operator and to the maintenance department.

Results - Preliminary studies on JM Low NO2 CRT system at **University of Minnesota** showed promising results (Zarling et al. 2005).

Zarling D, Waytulonis B, Kittelson D [2005]. Testing a Low NO2 CRT DPF System. University of Minnesota,

Development of Viable DPF System for Heavy-Duty Underground Mining Applications

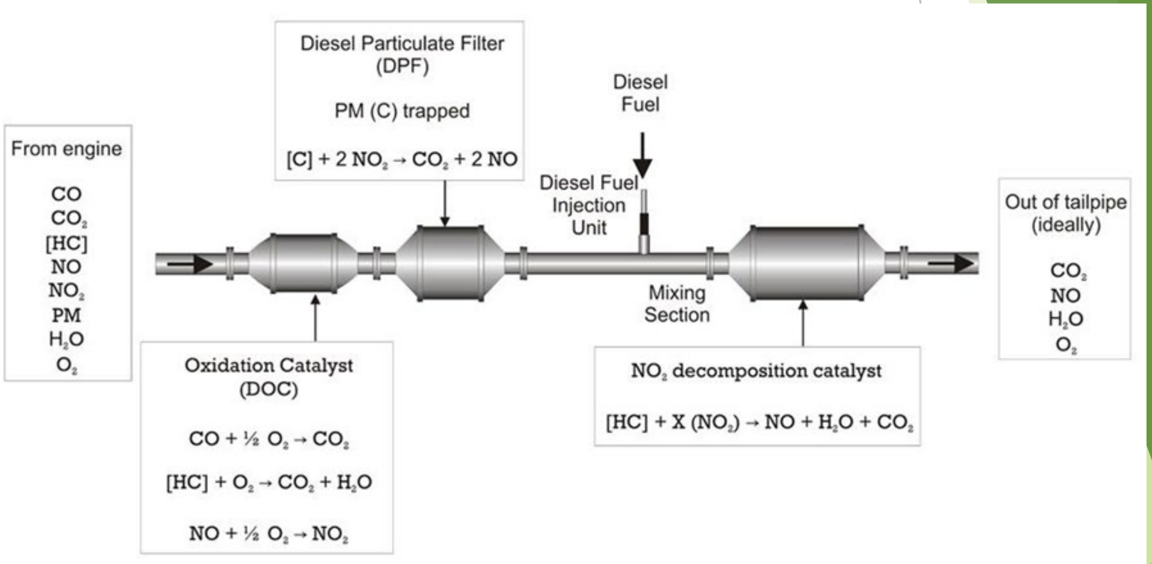
- **Low NO_2 Continuously Regenerated Trap (CRT) was developed**
- **for effective control of DPM from the heavy-duty underground diesel equipment:** and
- **no adverse effect on NO_2 emissions.**

Development of Viable DPF System for Heavy-Duty Underground Mining Applications

- **Prior to the installation on the production LHD vehicle, DPF system was extensively evaluated at Diesel Lab to:**
- characterize the effects of the system on particulate and gaseous emissions.
- **The evaluation was conducted in cooperation with: Vale, MIRARCO. NIOSH, CANMET, Johnson Matthey/ Germany,Toromont, and University of Minnesota**

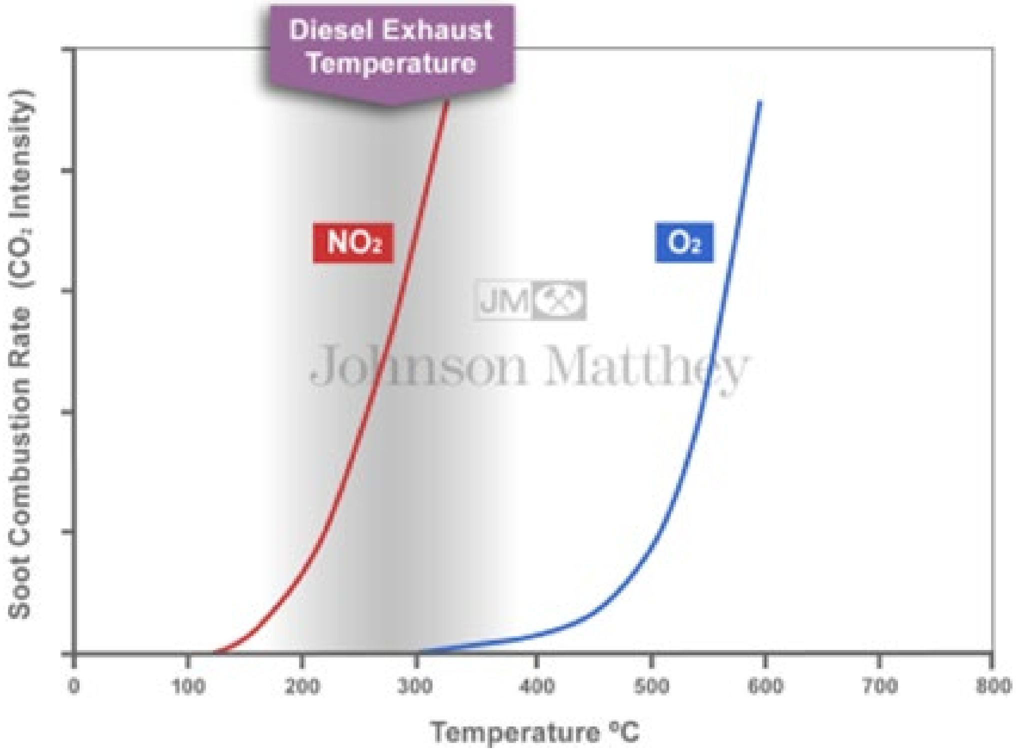
JM Mining CRT System - Principle of operation

- This **passive diesel** particulate filter (DPF) system consists of
- the **diesel oxidation catalytic** converter **(DOC),**
- full-flow wall flow filter **(DPF)** made with **Cordierite** monolith,
- **hydrocarbon** (diesel fuel) **injection** system, and
- **NO_2 decomposition** catalyst (NO_2 De-CAT).



JM Mining CRT System Principle of Operation

- Mining-CRT is designed to continuously regenerate at sustained exhaust temperatures **over 220 ˚C** (40 percent of time).
- The soot accumulated in the filter is burnt continuously with the aid of nitrogen dioxide (NO_2)

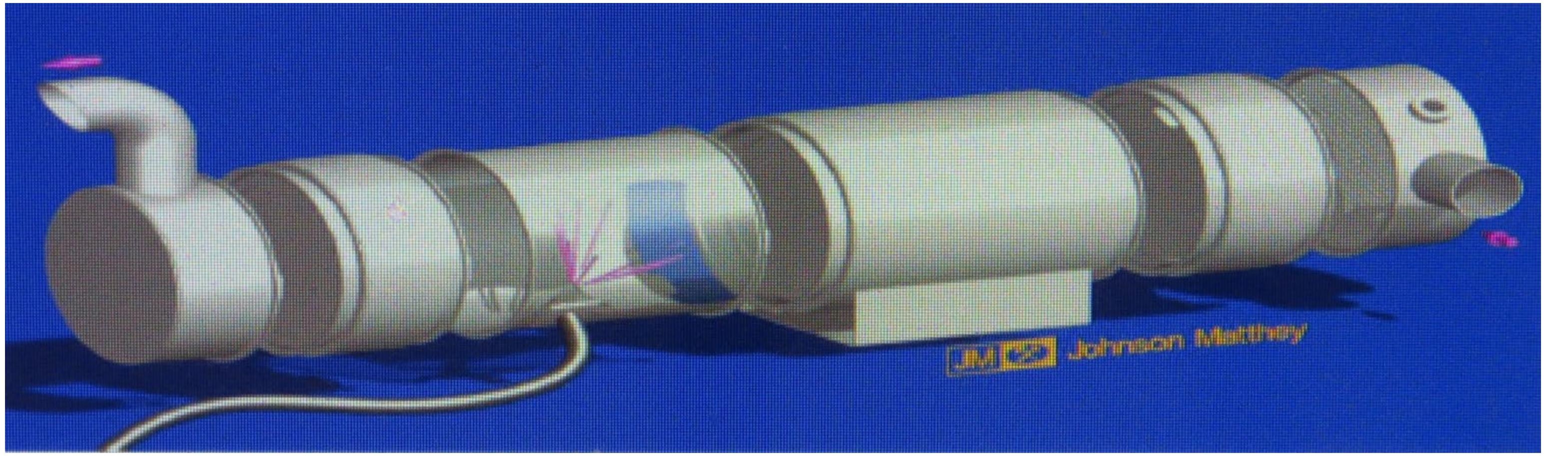


Four Phases of Field and Laboratory Evaluation of the DPF for Heavy Duty Engines - Multiyear Project

- Phase 1: Initial field trial at Vale’s Creighton Mine
  - Completed
- Phase 2: Bench testing of the system at CANMET’s diesel laboratory in Ottawa, Canada
  - Completed
- Phase 3: Field evaluation on surface operation at Vale's Totten Mine Project, Sudbury, Canada
  - Completed
- Phase 4: Field evaluation at Vale's Copper Cliff Mine, Sudbury, Canada
  - Completed

Field evaluation at underground operations at Creighton Mine – Phase 1

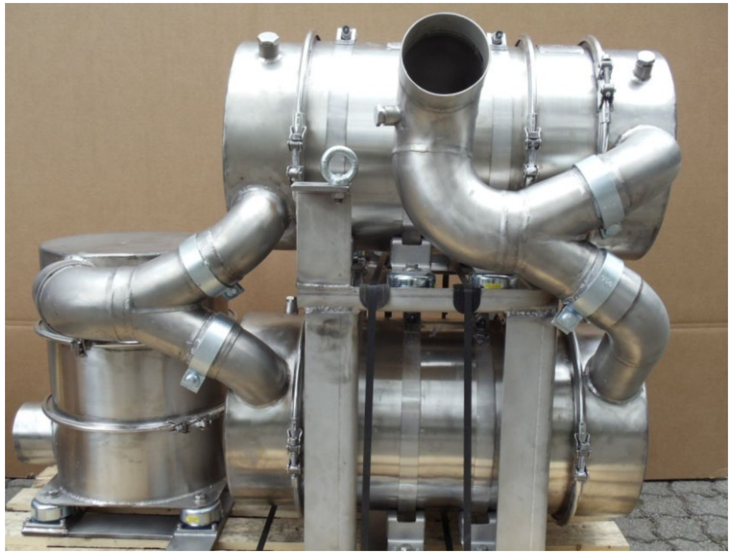
- The system quickly proved to be undersized for the application
- **Maximum engine backpressure exceeded manufacturer recommended value.**
- the system was redesigned to alleviate the engine backpressure problem



Field evaluation at underground operations at Creighton Mine – Phase 1

Outcome:

- JM/Germany re-designed the system with two filter elements in parallel configuration
- This design required removal of one of the fuel tanks.



Laboratory evaluation at CANMET Diesel Research Lab at Bell's Corner – Phase 2

- Redesigned system was tested over **steady and transient condition**

Conclusions - CANMET test – Phase 2

- Mining CRT system was effective in removal of **particles by number (99% reduction).**
- **Most importantly, the system did not have any adverse effects on NO_2 emissions (55% reduction).**
- The system also reduced CO (96%)
- The project was moved to Phase 3 (above ground loader testing)

Evaluation at surface operation at Vale's Totten Mine Project – Phase 3

Project Sponsors

- VALE – Sudbury
- VALE – Thompson
- GLENCORE -Timmins
- GLENCORE – Sudbury
- KGHM

LHD equipped with Low-NO2 CRT system was operated **remotely at the surface**

Phase 3 – Totten Project Management and Monitoring

- **Weekly meetings** were held at site to review progress and
- to **address any issues** arising during the previous period. Develop a path forward and assign work as required
- **ECOM exhaust** gas readings were **conducted weekly**
- **DPF system downloads were** collected **3 times per week -** results are sent to JM/Germany for review and analysis

Test Vehicle - LHD

Machine manufacturer	Caterpillar
Machine type	**Scoop tram R1700G**
Engine manufacturer	Caterpillar
Engine type	C11
Engine certification	**EPA TIER 3**
Engine power	263 kW
Engine speed	1800 RPM
Engine displacement	11.1 Litres
Number of cylinders	6, in-line
Aspiration	Turbo charged and aftercooled
Exhaust gas volume	3.143 m^3/hour / 1500 kg/h
Exhaust gas temperature	460-470 ° C
Fuel	Diesel fuel, max.15 ppm Sulphur

Phase 3: Field Evaluation at Surface Operation at Vale's Totten Mine Project

- Real time **on-board analyzer Sensors Inc**. SEMTEC DS was used to measure in **real time** in-use gaseous emissions.

- The results were used to **optimize the system parameters** for the application.

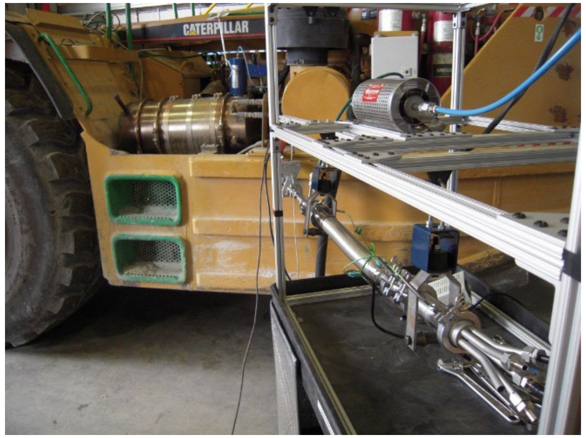
Phase 3-Surface Evaluation -Totten Mine Test Cycle

- **Load rock from ground stock pile** (~ 200,000 tons)
- Haul rock to dump sites located 100 to 1000 feet away
- Dump rock into cave area

Phase 3: **Emissions Testing at Totten Mine by NIOSH,USA**

- The series of the emissions tests were conducted on the system with **approximately 200 hours in operation** (Bugarski et al).

- The emissions of tested vehicles/engines were assessed for three engine operating conditions:
  - torque converter and hydraulic stall (TC&HS),
  - high idle (HI), and
  - low idle (LI).

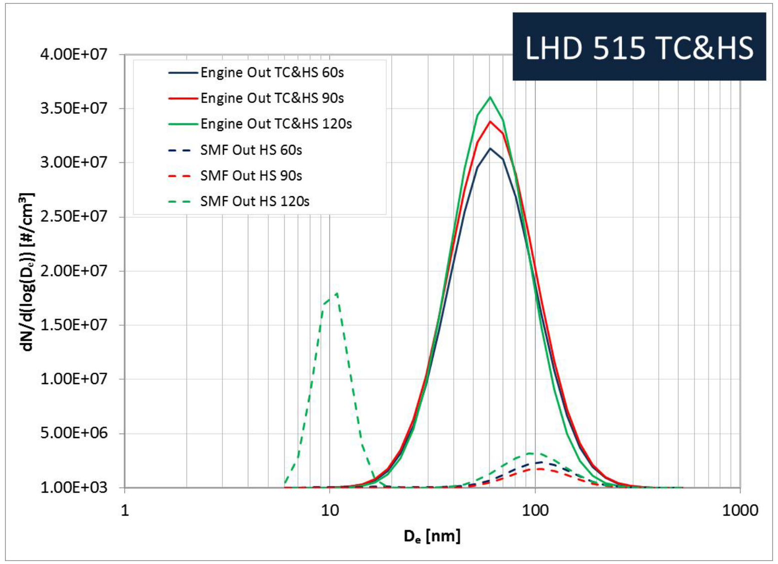


Reference:

- Bugarski, A.D., Mischler, S.E., Stachulak J.S. Effects of low-NO_2 continuously regenerated trap on aerosol and gaseous emissions from heavy-duty diesel powered underground mining vehicles. 18th Annual Mining Diesel Emissions Council (MDEC) Conference, Toronto, Ontario, Canada, October 2-4.

Phase 3 NIOSH Test -Results Totten Mine

- DPF system was **effective in reducing the number and surface area** concentrations of aerosols emitted by tested engine.



Operating Conditions	Average Efficiency [%]
TC&HS max	96.2
TC&HS min	68.3
HI	96.8
LI	76.4

Phase 3 Results and Comments Totten Mine

- Over-all the system operated very well with little maintenance issues and associated down time
- **DPF system accumulated 1200 hours**
- **Idle time had to be reduced below 20 minutes/hour to avoid problems with DPF regeneration**
- **After 630 hours of operation, a DPF system quality issue emerged and was corrected by manufacture - JM/Germany**
- Heat cured the rubber shock mounts resulting in excess vibration damage to DOC which moved inside of casing and blocked the filter (identified and heat shielding installed)

Phase 4: Underground Evaluation at Copper Cliff Mine - Multiyear Rigorous Evaluation

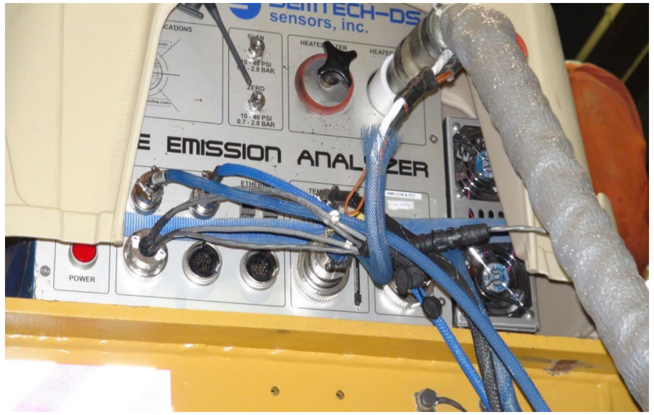
-Project Sponsors

- KGHM
- GLENCORE -Timmins
- GLENCORE - Sudbury
- VALE – Thompson
- VALE – Sudbury

- The vehicle was retrofitted with enclosed environmental cab to meet local health and safety requirements.

- **The modified version of Mining-CRT system was reinstalled on the vehicle.**

Phase 4: Underground Evaluation at Copper Cliff Mine -Multiyear Rigorous Evaluation



- The system was **optimized** using results of extensive testing conducted by: **Sensors Inc/USA, NIOSH, JM/Germany CANMET, MIRARCO.**

- Real time on-board SEMTEC DS analyzer **was used to optimize fuel injection.**

- The purpose of the calibration was to **optimize post DPF NO2 levels during transient work periods depicting a typical operating "mucking"** cycle

Phase 4: Underground Evaluation at Copper Cliff Mine - Multiyear Rigorous Evaluation

Cautious introduction:

- **Operated on day shift only for first 520 hours by trained operators**
- **Weekly meetings** with JM/Germany, Toromont, NIOSH, Mine maintenance and operations
- **Weekly download by maintenance** –
- **Download analysis** & report by JM/Germany

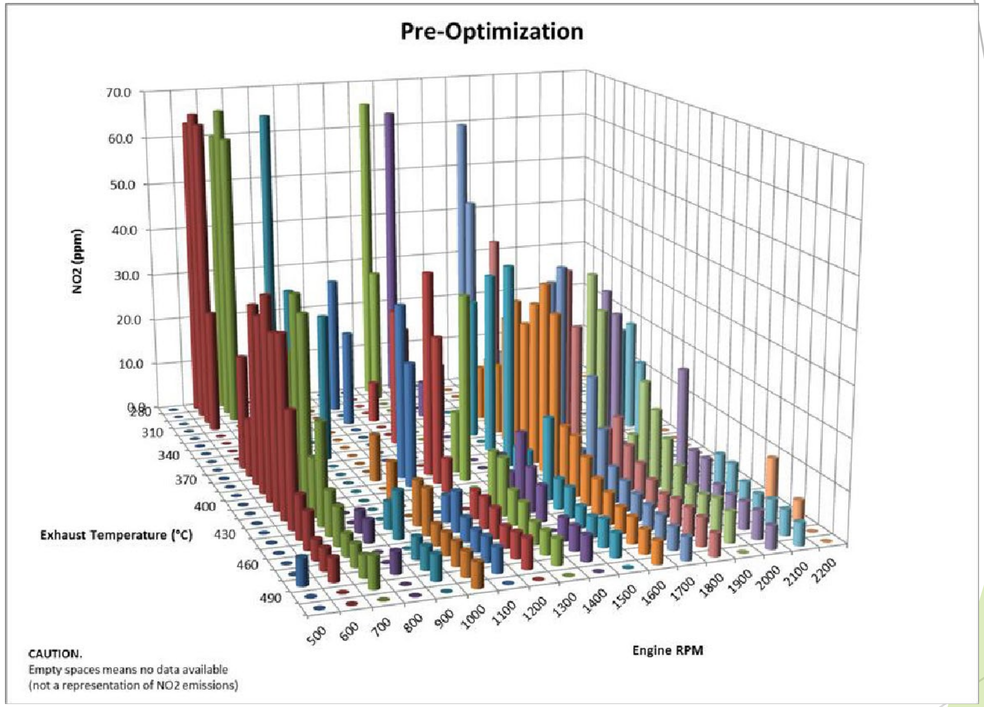
- **Performance of the system is verified weekly using ECOM measurements**

Phase 4: Multiyear rigorous evaluation at Copper Cliff Mine

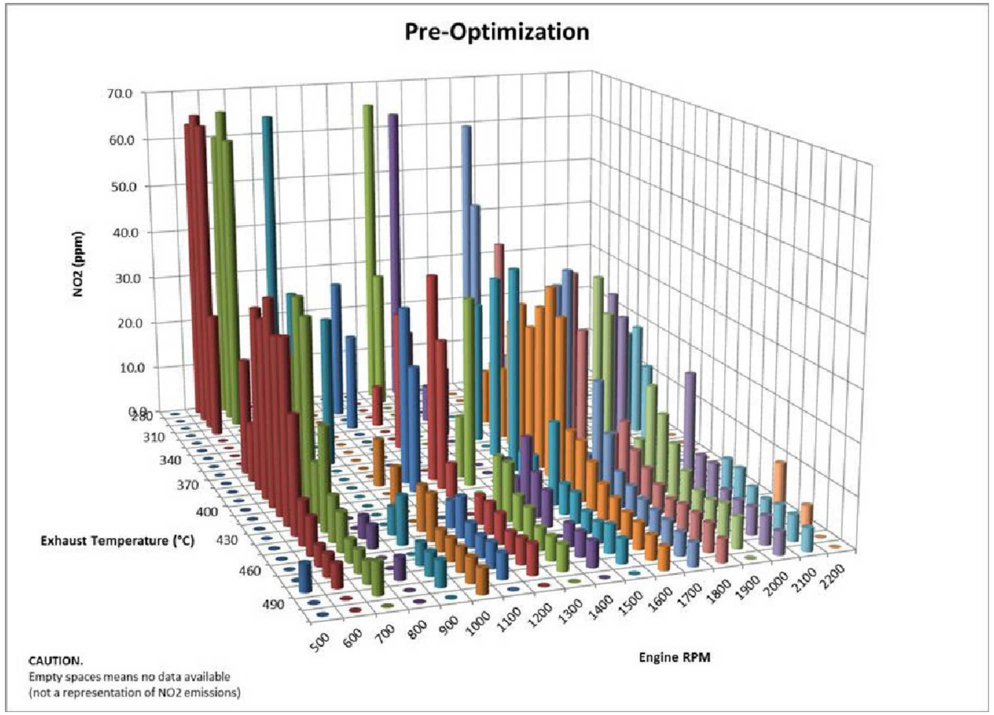
By **measuring** the **catalyst temperature, engine speed and NO2 levels,** the emissions could be

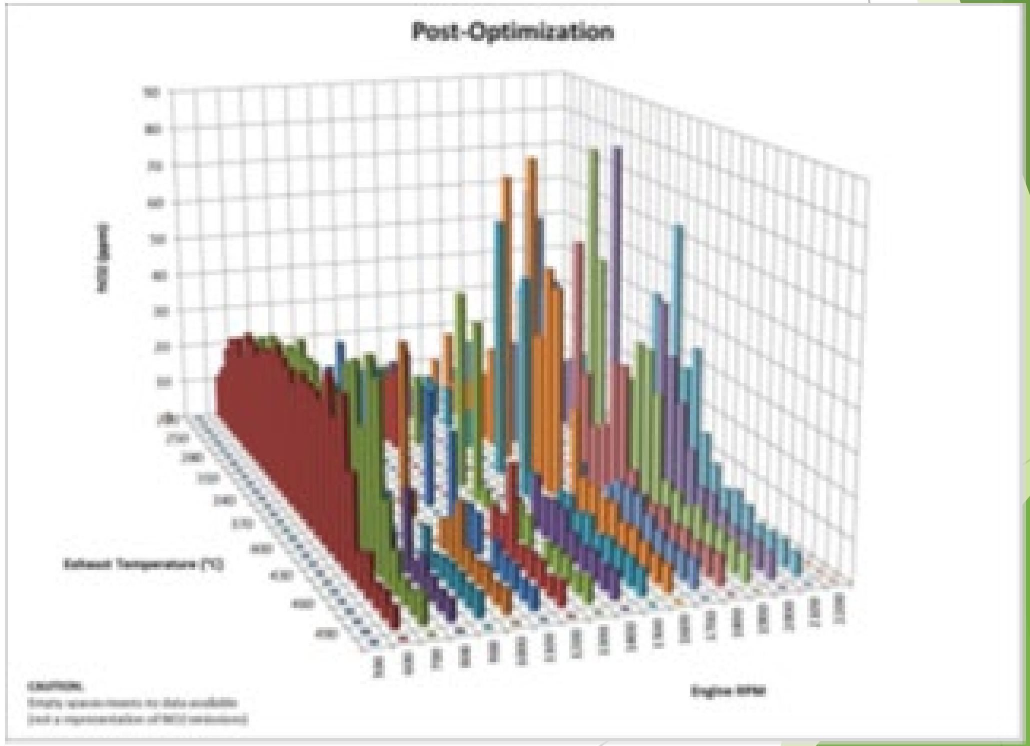
determined at **various engine** **oper**ating states, regardless of the time spent in each state

- In **mid-range temperature with high engine speed,**
- the **NO2 level spike** shown can be considered NO2 slip
- **and also when catalyst te**mperature is very low
- – this can be minimized by reducing idling upon startup



Phase 4: Multiyear rigorous evaluation at Copper Cliff Mine - **Pre and post optimization for NO2**

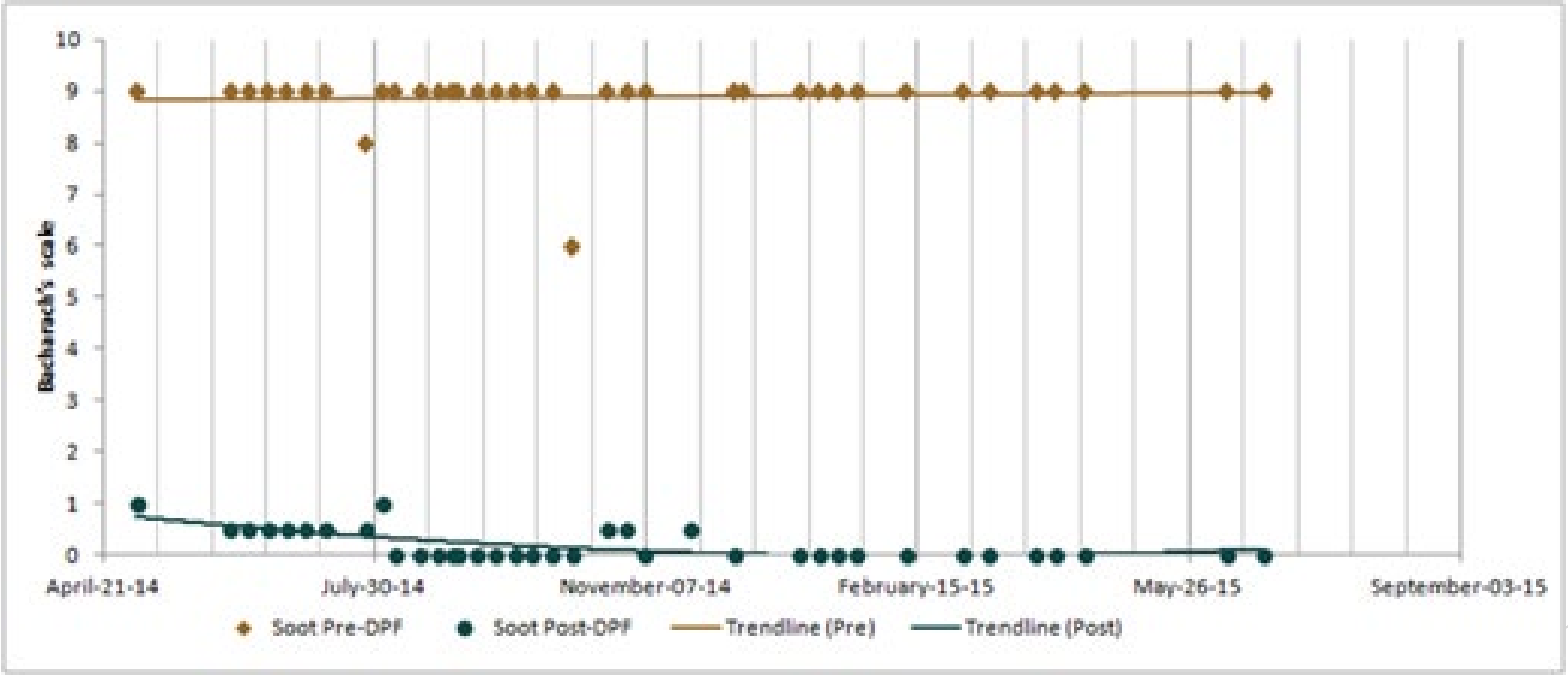




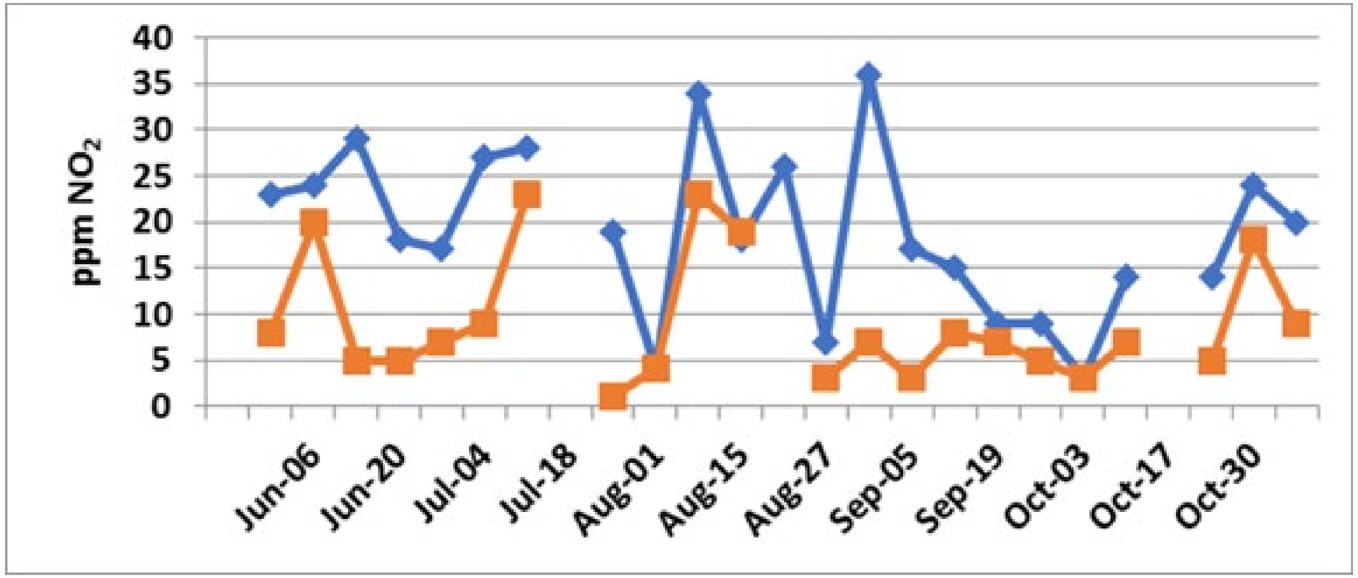
Phase 4: Multiyear rigorous evaluation at Copper Cliff Mine – ECOM

Phase 4: Multiyear rigorous evaluation at Copper Cliff Mine – ECOM

- This figure shows trend of weekly soot measurements over one year of operation at Pre DPF-**engine out** and Post DPF-**tailpipe out**
- The soot levels were essentially reduced from **dirtiest (9)**/Pre DPF-**engine out to clean (1) and below** when **DPF was installed**

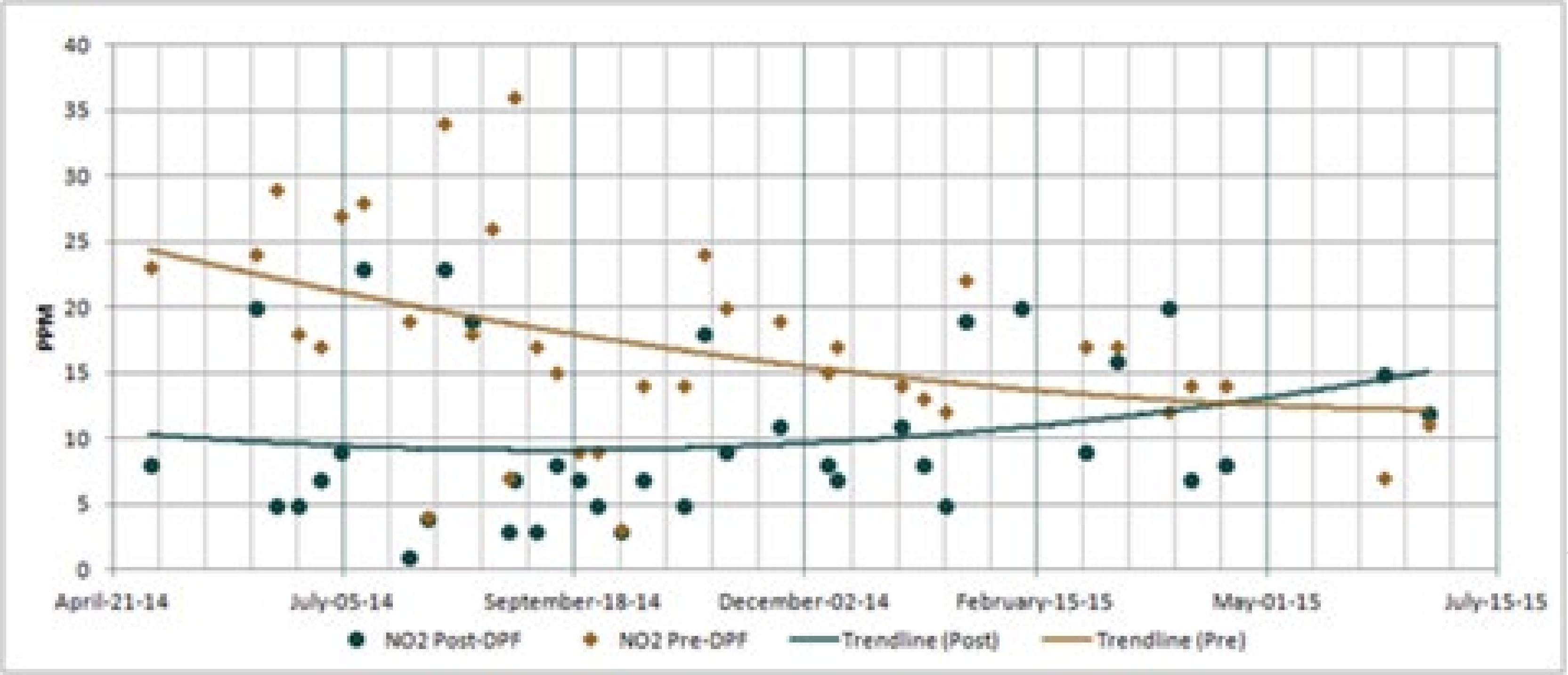


Phase 4: Multiyear rigorous evaluation at Copper Cliff Mine **– NO2 at engine out (blue)** and **tailpipe (orange)**

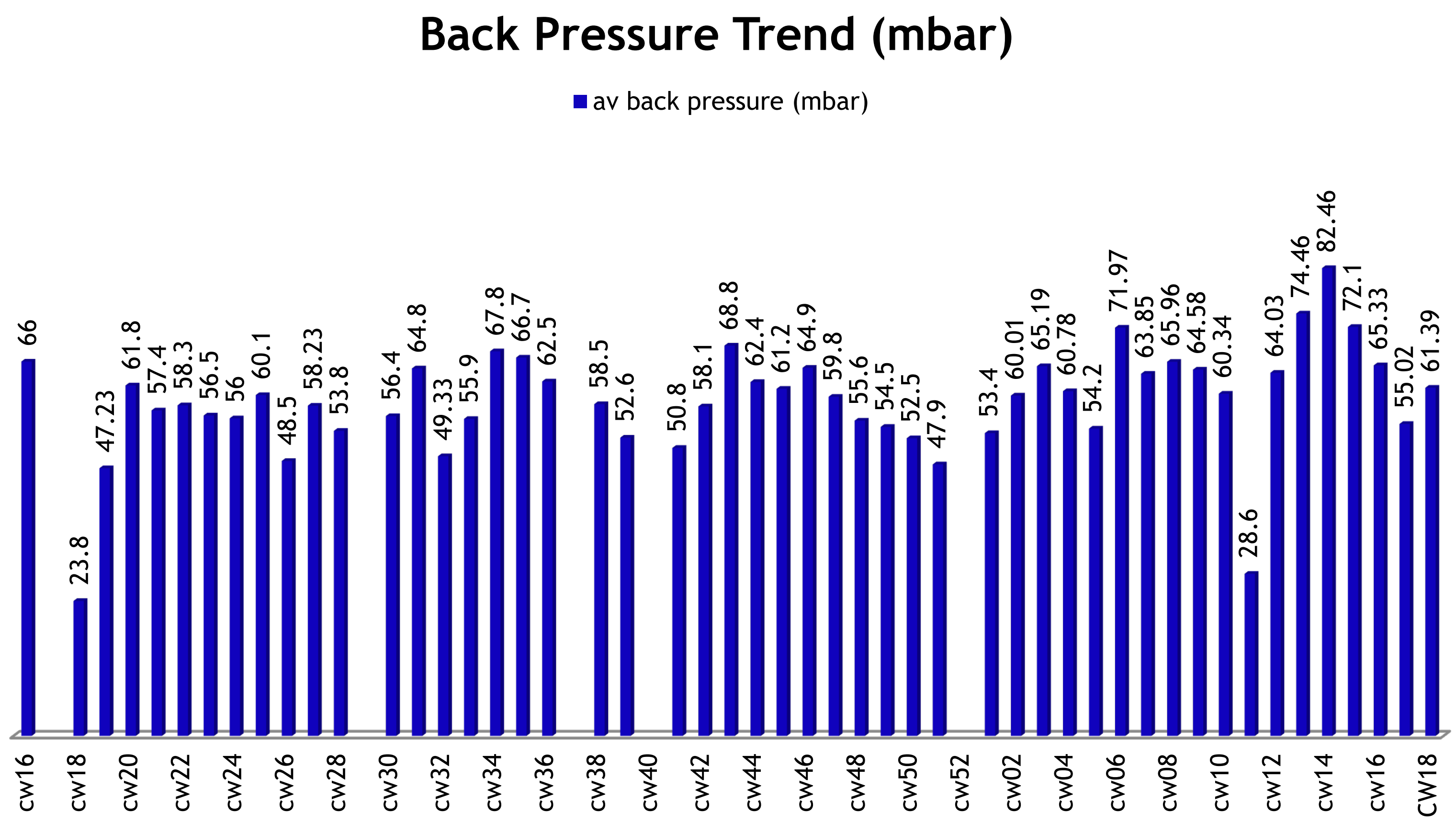


Phase 4: Multiyear rigorous evaluation at Copper Cliff Mine **– NO2 at engine out and tailpipe out**

- This figure summarizes NO2 measurements over **14 months of operation** – among all the tests,
- **94 %** of the post DPF/**tailpipe out,** read lower than pre DPF/**engine out with overall average of 8 ppm less.**

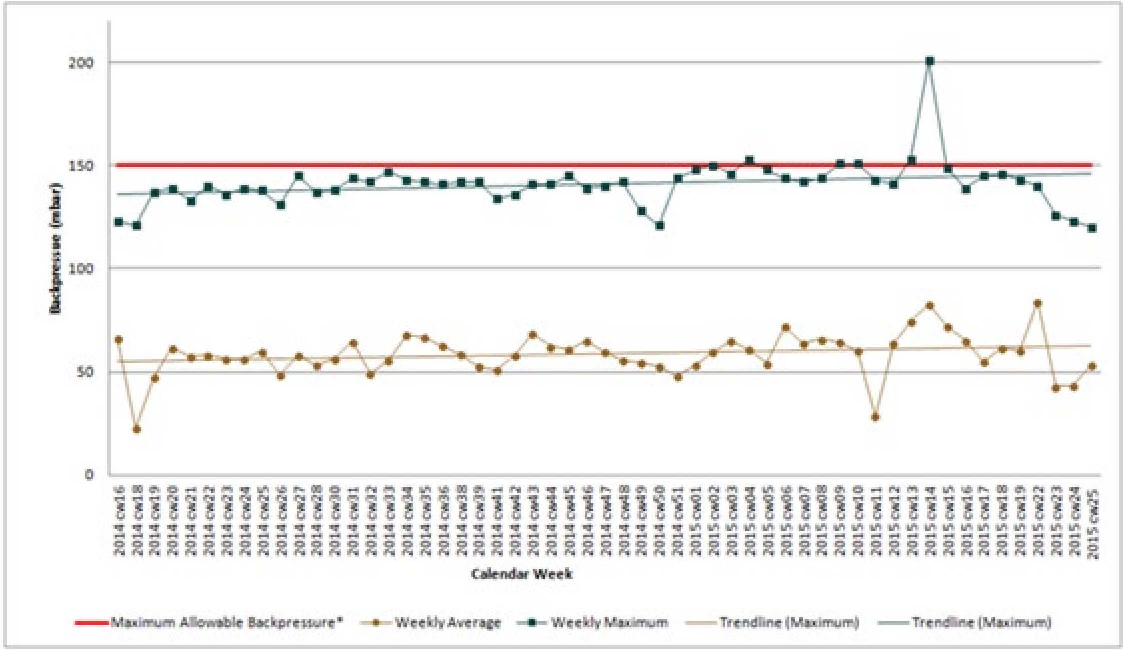


Phase 4: Multiyear rigorous evaluation at Copper Cliff Mine – engine **backpressure monitoring**



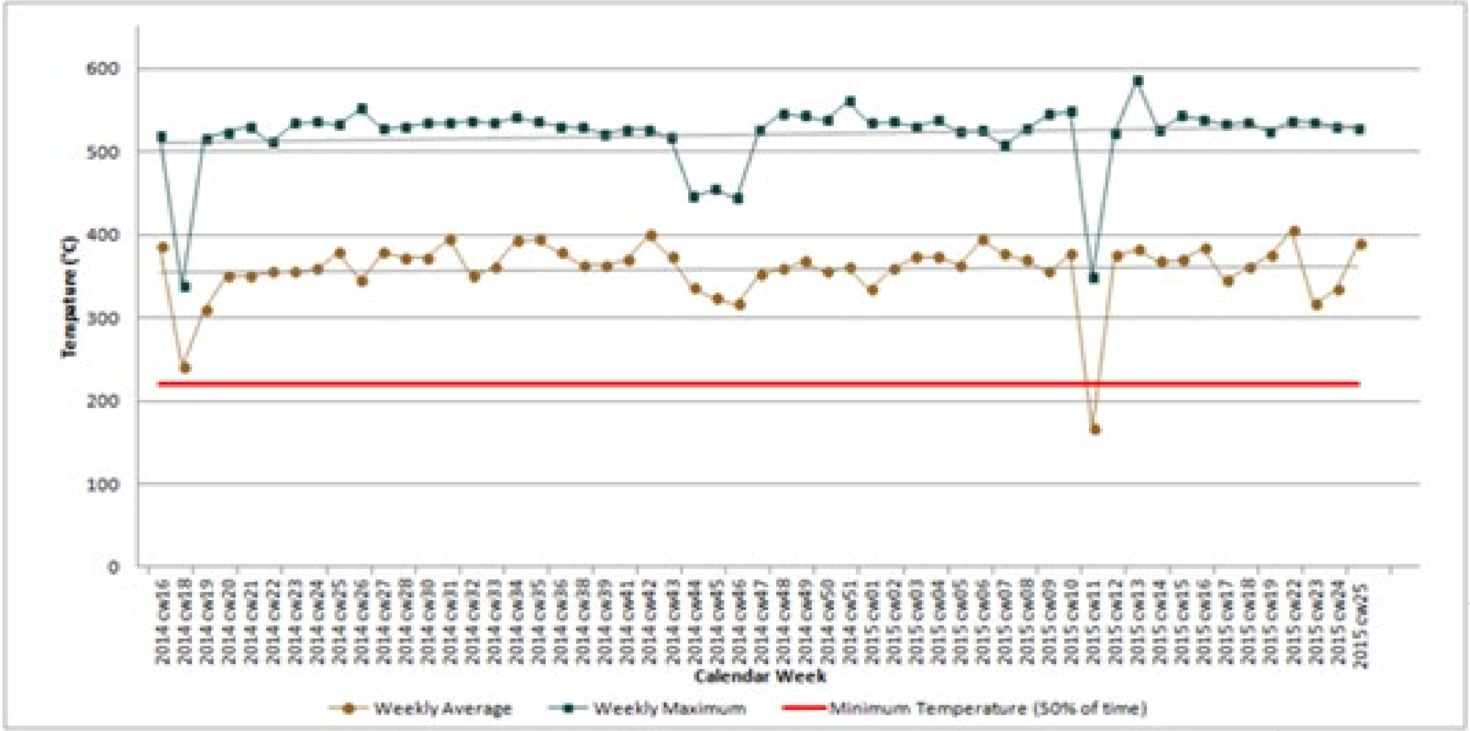
Phase 4: Multiyear rigorous evaluation at Copper Cliff Mine – engine **backpressure monitoring**

- During the **2000-**hours trial there were no indication that the filter **accumulated incombustible,** probably due **to high exhaust** temperature and **high quality** of fuel and oil.
- The **average backpressure** is in the range of **60 mbar**, which is below the engine manufacturer threshold of 120 mbar



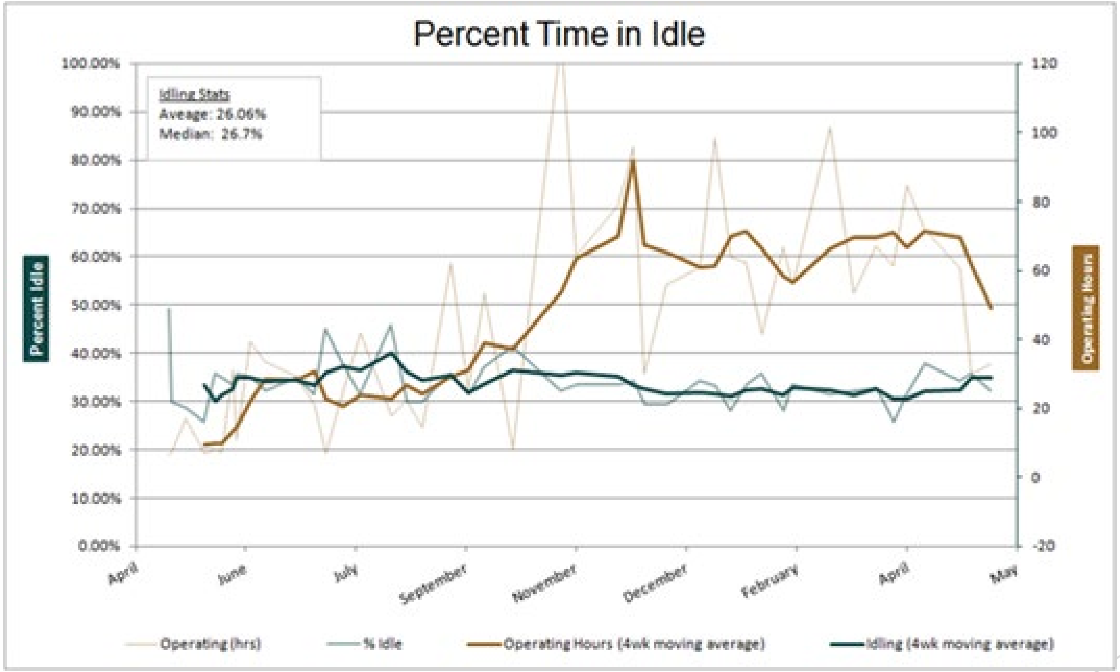
Phase 4: Multiyear rigorous evaluation at Copper Cliff Mine – exhaust **temperature over 2000 operating hou**rs – weekly trending

- The fuel injection stage of the DPF requires exhaust temperature to remain above **220 C, 40% of** the time to maintain continuous trouble free regeneration
- Results shown in figure below show that the **duty cycle of the LHD** keeps the exhaust **at** a sufficiently **high temperature** in the range of 380 C



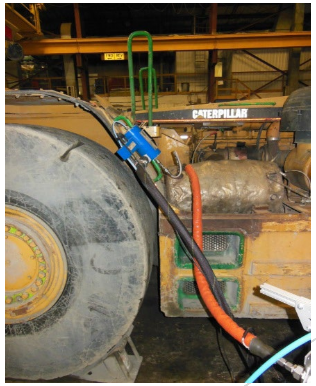
Phase 4: Multiyear rigorous evaluation at Copper Cliff Mine – **idle and operating time over 12 months**

- Increased NO2 from the engine is a **function of the exhaust temperature**, which is itself proportional to **the engine speed**
- When the **engine is idling**, the exhaust temperature drops and **NO2 levels increase**.
- The time spent by the engine in idle was **recorded weekly** to ensure that the duty cycle of the scoop would be **sufficient to prevent excess NO2** – as seen in the figure the **idle time was 26 % of the operating time**



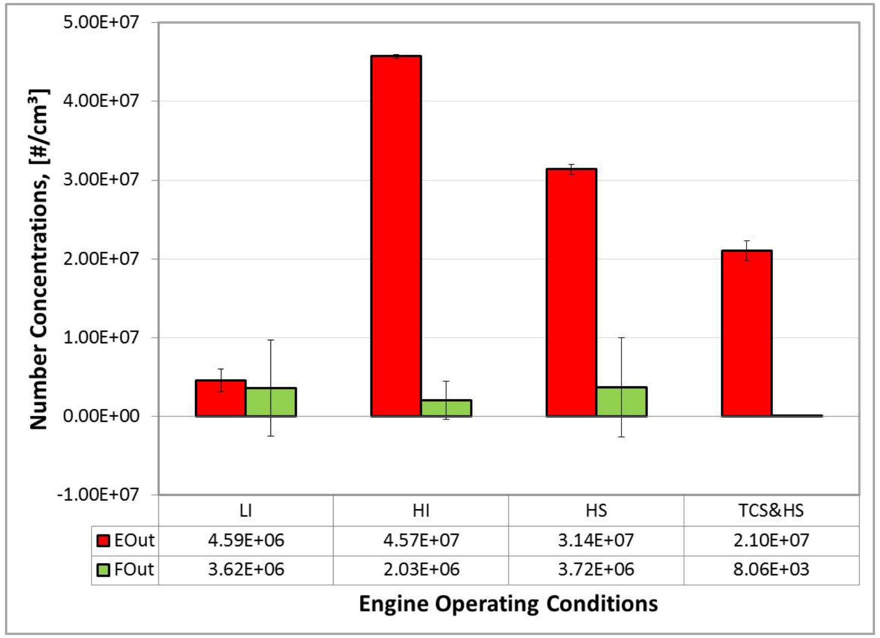
Phase 4: Multiyear rigorous evaluation at Copper Cliff Mine – DPF efficiency – **total nanoparticles number concentration reduction - NIOSH** – Dr.A.Bugarski

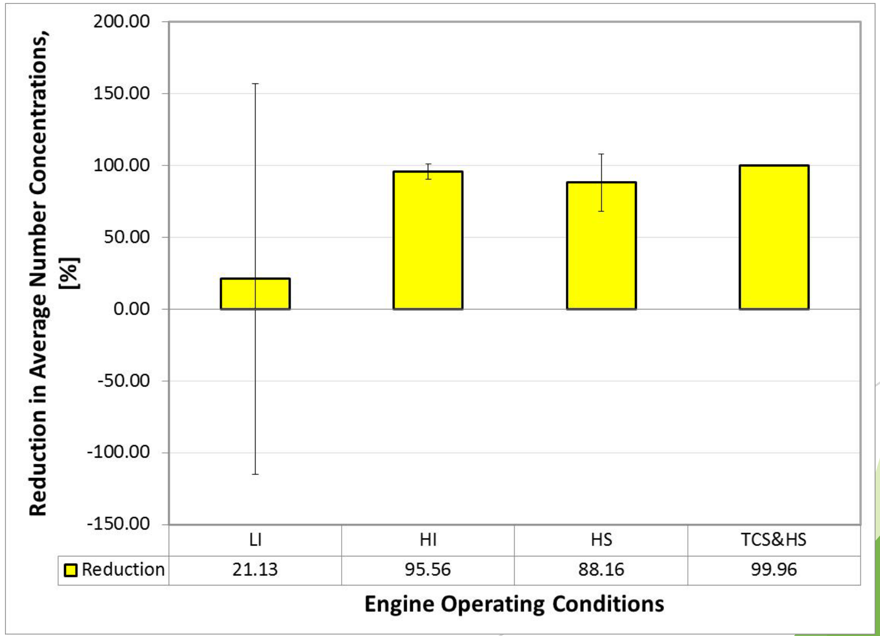
- A series of NIOSH tests were carried out at CCM to assess the effects of the system on **gas and aerosol emissions** from the Caterpillar C11 engine
- Prior to the tests, the JM system **accumulated about 1000-** operating hours.
- The emissions of tested vehicles/engines were assessed for **four different steady-state conditions:**
  - low idle (LI),
  - high idle (HI),
  - hydraulic stall (HS),
  - torque converter and hydraulic stall (TCS&HS).



Phase 4: Multiyear rigorous evaluation at Copper Cliff Mine – Mining CRT efficiency – **total nanoparticles number concentration reduction - NIOSH**

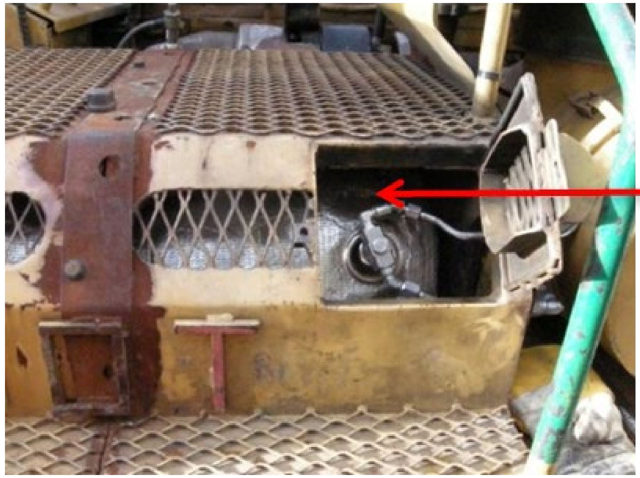
- For HI, HS, and TCS&HS conditions, the **system reduced aerosol concentrations by 88 to 99 percent.**
- The presence of relatively large concentrations of nucleation aerosols in the FOut LI case, caused the average reductions for LI conditions to be more modest.

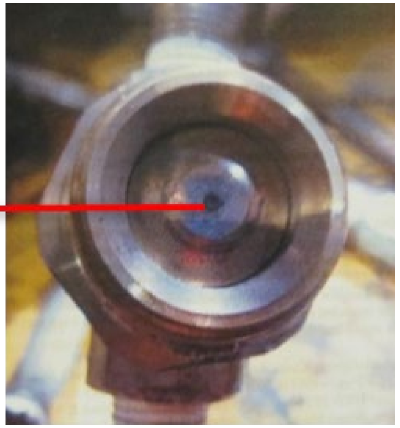




Phase 4 CCMine - Technical – operational issues

- Initially there **were several recurring** issues with the DPF system.
  - The most frequent complication was the **clogging of the fuel injection nozzle.**





  - This was a concern because clogging can **prevent fuel injection**, which would lead to **increased NO_2 levels**. - This has since been **solved** by installing an upgraded fuel injection nozzle.

Phase 4 CCMine - DPF Maintenance issues

- The maintenance requirements for the final DPF system were relatively **low when compared** to the LHD overall maintenance.
- A large portion of the DPF maintenance time is attributed to the **ECOM test, installation** and exchange.
- Due to the heat near the DPF, there were initially issues with **temperature and backpressure sensors, wiring and harness.**

Phase 4 CCMine – Summary

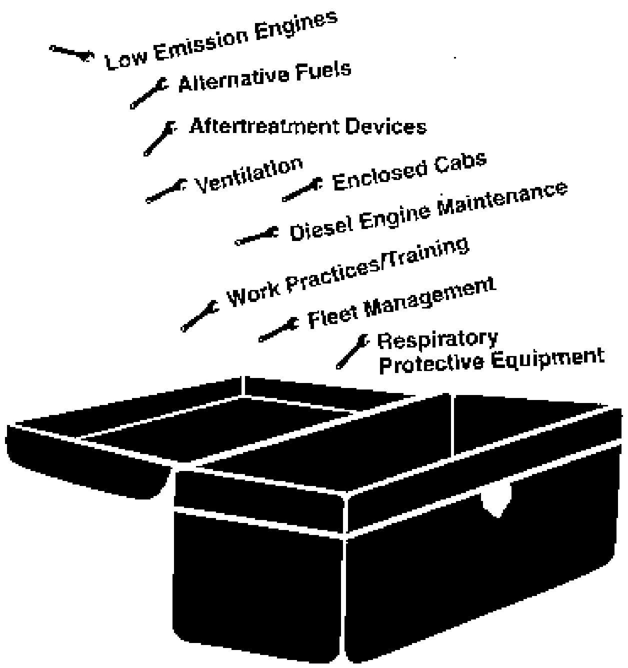
- JM Mining CRT has proven to be an **acceptable installation** in LHD-Scoops powered by EPA Tier III engines.
- the Mining CRT dual system was rigorously evaluated over a multiyear **20,000 hours** of operation.
- with **dedicated** involvement /support of **Vale's Copper Cliff mine** personnel, K.Watson, B. McLean and collaboration with MIRARCO, NIOSH and CANMET
- It acquired **7380 hours without the need for cleaning and replacement** while maintaining NO_2 emissions at engine level
- JM hase developed a single system that is substantially more compact and eliminates the requirements for removal of one of the fuel tanks on a Caterpillar R 1700 LHD.

JM–Mining CRT Operation at Vale's CCMine

LHD/SCOOP #	Mean Engine Exhaust Temp (˚C)	Mean Back Pressure (mbar)	Operating Hours
515 Toro1700	374	118	2936
657 Toro 1700	443	87	3060
561 Toro1700	367	73	1316
631 Toro 1700	424	25	1711

Summary - How can exposures to DPM be controlled?

- Performing routine preventive maintenance
- **Control at the source of generation by DPF systems**
- Low emission/**modern engine**
- Effective ventilation system design/workplace and practices
- Prohibiting/restricting unnecessary idling



Source:
https://www.osha.gov/dts/hazardalerts/diesel_exhaust_hazard_alert.html
CARB Verification
(http://www.arb.ca.gov/diesel/verdev/vt/cvt.htm)
MSHA Verification
(http://arlweb.msha.gov/01-995/Coal/DPM-FilterEfflist.pdf

http://arlweb.msha.gov/S&hinfo/toolbox/Tbcover.htm

VERT Filter List (http://www.Vert-dpf.eu)

Recommendation – Path forward

- Consolidate the diesel curtailment breakthrough
- Implementation strategy is underway.
- Research partners.. Canadian, International

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