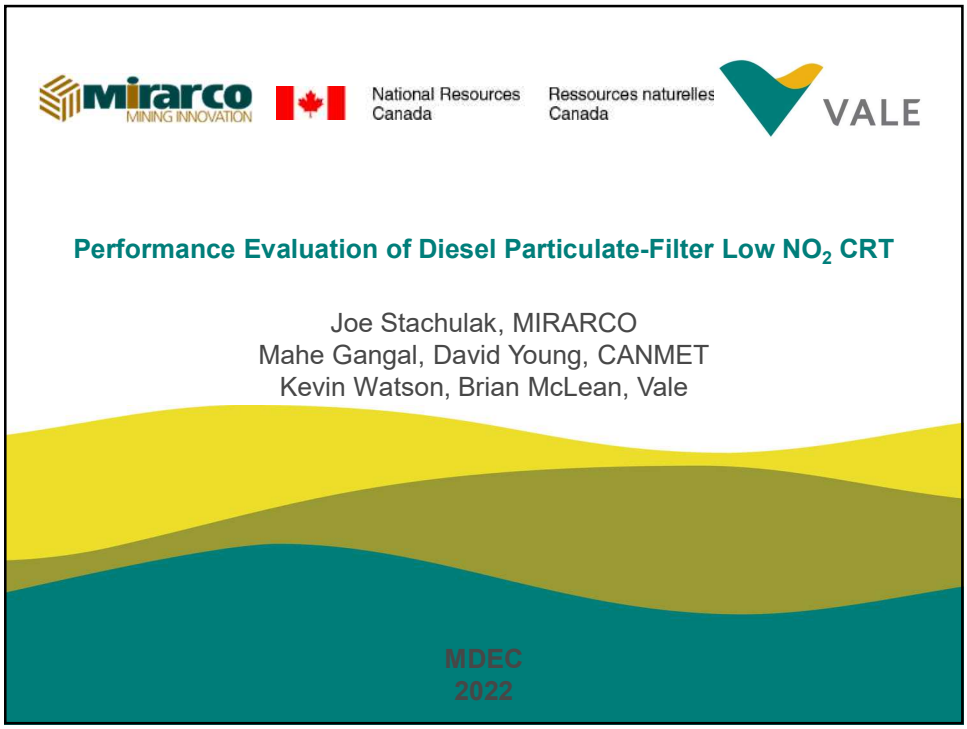

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Background

- This study evaluated the emissions from a Caterpillar engine C11, Tier 3, obtained with and without the application of Johnson Matthey **Diesel-Particulate-Filter Low NO_2-CRT** emission control device.
- The result of this study provides information on the emission performance of the DPF for application in Underground mines where increase of NO_2 in the mine environment is undesirable.
- The testing was performed at the Diesel Emissions Research Laboratory at CANMETMINING, Ottawa.

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Background

- The emission testing was performed on an engine dynamometer under controlled conditions using the ISO 8178-C1, 8-mode test cycle.
- Measurements were made for the basic engine parameters and exhaust gas concentrations were measured for
- carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), nitric oxide (NO), oxides of nitrogen (NOX), total hydrocarbons (THC), and diesel particulate matter (DPM).
- Measurements were also made for nano-particle distribution for each 8-mode cycle.
- Several steady state and transient test cycles were performed to calibrate and fine tune the fuel injection protocol for emission reduction device.

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Introduction

- The engine dynamometer followed ISO 8178-C1 8-mode test cycle plus CANMET 22 point emission mapping,
- and LHD transient test cycle protocol and used ultra-low sulphur diesel fuel.
- Two final 8-Mode tests were performed for this study including,
  - (1) engine only baseline, and
  - (2) engine CRT. These tests were used for final evaluation of the device.
- Diesel-Particulate-Filter Low NO_2-CRT was provided by Johnson Matthey Limited.
- The engine was provided by Toromont/Sudbury

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Experimental Approach

- This section provides some information on the test engine, test fuel, and test procedure for the evaluation of the DPM control technologies.
- **Test Engine**
  - The engine used for the testing was a Cat C11. Table 1 provides some engine specification data.

Table 1. Test engine specifications

Make	Caterpillar
Model	C11, Tier 3
Serial number	RSX05190
Displacement	11 Liter
Rated power, gross	353 hp @ 1800 rpm
Fuel rate at rated power	118.5 lb/hr
Peak torque	1089 lb.ft @1600 rpm
Peak torque speed	1600 rpm
Aspiration	Turbocharged
Fuel system	DI, Electronically controlled fuel injection
Max air intake restriction	15" H_2O
Max exhaust backpressure	40" H_2O
Low idle speed	700 rpm
High idle speed	2120 rpm

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Test Fuel

- The diesel fuel used for this study was an ultra-low sulphur diesel fuel with a sulphur value of 11 ppm (CAN/CGSB-3.517-2000).
- Some of the laboratory analysed fuel properties are given in Table 2.

Table 2. Some diesel fuel properties

Properties	ASTM test method	Analysis
Specific gravity 60/60F	D4052	0.8248
Density @ 15°C, kg/m^3	D4052	824.1
Carbon, wt%	D5291	86.32
Hydrogen, wt%	D5291	13.94
Nitrogen, wt%	D5291	<0.3
Flash point, °C	D93	54.1
Sulphur, ppm	D7039	10.8

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Gases and DPM Control Devices

- Johnson Matthey supplied a Diesel-Particulate-Filter Low NO_2-CRT diesel particulate filter for this study. The device was tested after it was tuned for optimum performance.
- Prior to testing, the devices was installed as shown in Figure 1.

Figure 1 - Diesel-Particulate-Filter Low NO_2-CRT emission control device and Caterpillar C 11 diesel engine installed in the CANMET test cell

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Gases and DPM Control Devices

- The device was calibrated according to the test cycles 1 to 6
- Test data received from these 6 test cycles was provided to the device manufacturer representative for calibration purposes

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Test Procedure

- The engine exhaust emissions were measured at all modes of the ISO 8178-C1 test cycle.
- The 8-Mode test cycle for the Caterpillar C11 engine is defined in Table 3.
- The integrated 8-Mode average values for all tests were calculated using the appropriate weighting factors for each mode.

Table 3. ISO 8178-C1 8- Mode test cycle

Mode #	1	2	3	4	5	6	7	8
Engine Speed, rpm	1800				1350			700
Torque, %	100	75	50	10	100	75	50	0
Weighting factor	0.15	0.15	0.15	0.1	0.1	0.1	0.1	0.15

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Gaseous Emission Measurement

- The raw exhaust gas concentrations were measured using a California Analytical Instruments (CAI) gas cart.
- The gas cart consists of an exhaust gas sampling and conditioning system, emission analysers, 64 point gas divider for system calibration, and NOx efficiency tester.
- The gas cart contains the following gas analyzers:
  - Low range carbon monoxide (CO), model CAI 100 IR, non-dispersive infrared (NDIR) detection system, span ranges 0-100 ppm and 0-2000 ppm.
  - Carbon dioxide (CO_2) and high carbon monoxide (HCO) model CAI 300 IR, non- dispersive infrared (NDIR) detection system, CO_2 span ranges 0-5.0% and
    - 0-20.0%, and CO span range 0-1.0%.
  - Oxygen (O_2), model CAI 300 Oxygen, paramagnetic (PMA) detection system, span ranges 0-5% and 0-25%.
  - Oxides of nitrogen (NO/NO_x), model CAI 400 HCLD heated, chemiluminescence (CLD) detection system, span ranges 0-1000 ppm and 0-3000 ppm. The gas cart has two NO/NO_x analyzers that provide simultaneous measurements of NO and NO_x. The concentration of NO_2 is determined by the difference of NO_x and NO concentrations.
  - Total hydrocarbons (THC), model CAI 300 HFID, heated flame ionization detector (HFID), span ranges 0-100 ppm and 0-1000 ppm.

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Particulate and Nanoparticle Measurement

Particulate Measurement

- The Diesel Particulate Matter (DPM) was measured gravimetrically using a Sierra BG-2 particulate partial flow sampling system

Nano-particle Measurement

- A Thermo Scientific Inc. scanning mobility particle sizer (SMPS) 3080 spectrometer was used to measure the size distribution of diluted diesel exhaust in the size 14 to nm to 710 nm distribution.

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Diesel – Particulate- Filter Low NO_2-CRT

- The Diesel-Particulate-Filter Low NO_2-CRT was installed and operated by the manufacturer representative.
- The regeneration of the filter is by NO_2 oxidation.
- Soot is burnt continuously in the filter unit with the aid of catalyst generated nitrogen dioxide (NO_2), which reacts with the soot collected in the filter, producing:
  - carbon dioxide (CO_2) and NO; CO and HC missions are also reduced by oxidation.
- The NO_2 slip is reduced using the reaction of injected HC (Diesel fuel) together with NO_2 over a special catalyst

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Diesel – Particulate- Filter Low NO_2-CRT – Test Results

- Test Results
- Table 4 provides 8-Mode integrated average values of specific emission data for gases and DPM

Integrated Specific emissions		Baseline Test 8	CRT Test 7	Reduction
CO_2	g/hr	86817.3	87687.2	-1.0%
CO	g/hr	279.7	11.5	95.9%
NO_2	g/hr	33.5	15.1	55.0%
NO	g/hr	242.3	250.1	-3.2%
NO_X	g/hr	275.8	265.3	3.8%
THC	g/hr	23.2	9.7	58.0%
DPM	g/hr	4.8	2.5	47.7%
SMPS	dw/dlogDp	6.9.E+06	7.6.E+04	98.9%

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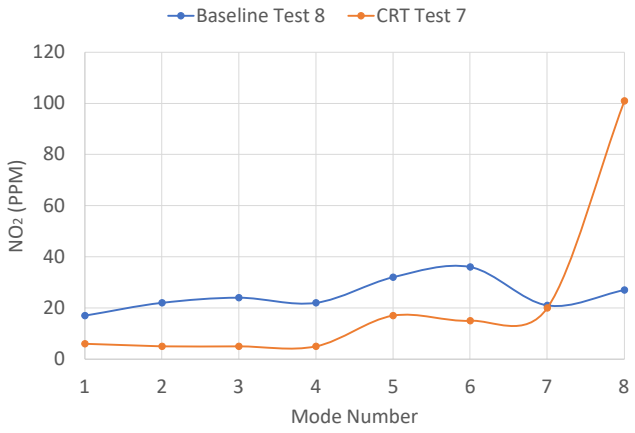
Exhaust gas concentration (wet) comparisons



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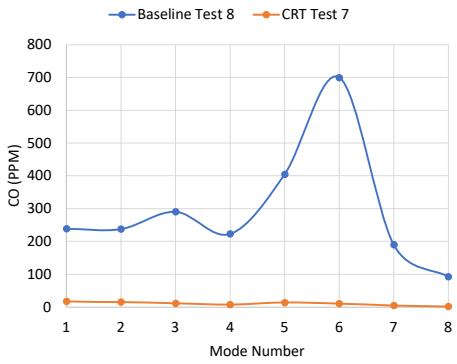
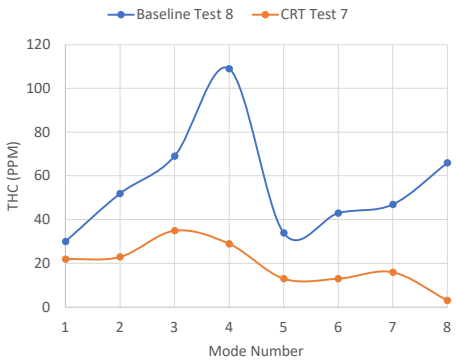
Exhaust gas concentration (wet) comparisons





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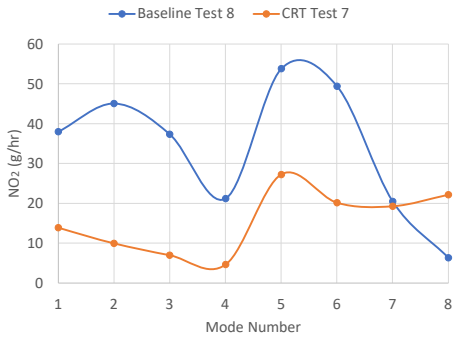
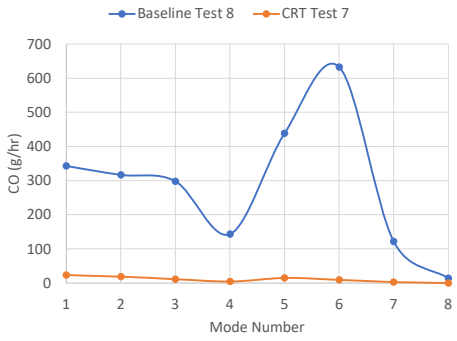
Specific emissions comparisons





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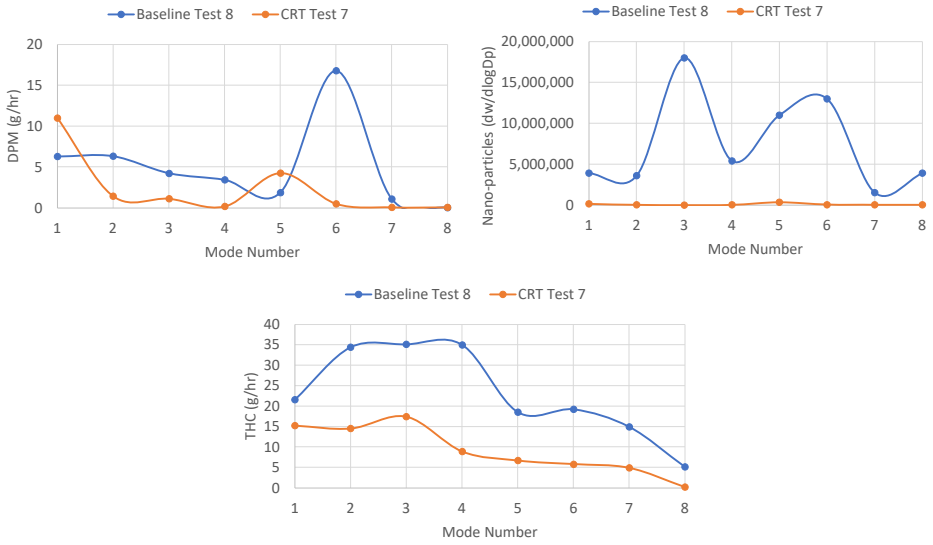
Specific emissions comparisons



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Test Results

- The overall DPM conversion of 47.7% reported over the Low NO_2 CRT® system is lower than expected. DPM removal over a ceramic wall flow filter is usually >90%.
- This lower than expected conversion over the filter system could be due to Diesel fuel droplets, derived from the fuel injection that takes place between the filter and the NO_2 decomposition system, slipping from the system and then being measured as DPM.

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Test Results

- This theory is supported by the relatively lower than expected reductions (58%) of THC found over the Low NO_2 CRT® system.
- A THC conversion of >90% is usually expected over a CRT® system operated at these temperatures and the higher tailpipe levels found over this DPF system probably result from the Diesel that is added after the filter to reduce tailpipe NO_2 levels.
- The very high (98.9%) reduction of nanoparticles again suggests that the filter is working efficiently and that the measured mass of particulate is largely due to condensed Diesel fuel rather than soot from the engine.
- It is expected that this level of Diesel fuel slip can be reduced in future tests by system optimisation.

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Summary

- Table 4 shows that the Diesel-Particulate-Filter Low NO_2-CRT® reduced CO by 96%, and nano-particles by 99% over the 8-Mode test cycle.
- Moreover, Table 4 indicates that the CRT system reduced the THC by 58% and NO_2 by 55% over the 8-Mode test cycle which is in line with the system design to keep THC and NO_2 lower than engine baseline.
- The reduction of exhaust gas emissions Johnson Matthey Diesel-Particulate-Filter Low NO_2-CRT® was evaluated on an engine dynamometer. Caterpillar C11, Tier 3 engine was emission tested over the 8-Mode test cycles.
- An ultra–low-sulphur (11 ppm) diesel fuel was used for this testing. The regulated gaseous emissions and particle counts were measured.

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JM's MCRT –DPF System Development at Vale Sudbury

Vale Testing Validates Performance & Value
Long Life

Customer	Run-Time	Machine
Vale - Copper Cliff Mine (Sudbury)	7380 hrs (w/o replacement)	CAT R1700 LHD, 263kW C11 Tier 3

Data for DPF filter from March 2017 – Feb 2021

- No DPF filter changes/cleaning needed for 7380 hrs
- Vale Team worked with Supplier to Optimize Product
- Average Exhaust Backpressure 60 – 110 mbar
- Continuously maintains low NO_2 emissions levels
- Still being used in the mine and performing well

Mining-CRT ® function successfully demonstrated

	Engine Exhaust	Filter System Exhaust
NO_x	516.6	514.8
NO_2	26.3	23.9
Gas temp (°C)	488	381

The success of this operation is attributed to hard work and dedication of Vale's Copper Cliff Mine team lead by Kevin Watson, Brian McLean and Cory Patrakka of Toromont with support from Johnson Mattey (JM) Germany/USA, CANMET/CANADA, NIOSH/USA, VERT/Switzerland.

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Thank You

Questions

Mirarco MINING INNOVATION | National Resources Canada | Ressources naturelles Canada | VALE

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