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Evaluation of a Catalyzed Diesel Particulate Filter Coated by a Mixture of Novel Soot Oxidation and $DeNO_X$ Catalysts Using a Tier 2 Diesel Engine

Progress Report: Phase 3

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NOMENCLATURE/GLOSSARY

ISO: International Standards Organization

NO_x: Oxides of nitrogen

O_2: Oxygen

NO: Nitric Oxide

NO_2: Nitrogen Dioxide

CO_2: Carbon Dioxide

CO: Carbon Monoxide

C: Black carbon

THC: Total hydrocarbons

DPM: Diesel Particulate Matter

CDPF: Catalyzed Diesel Particulate Filter

FTIR: Fourier Transform Infrared Spectroscopy

BPT: Balance Point Temperature

PLT: Progressive Load Test

EXECUTIVE SUMMARY

The effectiveness of dual catalyzed diesel particulate filters (CDPF) to simultaneously oxidize diesel particulate matter (DPM) and reduce oxides of nitrogen (NO_x) using selective catalytic reduction (SCR) was examined on an engine connected to a dynamometer. CanmetENERGY provided one dual catalyzed diesel particulate filter (CDPF) for this study. Balance point temperature was determined on the CDPF according to DECSE program [1]. The CanmetENERGY CDPFs (further referred to as CDPF in the report) showed some capacity to oxidize diesel particulate matter. The balance point temperature (BPT) for the CanmetENERGY CDPF was found at 394°C.

Progressive load test (PLT) on the CDPF showed a weak relationship between catalyst inlet temperature and catalyst activity as determined by increases and decreases in base engine emission concentrations.

ISO 8178-C1 8-Mode testing was performed on the CDPF as an alternative emission test to simulate engine operation in mining environment. The effectiveness of the CDPF for DPM removal was found to be 88%. Over the 8-Mode testing cycle, the SCR catalytic component was only able to achieve an integrated reduction in NO_x emissions of 15%. Although total NO_x reduction was poor, the CDPF system was able to achieve an 84% reduction of NO_2.

Finally, the determined CDPF BPT of 394˚C is comparable to similar systems. However, the system did not regenerate completely, leaving DPM retained in the CDPF.

1 INTRODUCTION

The following report is a multipart study to determine the impact of dual catalyzed diesel particulate filter (CDPF) on diesel exhaust emissions. The objective of this study was to evaluate the performance of the CanmetENERGY dual CPDF installed on a diesel engine. The most common CDPF design uses a wall-flow ceramic monolith made of cordierite or silicon carbide, packaged in a steel case, as shown in Figure 1. The porous walls of the monolith are coated with the catalyst to promote chemical reactions between gaseous components and DPM trapped in the filter. The catalyst formulations for this CDPF were developed by CanmetENERGY to simultaneously remove NO_x and DPM from diesel exhaust. Several main simultaneous reactions occur in dual CDPF, as expressed by Equations 1 to 6.

$$4NO + 4NH_3 + O_2 \leftrightarrow 4N_2 + 6H_2O \quad (1)$$

$$2NO_2 + 4NH_3 + O_2 \leftrightarrow 3N_2 + 6H_2O \quad (2)$$

$$C + O_2 \rightarrow CO_2 \quad (3)$$

$$2C + O_2 \rightarrow 2CO \quad (4)$$

$$C + 2NO_2 \rightarrow CO_2 + 2NO \quad (5)$$

$$C + NO_2 \rightarrow CO + NO \quad (6)$$

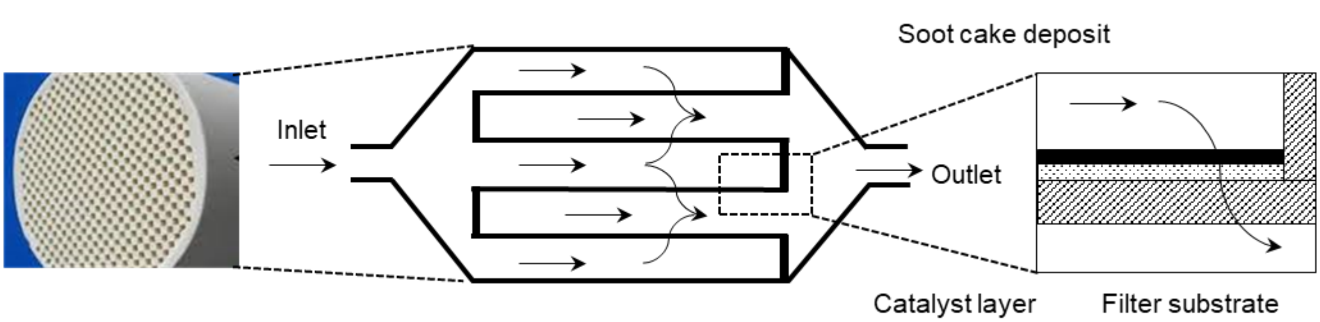

Figure 1 - Catalyzed Diesel Particulate Filter (CDPF) with a cross-section of the CDPF wall

Current diesel engine aftertreatment systems are complex and cumbersome and can include a diesel oxidation catalyst (DOC) for carbon monoxide (CO) and hydrocarbon (HC) removal, DPF for DPM control and selective catalyst reduction of NO_x (SCR-NO_x) Figure 2). CanmetENERGY developed an innovative catalyst technology that aims to eliminate NO_x and DPM emissions simultaneously and reduce overall size of the diesel exhaust systems, by loading the SCR-NO_x and DPM oxidation catalysts into a wall flow filter (particulate filter). Filtration is possible with this design. By contrast, a flow through monolith does not trap DPM. Additionally, a wall flow filter enables the SCR catalyst to be positioned closer to the engine. Closer proximity to the engine means that exhaust enters the catalyst at a higher temperature, which leads to a quicker increase of the operating temperature for the SCR process. Other advantages are lower mass, cost and size of the combined system.

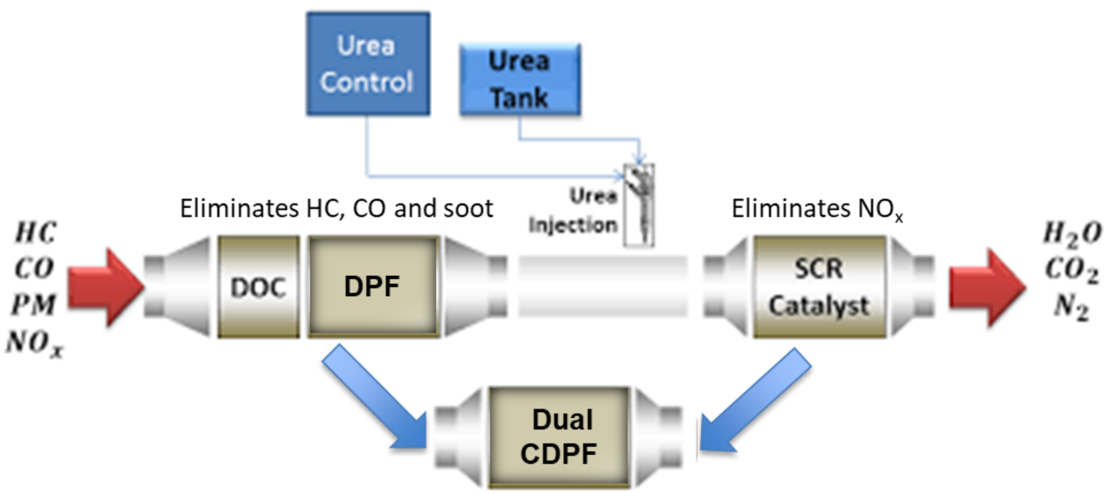

Figure 2 – Schematic of a typical diesel emission control system showing the combination of the DPF and SCR catalytic converter into one unit - CanmetENERGY dual CDPF

In work done previously, CanmetENERGY's catalyst mixture were tested under various locomotive operating conditions at bench scale and promising results were obtained [2]. The calculated NO_x conversion was greater than 95% between approximately 200-400°C under line-haul, switch and line-haul Notch 8 operating conditions. Furthermore, the catalyst was able to oxidize carbon black, which was used as a mimic of DPM[1], simultaneously under the same operating conditions in the temperature range of 400 to 600°C. Following these favorable results, the next step was to test the catalyst formulations on a relatively small diesel engine to determine its performance under real world conditions before potential testing on a larger locomotive engine.

2 EXPERIMENTAL METHODOLOGY

The effectiveness of the CDPF for DPM removal during engine operation conditions was assessed by measuring a balance point temperature (BPT). The BPT is the exhaust temperature at which combustion of DPM occurs at the same rate as DPM loading. The lower the BPT, the higher the filters' ability to remove DPM by oxidizing it with a catalyst. Additionally, the NO_x removal efficiency of the CDPF was determined as well as the impact of the converter on CO emissions. The NO_x removal efficiency, represented as a change in NO_x concentration between the inlet and outlet of the CDPF (Change %), is determined by the equation:

$$\text{Change \%} = 100 \times (NO_{x\ out} - NO_{x\ in}) / NO_{x\ in}$$

where $NO_{x\ out}$ is outlet NO_x concentration from the CDPF and $NO_{x\ in}$ is inlet NO_x concentration from the engine. The CO (or NO_2) removal efficiency was calculated with a similar equation using the difference between inlet and outlet CO (or NO_2) concentrations.

1 In fundamental studies, commercial carbon black is used as a diesel soot mimic because of similar morphology and particle size. This means that a catalyst was mixed with carbon black instead of diesel PM.

2.1 CDPF Preparation

CanmetENERGY provided the dual catalyzed diesel particulate filter (CDPF) for laboratory engine tests. A mixture of two novel catalysts (soot oxidation and deNO$_x$ catalysts) were loaded using a slurry forcing method on a commercial cordierite wall-flow monolith of 200 cpsi with a wall thickness of 0.3 mm, geometric dimensions of 23.0 cm × 30.5 cm (diameter × length) and a volume of 12.7 L. After drying and calcination, the CanmetENERGY CDPF was manufactured (referred to as CDPF in this report).

2.2 Fuel Properties

The diesel fuel used for this study is an ultra-low-sulphur mining diesel fuel with a sulphur value of 7 mg/kg (7 ppm). This fuel was analyzed by CanmetENERGY, and a copy of the fuel analysis results is given in Annex 2.

2.3 Engine Test Setup

The engine used for the testing was a Deutz F6L914 Tier 2 light duty diesel engine, rated at 71.5 kW at 2300 rpm. This engine complies with the CSA M424.2-16 standard for application in Canadian non-gassy underground mines (CANMET Approval #1312X). Table 1 provides engine specification data.

Table 1 - Engine Specification Data

Make	Deutz
Model	Deutz F6L914 T2
Serial number	87299570
Displacement	6.5 Liter
Rated power	71.5 kW @ 2300 rpm
Fuel rate at rated power	17.1 kg/hr
Peak torque	350 N.m @1500 rpm
Aspiration	Naturally aspirated
Fuel system	Mechanical
Max air intake restriction-clean air filter	3 kPa

Max exhaust backpressure	7.5. kPa
Low idle speed	650 rpm
High idle speed	2480 rpm

The overall experimental setup shown in Figure 3 consisted of a Deutz light duty diesel engine installed in the engine dynamometer lab and the CDPF. There was no diesel oxidation catalyst (DOC) in front of the filter. The engine exhaust flow was separated into 2 streams using a splitter control valve. The setup was controlled to allow the highest flow through the filter while limiting the difference in pressure across the filter to no more than 2 kPa. The pressure drop, and inlet and outlet temperatures of the filter were monitored by a differential pressure sensor and temperature thermocouples and logged with the laboratory ECCS (Emissions Cell Control System).

1 - Deutz test engine
2 - Ammonia static mixer
3 - CDPF unit
4 - Pre-CDPF sample port
5 - Post-CDPF sample port
6 - FTIR gas analyzer
7 - Heater sample lines
8 – Cylinder with ammonia

Figure 3 - Overall engine test setup with instrumentation for the CDPF evaluation

2.4 CDPF Performance

The effectiveness of the CE-O CDPF for DPM removal was assessed by determining the BPT. The emission characteristics were measured using a progressive load test (PLT) and 8-mode test cycle at the CanmetMINING laboratory, which is registered to ISO 9001:2000 standards. The full test procedures are given in APPENDIX C.

2.4.1 De-greening of CDPF

De-greening of CDPF was performed prior to assessing its performance characteristics. The purpose of the de-greening procedure was to break-in the CDPF and to establish steady baseline emission levels from the device before conducting further testing. The CDPF was exposed to engine emissions over a period of five (5) days. The five-day period is based on both experience and observed stability of measured emissions. The two test points selected were from the ISO 8178-C1 8-mode test cycle, Mode 4 (loading cycle) and Mode 1 (un-loading cycle). In this procedure the CDPF was run daily through a series of exhaust exposure cycles. Each cycle started with one hour of DPM loading (Mode 4) followed by one hour lighting-off of DPM (Mode 1:). This procedure was repeated for three cycles in succession for a total 6 hours per day. Gaseous emissions were measured on the final point of each day at Mode 1, with and without NH_3 injection.

2.4.2 Determination of Balance Point Temperature (BPT)

A test procedure to determine BPT was developed based on a progressive load test (PLT) in accordance with the Diesel Emission Control-Sulfur Effects (DECSE) Program [1]. An example of the DECSE test run is shown in Figure 4. The procedure involved preloading the filter with DPM at constant engine speed of 2300 rpm and at ~ 10% load over 16 hours according to ISO 8178 test cycle point Mode 4 to maintain catalyst temperature below its activation temperature (~ 200°C). Both inlet CDPF exhaust temperature and differential pressure measurements were made to monitor the loading rate.

After DPM preloading, the filter was exposed to the split exhaust to perform the progressive load test. During this test, the engine exhaust temperature was increased gradually by increasing the engine load. The engine torque was increased slowly in small (e.g., 1 minute) steps. Each step lasted a minimum of 10 min. Corresponding values of torque, temperatures and the pressure differential across the filter were recorded during the load ramp up. The results were plotted in the coordinates of pressure drop versus temperature. The temperature at which the pressure drop equaled zero was reported as the filter BPT (Fig.5) according to Majewski et al. [3].

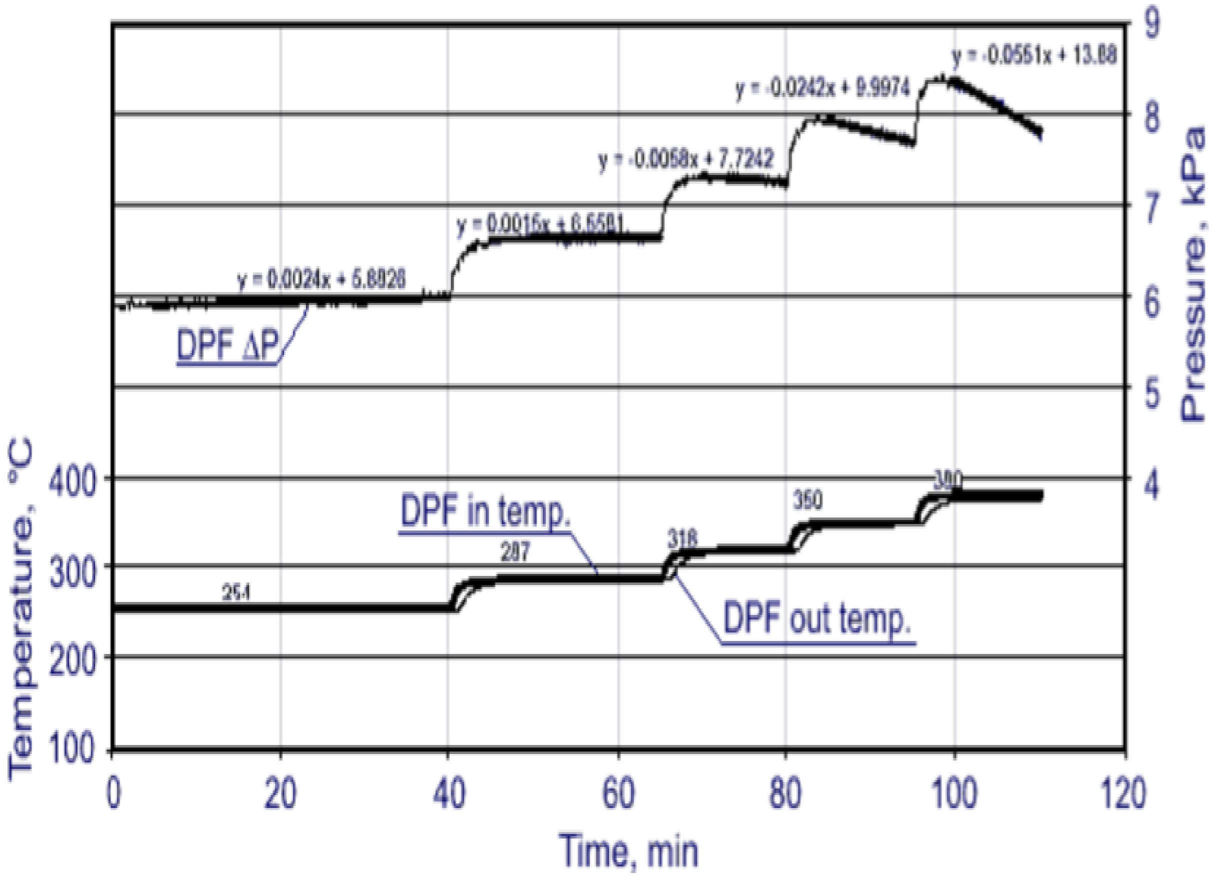

Figure 4 - DECSE 5-Mode BPT Test - Example Run Data from reference [1]

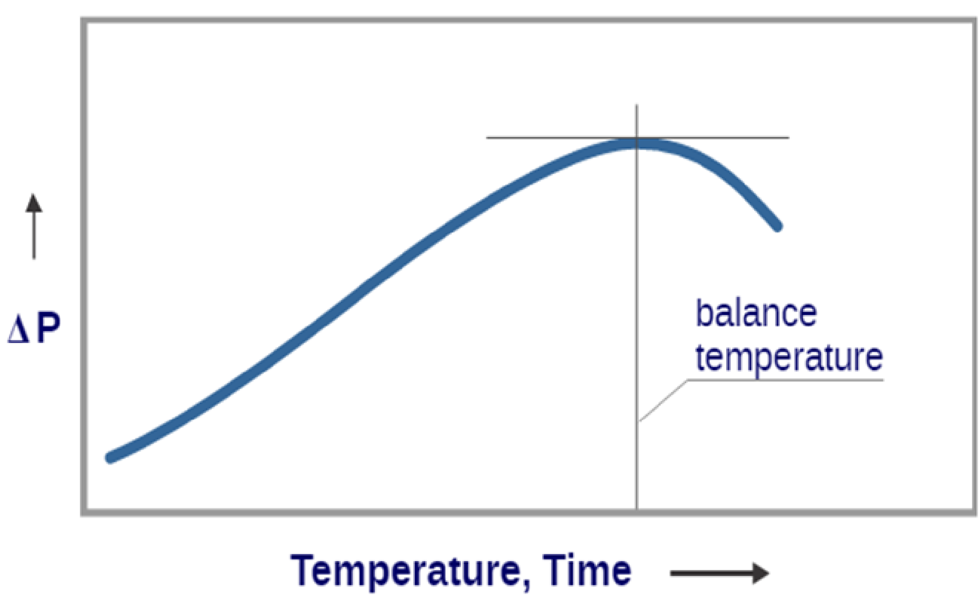

Figure 5 – Determination of the filter BPT from reference [3]

2.4.3 Progressive Load Test (PLT)

The progressive load test is used to generate a performance curve for CDPF over its entire operating temperature range. The PLT is achieved by setting the engine at peak torque speed and slowly increasing the engine load by increasing fuel flow. The engine exhaust flow is set to the catalyst manufacturer's design point and the exhaust temperature gradually increases as the engine load is increased, thereby heating up the CDPF. At a given temperature, the CDPF will start to work and its conversion efficiency will increase. The progressive load test is useful in comparing different engine operating points against one another and to determine the operating ranges where CO, total hydrocarbons (THC) and DPM are reduced and where NO_2 formation is possible.

The PLT cycle was carried out at engine's peak torque speed (1500 rpm) with ammonia (NH_3) injection in the exhaust, whereas there was no NH_3 injection during BPT determination. For this cycle, all engine basic conditions such as temperature and back pressure were monitored. The CDPF inlet exhaust gas temperature was increased gradually per step by increasing the engine load, where corresponding values of torque and temperature were recorded. This required testing at eighteen (18) points from zero load to the maximum load. The final PLT results are shown in Figure 6. During this test, gaseous emissions including carbon monoxide (CO) and nitrogen oxides (NO_x) were analyzed by a Fourier transform infrared (FTIR) gas analyzer continuously at each point before (inlet port) and after (outlet port) the CDPF.

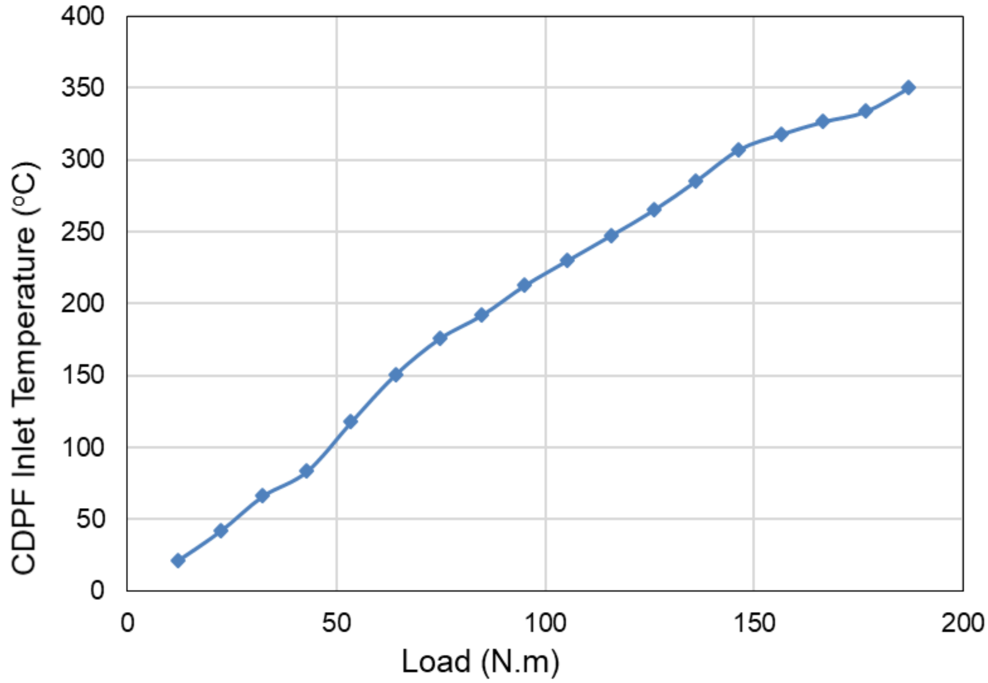

Figure 6 - Progressive Load Test: CDPF inlet temperature versus engine load at peak torque speed

2.4.4 8- Mode test cycle

The engine exhaust emissions were measured at the CDPF inlet and outlet ports of the ISO 8178-C1 8-Mode test cycle for non-road engine application. The 8-Mode test cycle for the Deutz F6L914 engine is defined in Table 2. Prior to the 8-Mode tests, the engine intake restriction at Mode 1 was adjusted to a maximum allowable value of 3 kPa for the engine, and similarly exhaust backpressure at Mode 1 was adjusted to a maximum allowable value of 10 kPa for all test cycles. The exhaust backpressure CDPF inlet and outlet pressure, and exhaust temperature at the inlet and the outlet of the devices were also measured. PM was analyzed using a Sierra BG-3 partial flow dilution sampler.

Table 2 - ISO 8178-C1 8-Mode test cycle

Mode #		1	2	3	4	5	6	7	8
Engine Speed, rpm		2300				1500			600
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

3 RESULTS AND DISCUSSION

3.1 CDPF de-greening

The Deutz F6L914 engine was run at rated power to set the engine intake air restriction at the maximum value for clean filter, and exhaust back pressure at the maximum value allowed by the engine manufacturer.

The CDPF was de-greened using the Mode 1 and Mode 4 test cycles. Initial plans were to run at Mode 2 and Mode 4 but was changed because of insufficient temperature to regenerate the CDPF at Mode 2. Thus, in this report, Day 1 test results (Mode 2) are not reported.

Figure 7 shows engine NO_x emissions concentration (ppm) and % change in NO_x concentration at Mode 1 per day of de-greening with NH_3 injection. The average CDPF inlet temperature was 471°C. As can be seen from the figure, the NO_x conversion had stabilized by Day 5. The average NO_x concentration change was ~ 25% at an average CDPF inlet temperature of 471˚C.

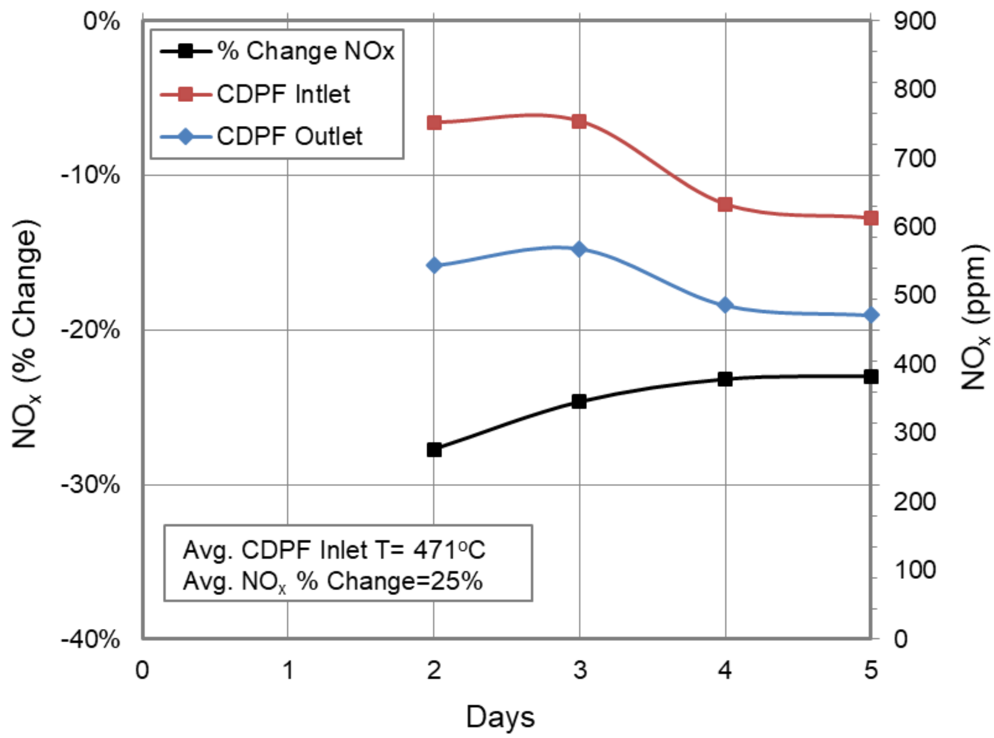

Figure 7 - Engine Exhaust NO_x concentration and % change at Mode 1 per day of de-greening

Figures 8 and 9 show that the CO and THC emissions increased and decreased respectively over the baseline engine values over the 5-day de-greening period. CO emissions had increased by ~ 12% at Mode 1 on Day 5. Finally, THC emissions showed an average reduction of ~59% over the five-day de-greening period and had stabilized by Day 5. Overall, the CDPF emissions in general stabilized to meet the objective of de-greening of the CDPF in preparation for further testing. Appendix D shows engine condition and full emissions summary over five days of testing for CDPF de-greening.

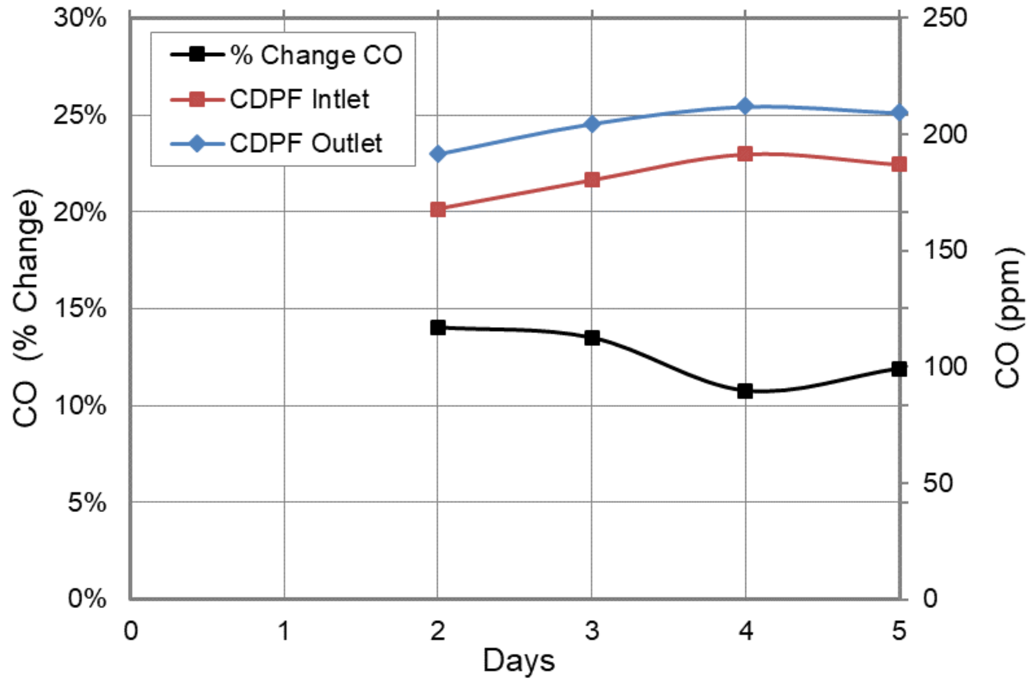

Figure 8 - Engine Exhaust CO concentration and % change at Mode 1 per day of de-greening

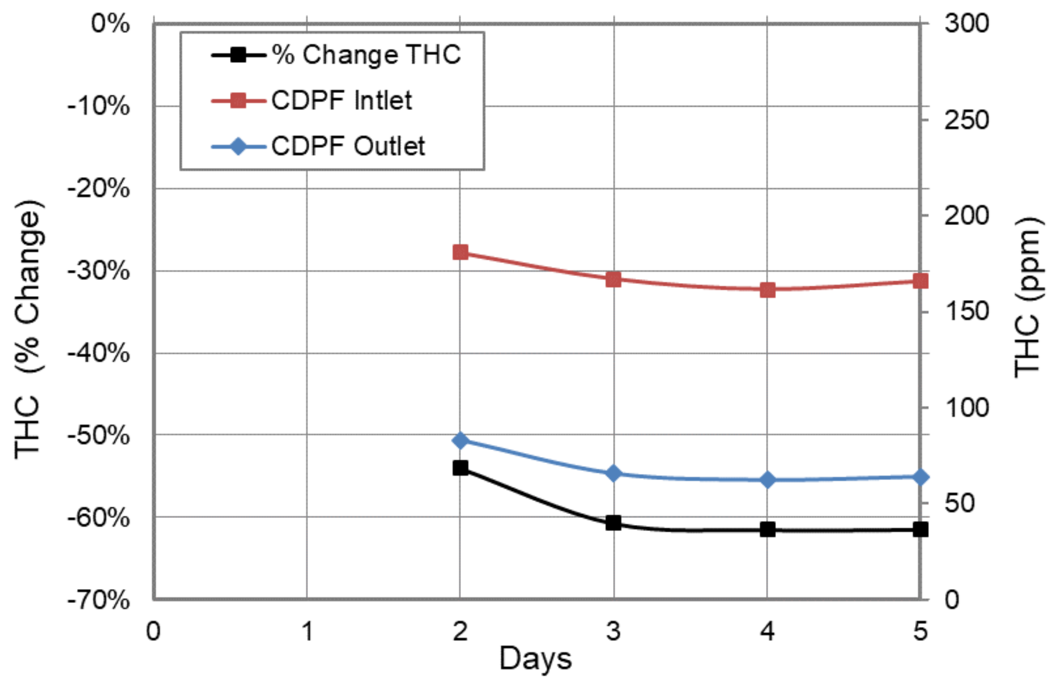

Figure 9 - Engine Exhaust THC concentration and % change at Mode 1 per day of de-greening

3.2 BPT determination test

3.2.1 DPM pre-loading on CDPF

Figure 10 shows the CDPF differential pressure drop during the DPM loading cycle. In general, the differential pressure increased in time at Mode 4 while engine load remained relatively stable. The average filter inlet temperature was 193°C. The DPM mass collected inside the filter was weighed as 144 g after 16 hours of engine operation. Loading was sufficient for BPT determination.

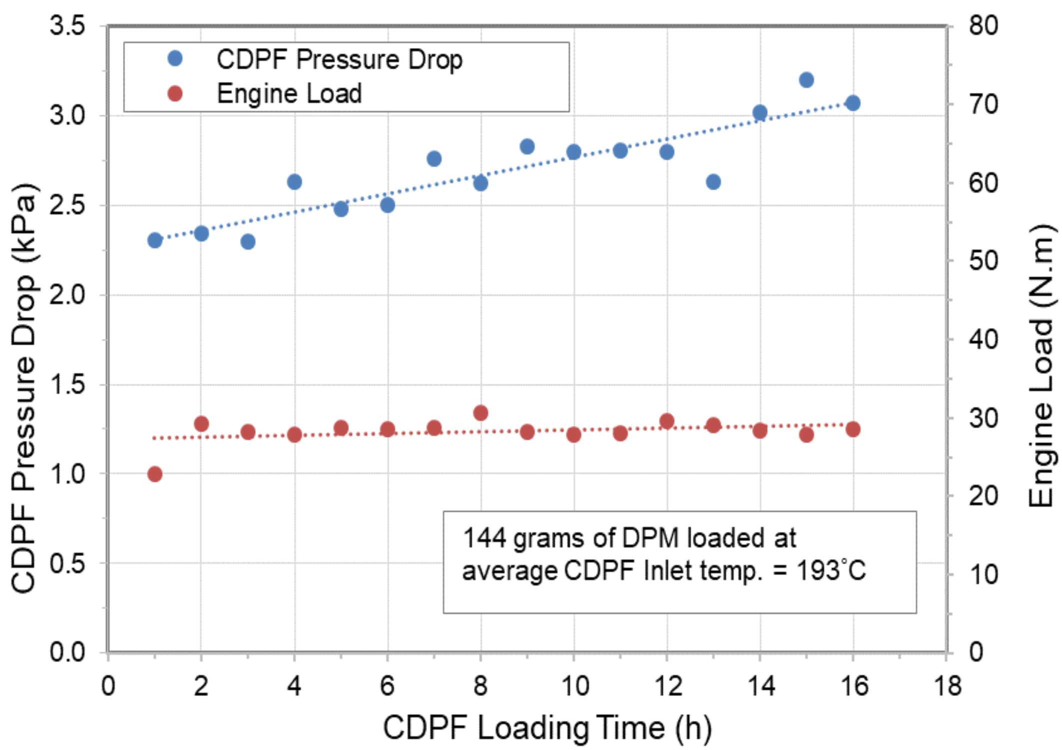

Figure 10 - CDPF differential pressure drop during the DPM loading cycle (linear trend lines shown in dashes)

3.2.2 Balance point temperature

After the DPM-loading process, the efficiency of the CDPF for DPM removal was evaluated via a BPT measurement without ammonia injection during the progressive load test. Figures 11A depicts the BPT test results. The exhaust temperature increased with the filter loading monotonically (red line). The pressure drop across the filter increased clearly with the engine loading in the temperature range from 100 to 350°C that corresponded to the first phase on the graph (Fig.11A). Once the temperature reached a certain point above 350°C (the second phase), differential pressure changed direction from positive to zero as shown in Figure 11A in the second area from testing point 14 to 16. The best estimate of the BPT was performed at the point where the slope of differential pressure changes from positive to negative (test point 15 in Fig.11B). The third phase of the test represents temperatures > 416°C showing the increase of differential pressure with further engine load due to the DPM loading being higher compared to the rate of DPM oxidation. The value of the CDPF BPT of 394 °C was finally determined.

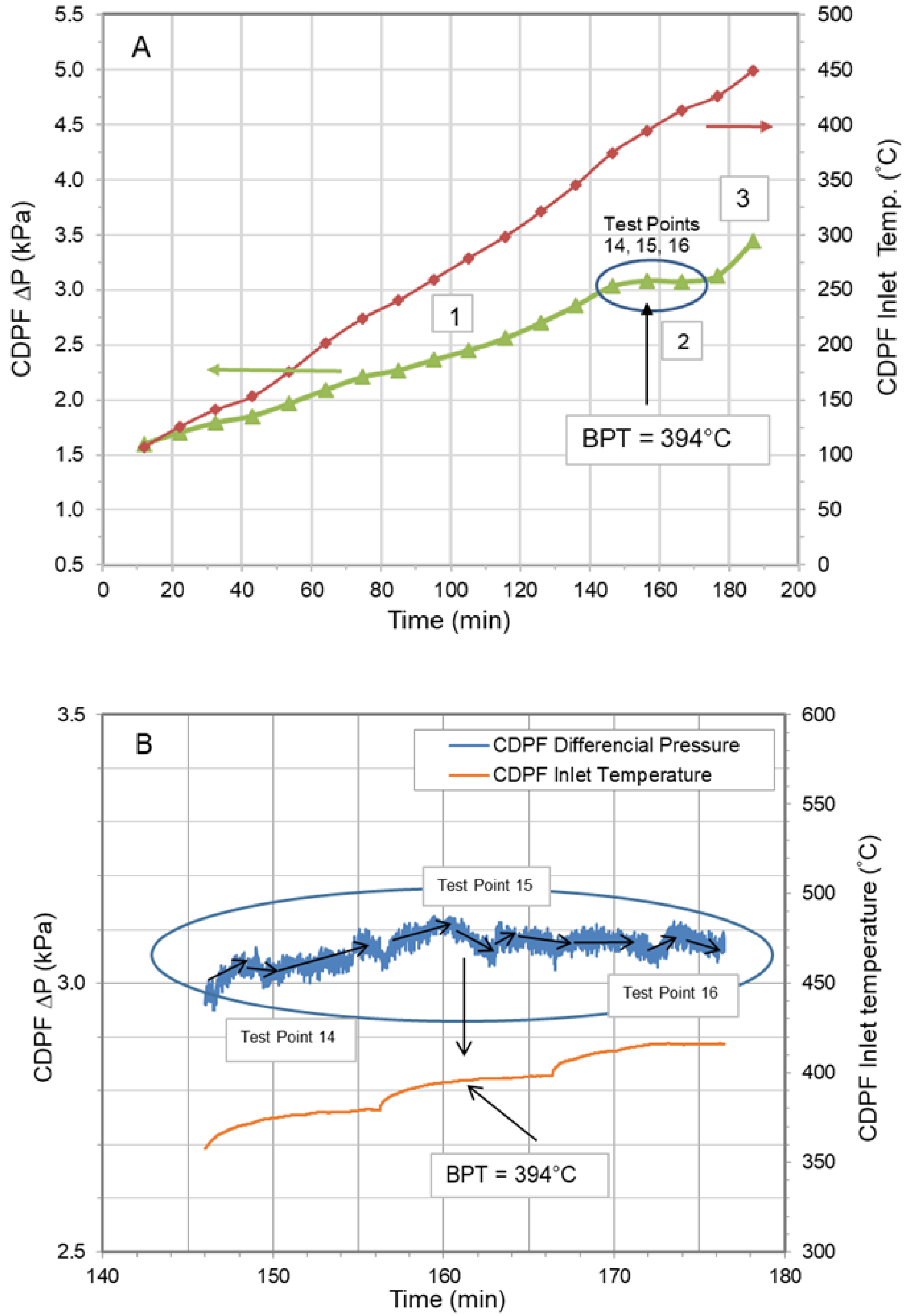

Figure 11 – (A) CDPF differential pressure drop and CDPF temperature drop during CDPF BPT determination; (B) inset of the circled area 2

3.3 Emission test results

3.3.1 Progressive load test during balance point temperature measurements (no NH_3 dosing)

As described in the previous section, for the BPT determination, the PLT cycle was run at 1500 rpm at eighteen load points without NH_3 injection. Gaseous emission concentrations were measured at the CDPF inlet and outlet ports for CO, NO_2, and NO. The obtained results are shown in Figures 12, 13 and 14.

Gaseous CO emissions were essentially the same for the inlet and outlet up to ~300°C (Fig. 12), then steadily increased above base engine emissions up to ~450°C. A small increase in CO concentration at the outlet compared to inlet was observed in the temperature range from 300 to 450°C. This difference could be due to incomplete combustion of trapped DPM.

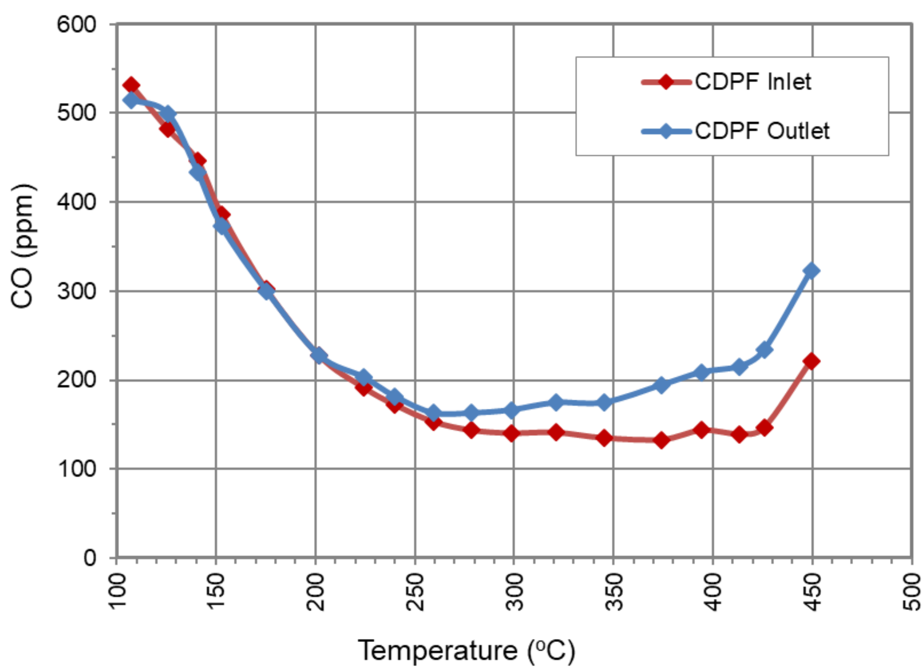

Figure 12 - Engine exhaust CO concentration versus temperature as measured at the CDPF inlet

Gaseous NO_x emissions showed some minor variations between inlet and outlet of the filter as shown in Figure 13. Overall NO_x conversion was a result of the NO_2 concentration decrease.

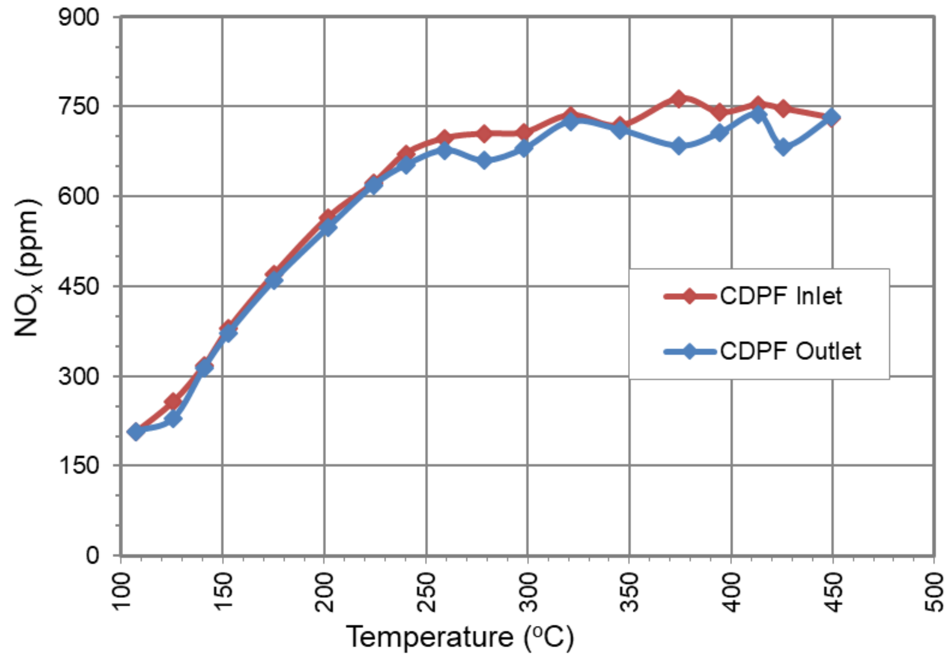

Figure 13 - Engine exhaust NO_x concentration versus temperature as measured at the CDPF inlet

The NO_2 concentration decrease appeared over a broad temperature range. In the temperature range from 150 to 450°C the continuous decrease in the filter inlet NO_2 concentration was observed because the thermodynamic equilibrium shifted towards NO and O_2 at high temperatures [4]. The outlet NO_2 concentration changed differently. At relatively low temperatures (<300°C) high decrease of NO_2 in the outlet port might be due to its adsorption on the surface of the catalyst inside the CDPF. With temperature increasing, nitrates decompose and released NO_2 may convert to NO through DPM oxidation. Oxidation of soot by NO_2 is a well-known mechanism for DPF regeneration (eq. 5 and 6) [5]. Without catalyst assistance, DPM oxidation by NO_2 can occur at temperatures from 300 to 450°C compared to DPM oxidation by O_2 at 450–600°C.

Platinum-based catalysts accelerate soot oxidation by producing NO_2 from NO that results in lowering the temperature range by 50 – 100°C for soot oxidation in the presence of NO [6]. The total amount of NO_x did not change significantly during DPM oxidation due to the back reduction of NO_2 to NO.

Overall, the catalyst coating of the CDPF did not produce extra NO_2 at all exhaust temperatures as shown in Figure 14.

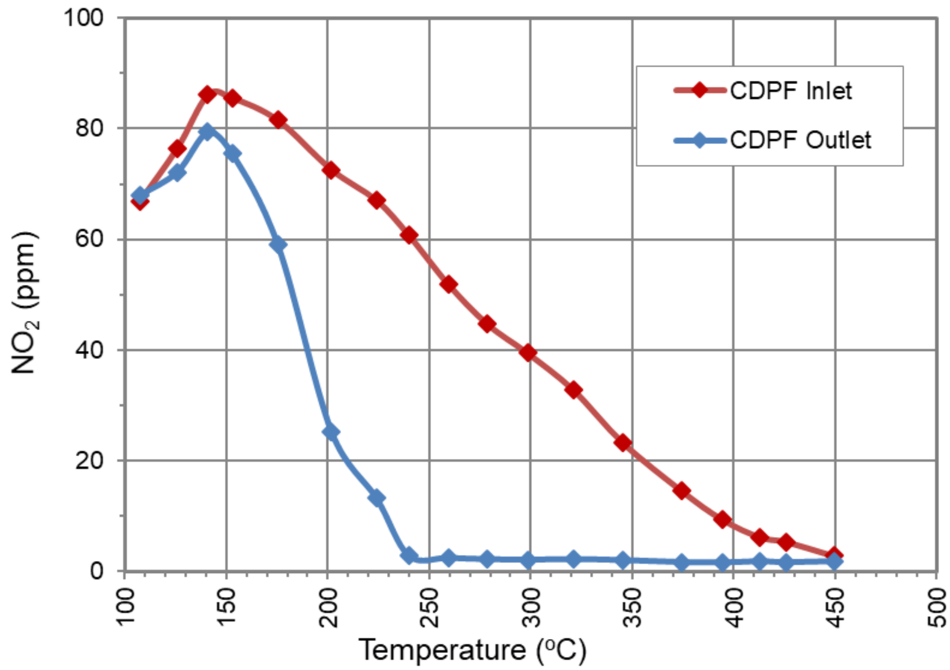

Figure 14 - Engine exhaust NO_2 concentration versus temperature as measured at the CDPF inlet

3.3.2 Emission test during progressive load test with NH_3 dosing

The PLT test cycle was repeated for eighteen load points with NH_3 injection to assess the performance of the CDPF for NO_x and CO conversion. It should be noted that 75 grams of DPM remained in the CDPF filter after completion the BPT determination test. The obtained results are shown in Figures 15, 16, 17 and 18. Changes in CO emissions over temperature were similar to the trend obtained in the absence of ammonia in the feed.

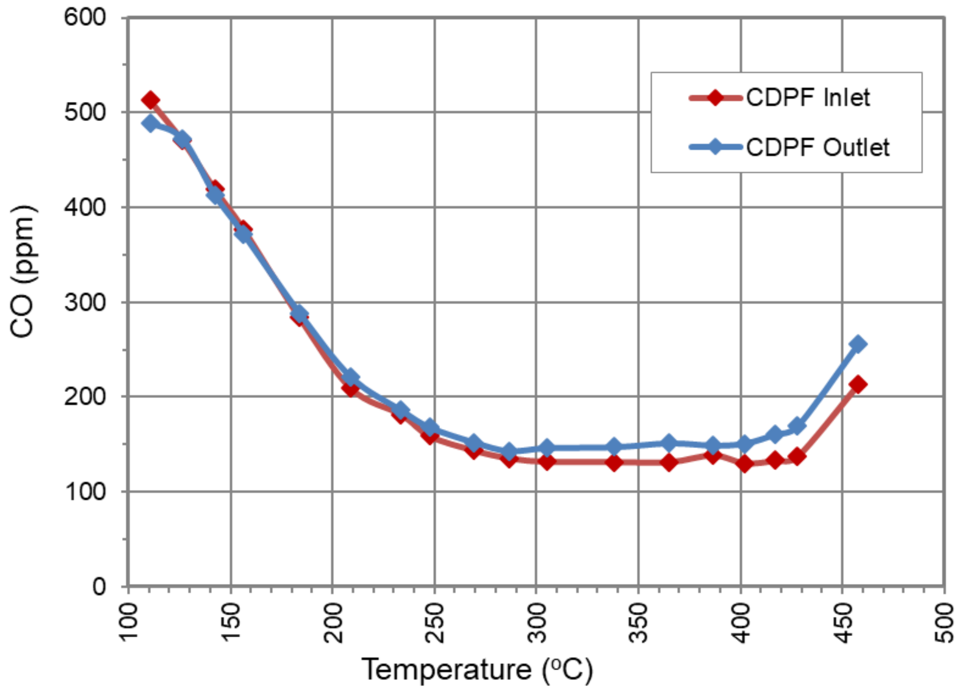

Figure 15 - Engine exhaust CO concentration versus temperature as measured at the CDPF inlet

The overall impact of the CDPF on NO_x emissions was not pronounced since both inlet and outlet NO_x concentration curves were close as shown in Figure 16. NO_x conversion remained virtually the same as reported in the PLT without NH_3 injection except the temperature range between 400-450°C where some additional NO_x conversion does occur. The differences in NO_x concentrations at high temperatures can be explained by reduction of NO_x with the SCR catalyst assistance (eq.1 and 2). DPM is likely to oxidize at this temperature region as observed from the BPT values. Therefore, the DPM-covered SCR catalyst became partially clean and could react with ammonia and NO_x. On the other hand, to achieve a high catalytic reduction of NO_x, a high ratio of NO to NO_2 needs to be present in the feed (fast SCR mechanism). In the temperature range from 200 to 450°C, NO_2 concentration decreased continually (Fig. 17) by reasons discussed in the previous section.

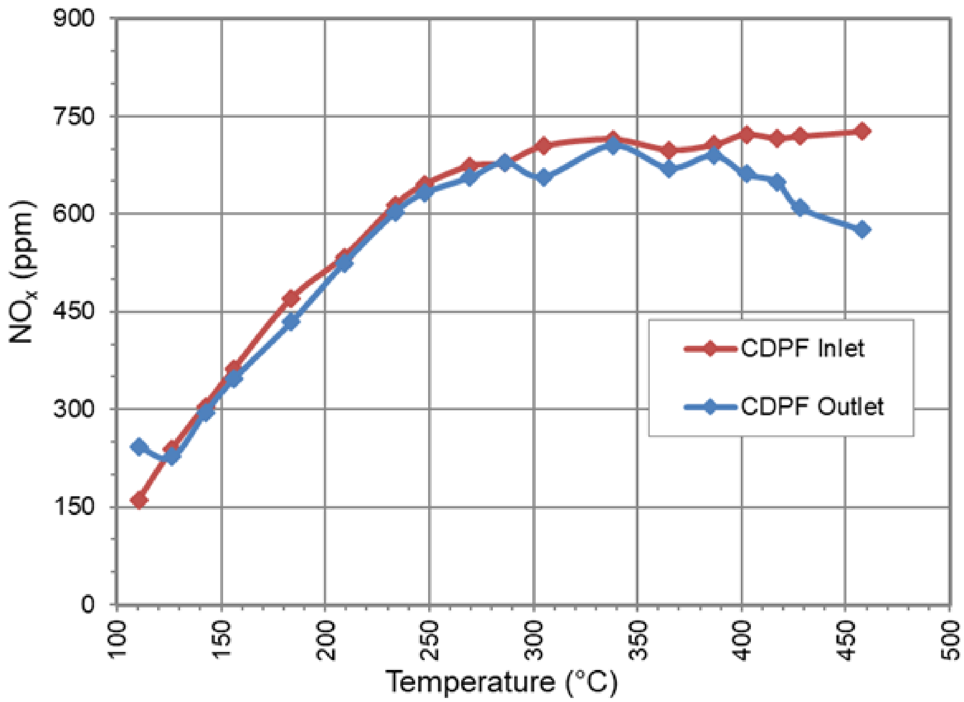

Figure 16 - Engine exhaust NO_x concentration and temperature as measured at the CDPF inlet

Figure 17 displays the variation in NO_2 concentration for different loading conditions. It can be seen that the presence of ammonia in the exhaust did not change the general trend in NO_2 concentrations with the temperature (Fig. 14 vs Fig. 17).

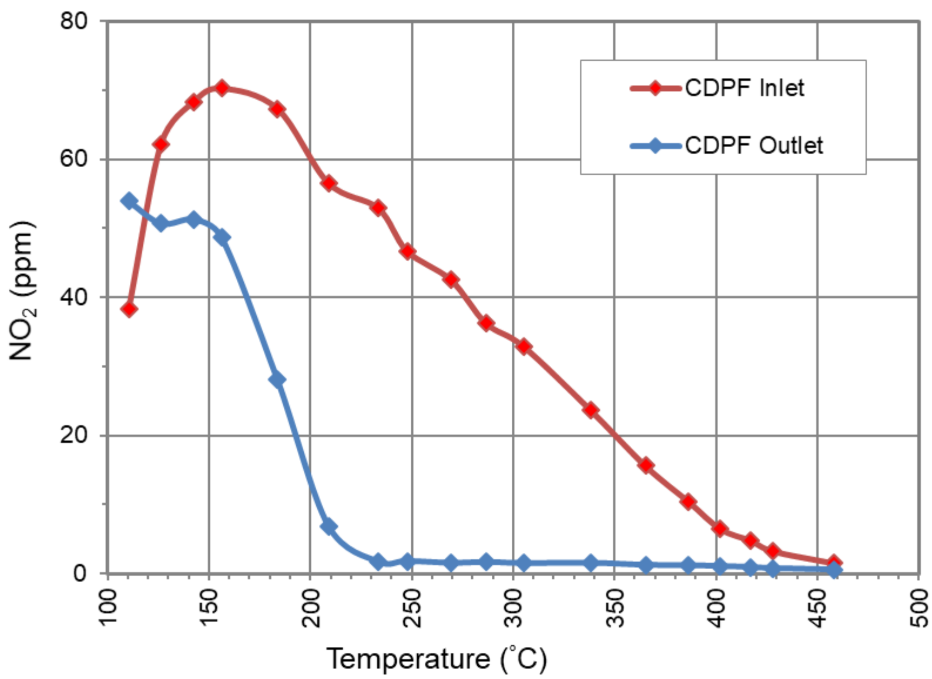

Figure 17 - Engine exhaust NO_2 concentration and temperature as measured at the CDPF inlet

3.3.3 Emission 8-Mode Test

Figures 18 and 19 show a concentration and change of NO_x concentration as measured at the CDPF inlet and outlet ports through the entire 8-mode test cycle. For the 8-Mode test, NO_x concentration (Fig. 18) was weakly related to CDPF inlet temperature with peak conversion at Mode 1 and lowest conversion at Mode 6.

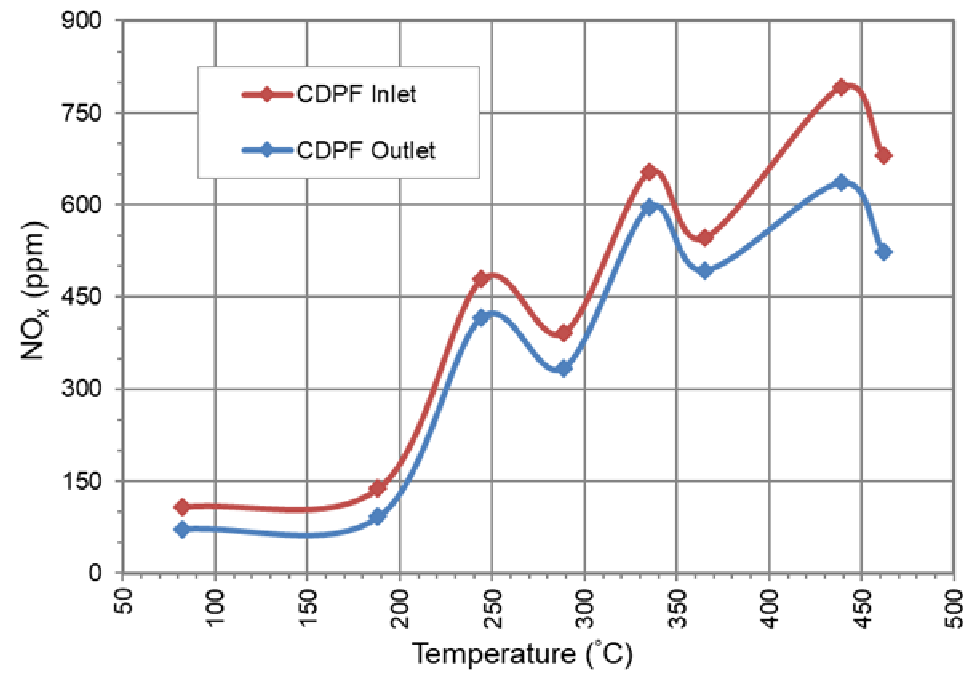

Figure 18 - Engine exhaust NO_x concentration versus CDPF inlet temperature

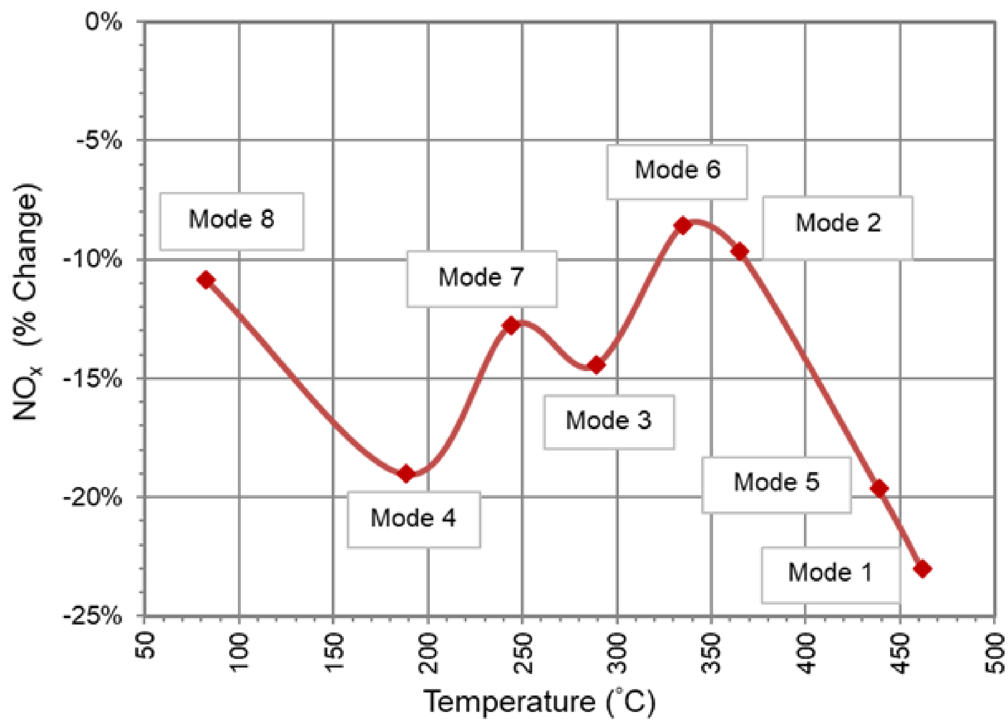

Figure 19 – % Change in NO_x concentration between inlet and outlet of CDPF versus CDPF inlet temperature

Figure 20 shows NO_2 emissions measured during the 8-Mode test cycle. The NO_2 reduction appeared over a broad temperature range very similar to the PLT test results with ammonia dosing. Most of the NO_x conversion was a result of NO_2 decreasing in front of CDPF (inlet concentration) up to 450°C, and after the catalyst treatment where NO concentration began to increase (Figure 21).

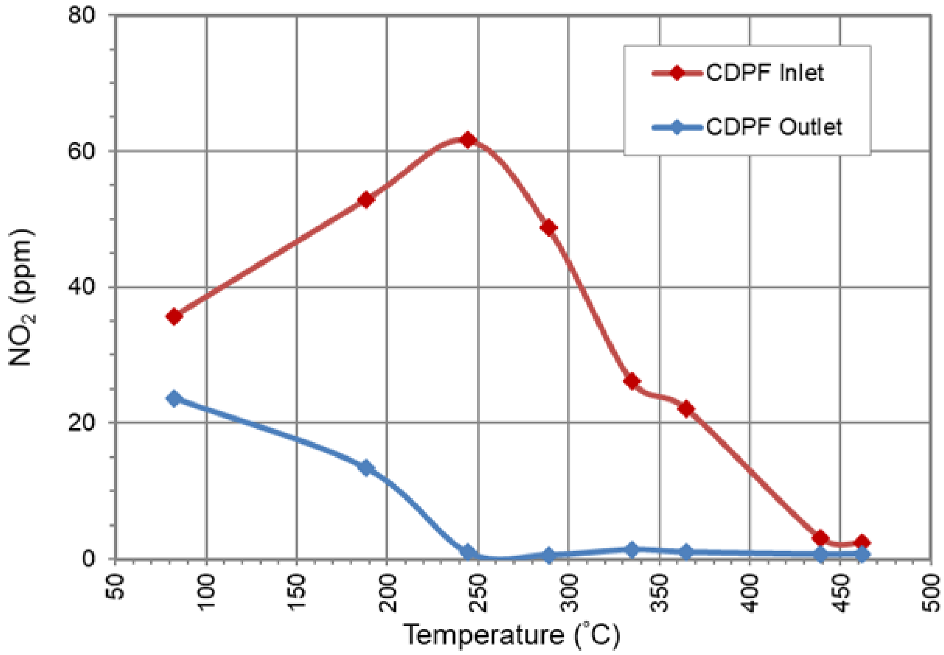

Figure 20 - Engine exhaust NO_2 concentration versus temperature as measured at the CDPF inlet

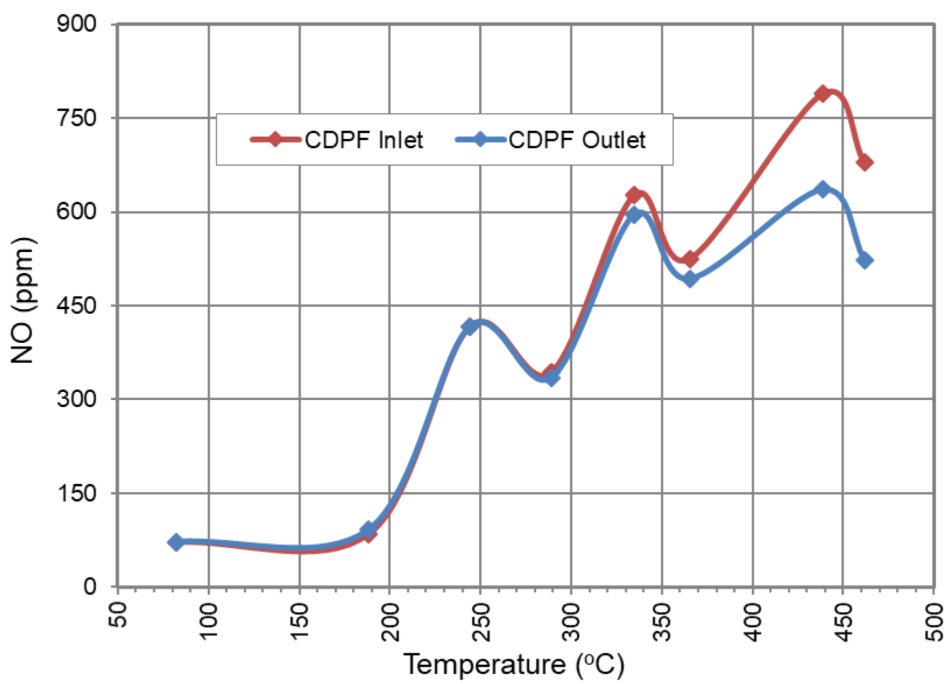

Figure 21 – Engine exhaust NO concentration versus CDPF inlet temperature

As stated previously, gaseous CO emissions measured during the 8-Mode test cycle showed some minor increase as measured at the CDPF inlet and outlet ports. This observation (Figure 24) agrees with the emission results obtained during the PLT.

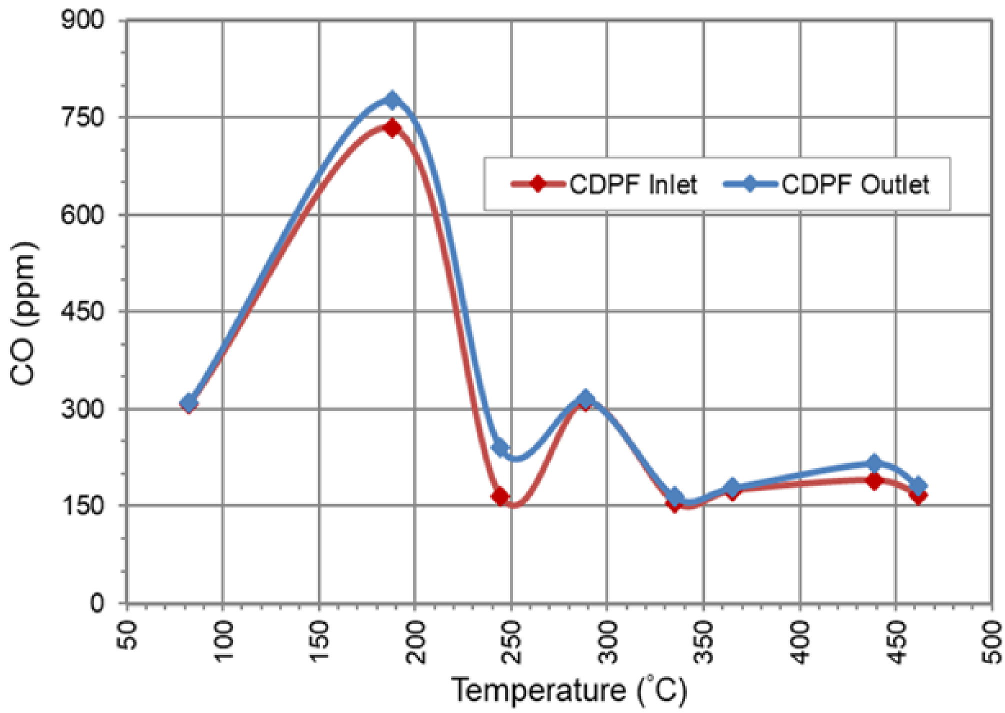

Figure 22 – Engine exhaust CO concentration versus CDPF inlet temperature

The average percentage of emission changes were calculated from the 8-Mode test. At an average CDPF inlet temperature of 300˚C, the gas concentrations through the CDPF increased for CO by 7.1%, reduced for NO_2 by 79.9%, and converted for NO_x by 15.4%. DPM through the CDPF was reduced by 88%, which is near the lower limit for this DPF model type. A summary of engine exhaust emissions measured before and after the CDPF for the 8-Mode test cycle calculated according to the ISO 8178 method are given in Table 3 below.

Table 3 - CDPF Integrated 8-Mode Emissions

Specific emissions		CDPF Inlet	CDPF Outlet	Emission Change (%)
	Units	Average	Average	
CO	ppm	269	288	+7.1
NO_2	ppm	31	6	-79.9%
NO	ppm	435	388	-10.8%
NO_x	ppm	465	394	-15.4%
DPM	g/hr	3.86	0.46	-88.0%

The CDPF BPT was 394°C, which is comparable to similar commercial systems. However, the CDPF did not regenerate completely under operating conditions, retaining unburnt DPM in the CDPF. At temperatures from 350 to 550°C, DPM started to oxidize but the rate of reaction is not sufficient to balance the DPM accumulation rate at higher engine loads. Additionally, the high length/diameter ratio of the substrate may impact the DPM build up in channels.

The SCR catalyst component showed only 15% reduction in NO_x whereas initial performance (after de-greening) was found to be a 24% reduction in NO_x. Both NO_x conversion values are well below what was seen in the lab-scale reactor tests (Appendix A). There are some possible explanations for this unexpected drop in NO_x reduction. First, high DPM loading, which was found to be occurring, blocks/plugs SCR catalyst active sites and renders them inaccessible/ unavailable for the SCR reaction [7]. Second, an abnormal rise in local temperatures due to exothermal DPM oxidation could thermally deactivate the SCR catalyst [8].

Moreover, the authors compared flow-through and wall-flow SCR catalyst designs and found that the flow-through unit has a NO_x conversion advantage due to better mass transfer. Additionally, the SCR reaction and soot oxidation are competitive for NO_2; thus, to obtain a high NO_x conversion efficiency, a ratio of $NO:NO_2 = 1:1$ needs to be maintained according to the reaction:

$$NO + NO_2 + 2NH_3 \leftrightarrow 2N_2 + 3H_2O$$

Finally, the SCR catalyst may be poisoned by hydrocarbons in the exhaust which are usually oxidized by DOC [9]. Consequently construction of a combined, dual-coated DPF/SCR system is challenging. There have only been a few commercial combined systems such as the Toyota combined SCR/DPF system but their use was mostly restricted to light-duty applications [10]. The attractiveness of a combined system for heavy-duty applications in terms of cost and packaging still remains. Further development of CDPF is recommended. A few options may be considered for improving the performance of CDPF in the future. For one thing, the order/sequence of catalysts could be altered to prevent the blockage of SCR catalyst by DPM. Additionally, the current soot oxidation catalyst may be replaced with another more active catalyst that is able to keep the levels of DPM low during typical engine operating conditions. Finally, a DOC unit (absent in this study/analysis/investigation) that can produce higher concentrations of NO2 for faster SCR reaction rates may be considered.

4- CONCLUSIONS

The CDPF component was effective at removing particulate matter emissions by 88% over the ISO 8178 cycle. The SCR component was only able to achieve an average reduction in NO_x emissions of 15%. The unexpected performance of the SCR component of the CDPF might be linked to the blockage of the SCR catalyst surface by DPM and making it impossible to react with NO_x. Thus, lower DPM loadings need to be maintained by using more active catalyst for DPM oxidation. Although total NO_x reduction was poor, the CDPF system did not produce extra NO_2, and even better the system was able to achieve 84% reduction of NO_2 for the ISO 8178 cycle.

The analysis of test results in this study provides future research directions for better dual CDPF functionality. Additional research could seek to improve activity and thermal stability of the SCR catalyst, change the ratio between the soot oxidation and SCR catalysts as well as coat each catalyst in different areas inside the CDPF. Further engine test studies could be performed with various DOCs of different sizes and efficiencies in front of the CDPF to optimize NO_2 concentrations.

ACKNOWLEDGEMENTS

The authors would like to than Vince Feres from CanmetMINING for performing the engine test and emissions measurements. The authors would also like to thank Raymond Burich for performing la-scale testing and the NH_3 dosing and emissions measurement for the test Dr. Maffei for his contribution to the catalyst synthesis and lab-scale testing.

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REFERENCES

1. Diesel Emissions Control Sulfur Effects (DECSE) Program, Phase 1, Interim Report 1, US Department of Energy, Washington DC (1999)

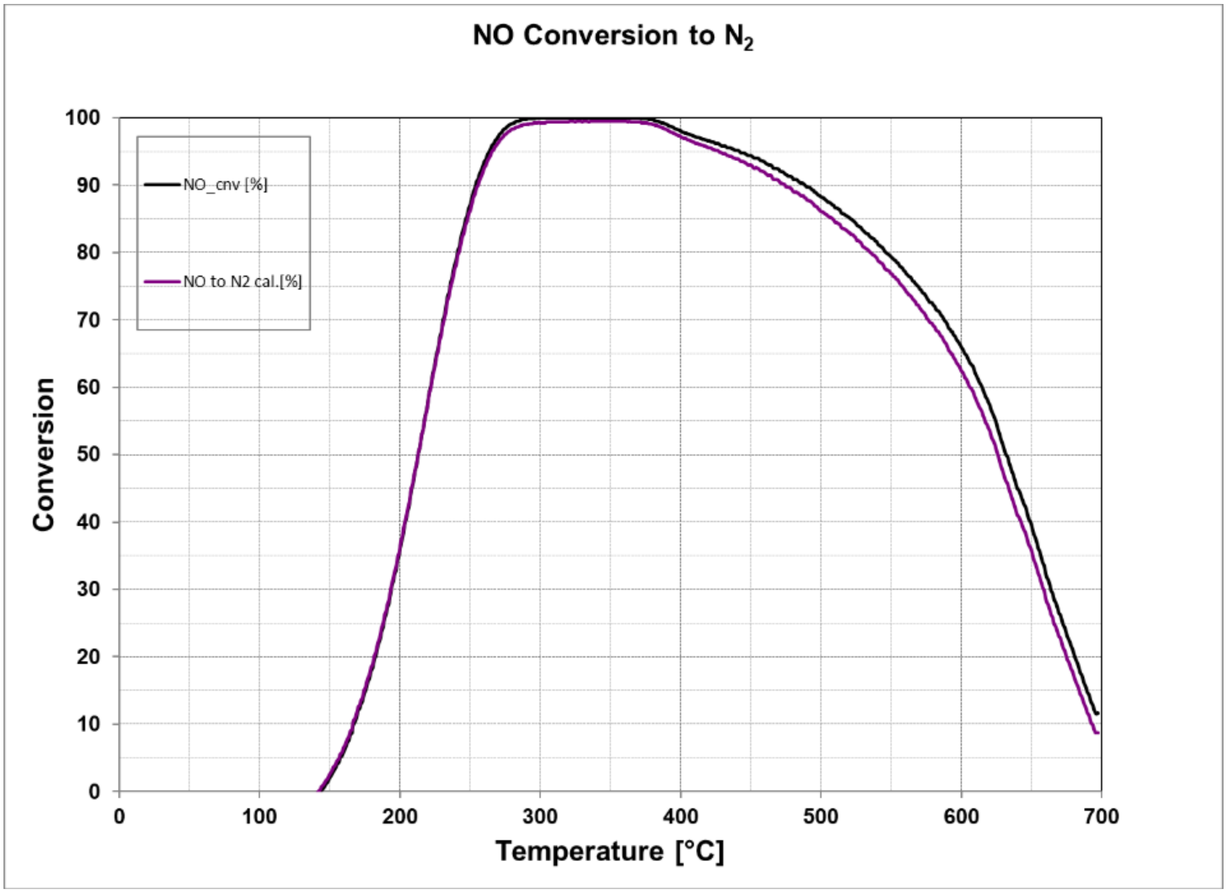
2. Caravaggio, G. Nossova L., Maffei N., Burich R, Two-in-one catalytic converter for simultaneous removal of NOx and PM for locomotives, Progress Report: Phase 2, April 2021
3. Majewski, W. A., Khair, M. K. “Diesel Emissions and Their Control”, Publisher: SAE International, Product Code of R-303, 2006
4. Heywood, John B. Internal Combustion Engine Fundamentals. New York: McGraw-Hill, 1988.
5. Zouaoui, N., Labaki, M., Jeguirim, M. “Diesel soot oxidation by nitrogen dioxide, oxygen and water under engine exhaust conditions: Kinetics data related to the reaction mechanism”, Comptes Rendus Chimie, v.17, p. 672-680,2014
6. Johnson Matthey: The Continuously Regenerating Trap. https://matthey.com/en/products-and-services/stationary-emissions-control/continuously-regenerating-trap-c-crt-systems
7. Oladipo, B., Bailey, O., Price, K., Balzan, N., Kau, S., “Simplification of Diesel Emission Control System Packaging Using SCR Coated on DPF”, 14th Diesel Engine-Efficiency and Emissions Research (DEER) Conference, Aug. 4 – 7, 2008
8. Devarakonda, M., “Technical Challenges in the Integration of DPF and SCR Aftertreatment on a Single Substrate – Review from a Systems and Modeling Perspective”, DOE-CLEERS Workshop, Dearborn, MI, April 28-30, 2009
9. Martinovic. F., Castoldi, L., Deorsola, F.A., “Aftertreatment Technologies for diesel engines: an overview of the combined systems”, Catalysts, v.11, p.653, 2021
10. Mizuno, T. and Suzuki, J., "Development of a New DPNR Catalyst," SAE Technical Paper 2004-01-0578, 2004

APPENDIX A

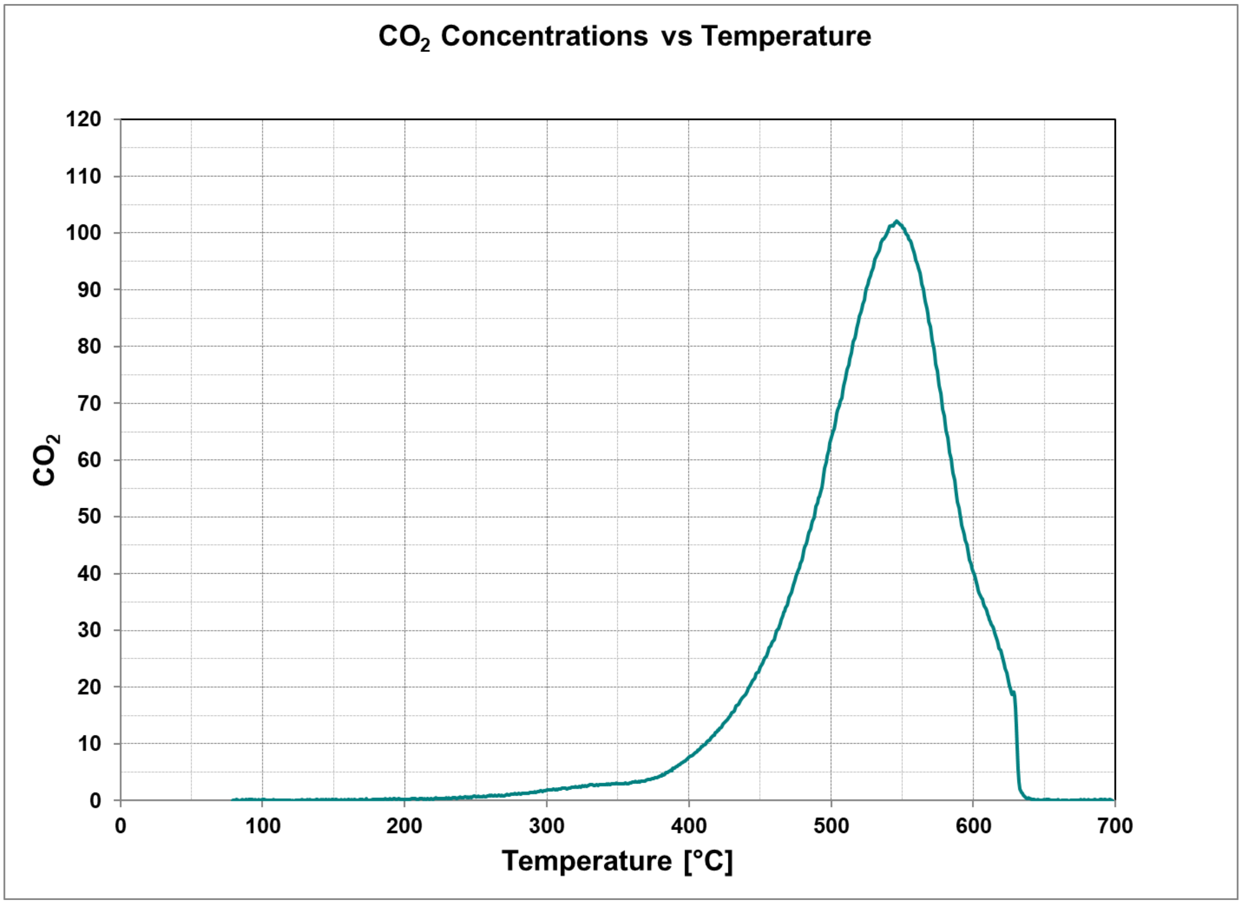
CanmetENERGY Catalyst Lab-scale Testing

NO conversion % and NO to N_2 conversion (Ramp200131 with Catalyst CETC190503_i')

Run conditions, simulated line haul locomotive: Flow 500 ml/min, O_2: 14.9%, CO_2: 4.4%, NH_3: 795 ppm, NO: 795 ppm, H_2O: 5%, balance nitrogen, GHSV: 65K h^{-1}, Catalyst:Carbon ratio 10:1, Loose contact, diluted with cordierite w/w = 1:1.



Soot oxidation (Ramp200131 with Catalyst CETC190503_i')



APPENDIX B

Mining Diesel Fuel Analysis

CanmetENERGY OTTAWA / CHARACTERIZATION LABORATORY
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clabc@nrcan.gc.ca

2015-04-28

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ISO 9001:2008
FS 64051

Client Name:	Mining and Mineral Science Laboratories	Group Number	15193
Project Code:	P-000005.001	Job Number:	
Due Date:	2015-04-28	Submitted by:	Brent Rubeili
Project Title:	CSA Mines Fuel	Index Date:	2015-04-21
Project Info:		Approved by:	Huena_Corbett

SampleNumber: 15193-01

CustomerSampleNumber: Mines Diesel

Submission Date: 2015-04-21

Comment Diesel Fuel

Test Results

Parameter	Method		
Carbon	ASTM D5291 modified	86.1	wt%
Hydrogen	ASTM D5291 modified	13.9	wt%
Nitrogen	ASTM D5291 modified	<0.15	wt%

Test Results

Parameter	Method		
Density @ 15°C	ASTM D4052	814.9	kg/m3
Flash Point, Pensky-Marten Closed Cu	ASTM D93	49.5	°C
Specific Gravity 60/60F	ASTM D4052	0.8156	GRAV
Sulphur	ASTM D7039	6.9	mg/kg

APPENDIX C

Test Procedure

ENGINE TEST Procedure – Deutz F6L914 T2 71,5 kW
Engine w/ CanmetENERGY
(Dual Catalyst CDPF)
P-002576.034

SAP# P- 002576.034 File ID: Deutz F6L914 T2 P-002576.034

Purpose: Laboratory Evaluation of CanmetENERGY Dual Catalyst CDPCs for balance point and NOx conversion efficiency

Test Protocol: De-greening of CDPF, Progressive load testing and balance point determination, and C1 test Cycle

Engine: Deutz F6L914, 6.5 L (8729570), Tier 2, rated at 88.4 hp @ 2300 rpm, 6 cylinder, naturally aspirated

General Engine Test Conditions:
Low idling speed: 870 rpm, high idling speed: 2480 rpm

Rated power: 2300 rpm, 202 ft.lb torque, 89 hp, 36.6 lb/h fuel, exhaust temp 979ºF (526°C)

Peak torque: 1500 rpm, 260 ft.lb torque, 74 hp, 27.6 lb/h fuel, exhaust temp 993ºF (534°C)

Maximum intake air is 938 lb/hr
Max intake air restriction, clean filter = 4 kPa (+- 10%)
Max exhaust manifold pressure = 7.5 kPa (+_ 10%)

<u>Engine Monitoring and Alarm Levels:</u> (See D914 Installation Note)
Max cylinder head temperature = 205°C (400°F)
Max oil temperature = 135°C (275°F)
Max exhaust temperature = 650°C (1200°F)

Fuel: CGSB 3.16 diesel fuel.

INSTALLATION OF CDPF AND GAS DIFFUSER:

- Install CanmetENERGY diffuser and CDPF as per plan.
- Install separate gas sample ports on the CDPF inlet and outlet for the test cell gas bench and CanmetENERGY FTIR analysers.
- Install EPA type gas sample probes in all gas sample ports.
- Install separate temperature and pressure ports on the CDPF inlet and outlet.
- Install a separate port for ammonia injection in the diffuser
- Insert a stainless steel tube to the inlet side of the diffuser pipe at centreline, bent at 90° facing upstream.

FTIR and Gas bench inlet gas sample probes should be separated; the gas bench inlet sample probe must be located upstream from NH_3 injection port; the FTIR inlet gas sample probe must be downstream from NH_3 injection port and after the diffuser. Gas bench and FTIR outlet gas sample probes can be in close proximity.

Safety: There will be no entry into the test cell while the engine is in operation. Covid guidelines must be followed where shield and masks must be worn at all times

DYNO TESTING:
De-greening of CanmetENERGY CDPF

CDPF DPM loading and regenerating

Weigh CDPF on top loader (balance room) (wt1) = ___________ (g)

Note: No other modifications to the CDPF should be made that may effects its weight.

Engine power rating.

(1) Set basic engine conditions; engine intake (4kPa), exhaust restrictions (7.5kPa) at rated power). Stabilise the engine 5 minutes, data log engine conditions; set engine to peak torque speed (1500 rpm, 100% load); stabilise 5 minutes; ECCS data log sample rate is at 1 Hz for one (1) minute.
(2) Set engine speed to 2300 rpm 10% load. Run engine to maintain temperature at CDPF inlet to ~ 200 °C Commence loading of the CDPF for one (1) hour. ECCS data log sample rate is at 1 Hz for one (1) minute before proceeding to Step (3).
(3) Set engine to 2300 rpm 75% load. Run engine to maintain temperature at CDPF inlet to ~ 400 oC. Re-generate the CDPF for one (1) hour. ECCS data log sample rate is at 1 Hz for one (1) minute. before proceeding back to next step (2). At the end of each day when completing the final test point (6) at engine speed 2300 rpm 50% load, measure gaseous emission with CAI; ECCS data log sample rate is at 1 Hz for one (1) minute before and after the CDPF, without NH3 injection. Shutdown the gas cart pump.
(4) CanmetENERGY will inject a fixed amount of ammonia (NH_3) upstream of the flow mixer and allow flow to stabilise. CanmetENERGY will measure gasses with FTIR before and after CDPF (Table 2)
(5) Repeat steps 1, 2, 3 and 4 each day for five days.
(6) Set basic engine conditions; engine intake (4 kPa), exhaust restrictions (7.5 kPa) at rated power). Stabilise 5 minutes, ECCS data log sample rate is at 1 Hz for one (1) minute; set engine to peak torque speed (1500 rpm, 100% load); stabilise 5 minutes and ECCS data log sample rate is at 1 Hz for one (1) minute. Shut engine down and allow CDPF to cool to room temperature.

Remove CDPF and weigh on top loader (balance room) (wt2) = _________ g

∆wt = wt2- wt1: please confer with project leader

CDPF DPM loading: total mass of diesel particulate matter (DPM) to be collected is ~81g

Note: No other modifications to the CDPF should be made that may effects its weight.

Engine power rating.

Set the engine basic conditions (engine intake, exhaust restrictions (TBD) at rated power, etc.). Record engine data at rated speed and peak torque speeds. Shut engine down and allow to cool for 1 hour

Set engine speed to 2300 rpm 10% load. Run engine to maintain temperature at CDPF inlet to ~ 200°C. Loading of the CDPF is expected to take ~ 20 hours. Data log engine conditions every 1 hour (60 second, average basis) during loading period.

Allow CDPF to cool, remove and weigh CDPF on top loader (balance room) (wt3) = _________ g

∆wt = wt3- wt2: please confer with project leader.

Balance Point Temperature Test:

CanmetMINING will monitor and record on one (1 Hz) basis all engine parameters and emissions per test point. See Table 1 for ~ test engine load and CDPF inlet temperatures conditions (data from previous assessment).

Set engine speed to 1500 rpm, minimum load. Run progressive load points per Table 1. Allow 10 minutes for temperature stabilization per load change. Data log over the stabilisation period (ECCS). ECCS data log sample rate is at 1 Hz while the FTIR sample rate is set at ~17 Hz.

Observe inlet/outlet temperature and pressure of CDPF

Note: Both the gas bench and FTIR analysers will monitor CDPF inlet and outlet gases. Switching between gas sample lines can be carried out at the discretion of the operator; however, it's recommended that switching be carried out during the final five (5) minutes of the stabilization period.

Progressive Load Test – CDPF Emissions Assessment (gases only, with NH3 injection)

Set engine speed to 1500 rpm, minimum load. Run progressive load points per Table 2. Allow 10 minutes for temperature stabilization per load change. Inject NH_3 per sample point values (Table 2) and wait until NOx concentrations have stabilised. Data log gaseous emissions (60 second, average basis) from both the CDPF inlet and outlet.

Note: A quick check NO_X mass flow can be made for each test point where required in order to adjust NH_3 flow rate if necessary.

Note: Both the gas bench and FTIR analysers will monitor CDPF inlet and outlet gases. Switching between gas sample lines can be carried out at the discretion of the operator; however, it's recommended that switching be carried out during the final five (5) minutes of the stabilization period when NH_3 injection is sufficient (Table 2).

Reset the engine basic conditions (engine intake, exhaust restrictions at rated power, etc.), Record engine data at rated speed and peak torque speed

Engine Emissions Test – (duplicate 8-Mode test)

rpm %load ->	100	75	50	10	
2300 (rated power)	**y***	**y**	**y**	**y**	*** DPM duplicate sampling**
1500 (peak torque)	**y***	**y**	**y**	y	
low idle, minimum load					
high idle, minimum load					

- Measure gases, and DPM (5 minute sampling) at tailpipe location for all 8 points
- Measure gases, (5 minute sampling) at inlet CDPF location for all 8 points
- Inject NH_3 at each sample point or until NOx concentrations have stabilised as done previously.
- (CanmetENERGY). Data log gaseous emissions (60 second, average basis) on both the CDPF inlet and outlet.

Note: Both the gas bench and FTIR analysers will monitor CDPF inlet and outlet gases. Switching between gas sample lines can be carried out at the discretion of the operator; however, it's recommended that switching be carried out during the final five (5) minutes of the stabilization period when NH_3 injection is sufficient.

Table 1
8-Mode Test with estimated gas flows
(Previous - Deutz F6L914@ 8 Mode data)

Mode	Speed	Load	Catalyst Inlet Temp	Total Wet Exhaust flow - corrected	NO_2	NO	NOx	NH_3	NH_3
	rpm	lb.ft	°C	l/min	moles/min	moles/min	moles/min	(g/min)	l/min
Mode 1	2300	201.6	499.6	5838	0.004	0.184	0.187	3.2	4.4
Mode 2	2299	151.7	394.9	5893	0.011	0.146	0.157	2.7	3.7
Mode 3	2302	101.4	308.9	5924	0.017	0.100	0.116	2.0	2.7
Mode 4	2300	20.7	199.7	5925	0.019	0.026	0.045	0.8	1.1
Mode 5	1500	259.9	493.4	3977	-	0.160	0.158	2.7	3.7
Mode 6	1502	195.1	365.8	4052	0.003	0.129	0.132	2.2	3.1
Mode 7	1500	130.2	258.9	4091	0.009	0.096	0.105	1.8	2.4
Mode 8	864	1.3	90.5	2442	0.005	0.008	0.013	0.2	0.3

Table 2
Progressive Load Test with estimated gas flows
(Previous - Deutz F6L914@ 1500rpm data)

Point	Catalyst Inlet Temp.	Load	Wet Exhaust Flow	NO_2	NO	NOx	NH_3	NH_3
-	^oC	(lb.ft)	l/min	moles/min	moles/min	moles/min	(g/min)	l/min
1	122.3	15.2	4122	0.014	0.024	0.039	0.658	0.90
	120.6	13.2	4121	0.012	0.028	0.040	0.676	0.93
2	134.4	28.8	4100	0.015	0.032	0.048	0.811	1.11
	134.0	28.8	4098	0.013	0.035	0.048	0.823	1.13
3	153.5	49.9	4096	0.016	0.046	0.062	1.058	1.45
	154.5	50.9	4101	0.014	0.049	0.063	1.074	1.47
4	168.2	64.8	4108	0.016	0.057	0.073	1.250	1.71
	167.7	64.8	4108	0.014	0.061	0.074	1.266	1.73
5	193.6	88.9	4108	0.016	0.077	0.093	1.583	2.17
	193.8	88.7	4108	0.010	0.084	0.094	1.601	2.19
6	221.5	112.5	4101	0.015	0.096	0.111	1.890	2.59
	221.7	112.2	4102	0.006	0.105	0.110	1.875	2.57
7	241.4	128.2	4105	0.014	0.109	0.123	2.096	2.87
	240.9	127.7	4101	0.003	0.117	0.120	2.037	2.79
8	258.3	140.3	4100	0.013	0.118	0.131	2.237	3.06
	257.9	140.1	4095	0.002	0.126	0.128	2.179	2.98
9	281.0	157.5	4098	0.011	0.130	0.141	2.405	3.29
	282.0	157.7	4094	0.001	0.137	0.138	2.353	3.22
10	304.8	172.1	4084	0.010	0.136	0.147	2.496	3.42
	304.5	171.6	4082	0.001	0.140	0.141	2.408	3.30
11	325.2	184.7	4075	0.009	0.139	0.148	2.524	3.46
	325.8	184.7	4074	0.002	0.142	0.144	2.452	3.36
12	351.8	199.7	4058	0.007	0.144	0.152	2.582	3.54
	350.6	198.5	4067	0.005	0.143	0.148	2.519	3.45
13	381.4	215.2	4052	0.005	0.151	0.156	2.663	3.65
	382.3	215.7	4045	0.007	0.144	0.151	2.573	3.52
14	407.9	227.2	4040	0.005	0.149	0.154	2.621	3.59
	409.2	226.6	4035	0.008	0.143	0.151	2.567	3.52
15	430.9	237.3	4036	0.004	0.152	0.156	2.650	3.63
	431.2	236.7	4034	0.008	0.144	0.152	2.583	3.54
16	443.4	241.5	4024	0.006	0.149	0.155	2.633	3.61
	444.0	241.6	4025	0.007	0.145	0.152	2.596	3.56
17	452.2	244.7	4023	0.004	0.151	0.155	2.638	3.61
	452.1	244.8	4026	0.007	0.146	0.153	2.607	3.57
18	484.1	258.4	4004	0.002	0.153	0.155	2.643	3.62
	486.0	258.2	4006	0.004	0.148	0.152	2.591	3.55

APPENDIX D

De-greening Emissions Results

Test Days->		Day 1			Day 2			Day 3			Day 4			Day 5			Day 2 to 5
Para-meters		Catalyst Inlet	Catalyst Outlet	% Change	Catalyst Inlet	Catalyst Outlet	% Change	Catalyst Inlet	Catalyst Outlet	% Change	Catalyst Inlet	Catalyst Outlet	% Change	Catalyst Inlet	Catalyst Outlet	% Change	
	Units	Mode 2	Mode 2		Mode 1	Mode 1		Mode 1	Mode 1		Mode 1	Mode 1		Mode 1	Mode 1		Average
Speed	*rpm*	2300	2300	0.0%	2300	2300	0.0%	2300	2300	0.0%	2300	2300	0.0%	2300	2300	0.0%	0.0%
Torque	*N.m*	204.1	205.2	-0.5%	273.7	274.0	-0.1%	280.6	280.6	0.0%	281.2	282.1	-0.3%	281.1	281.2	0.0%	-0.1%
Power	*kW*	49.2	49.4	-0.5%	65.9	66.0	-0.1%	67.6	67.6	0.0%	67.7	67.9	-0.3%	67.7	67.7	0.0%	-0.1%
Engine exhaust temp.	*°C*	415.5	415.9	-0.1%	530.6	531.0	-0.1%	540.9	540.3	0.1%	546.6	545.6	0.2%	549.2	549.9	-0.1%	0.0%
CDPF outlet temp.	*°C*	369.0	368.2	0.2%	465.0	464.4	0.1%	472.9	471.8	0.2%	476.5	475.4	0.2%	478.5	478.5	0.0%	0.1%
Exhaust gas conc. - wet																	
CO2	*%*	6.1	6.1	-0.1%	7.7	7.8	-0.3%	8.0	8.0	-0.5%	8.2	8.2	0.0%	8.2	8.3	-0.5%	-0.3%
CO	*ppm*	182	192	-5.8%	168	191	-14.0%	180	205	-13.5%	191	212	-10.8%	187	209	-11.9%	-12.5%
NO_2	*ppm*	35	1	98.4%	14	1	96.5%	12	1	93.2%	8	1	93.3%	5	1	90.2%	93.3%
NO	*ppm*	561	522	6.9%	723	539	25.4%	722	551	23.7%	717	556	22.5%	696	540	22.4%	23.5%
NOx	*ppm*	565	486	14.0%	752	544	27.7%	755	568	24.7%	633	486	23.2%	613	472	23.0%	24.6%
THC	*ppm*	195	142	27.0%	181	83	54.0%	167	66	60.7%	162	62	61.5%	166	64	61.4%	59.4%
Specific emission																	
CO2	*g/hr*	39333	39419	-0.2%	49427	49587	-0.3%	50577	50699	-0.2%	51792	51904	-0.2%	51694	51912	-0.4%	-0.3%
CO	*g/hr*	75	79	-6.0%	68	78	-14.0%	73	82	-13.2%	77	85	-11.0%	75	83	-11.8%	-12.5%
NO_2	*g/hr*	24	0	98.4%	10	0	96.5%	8	1	93.2%	5	0	93.3%	3	0	90.2%	93.3%
NO	*g/hr*	248	231	6.7%	315	235	25.4%	313	238	23.9%	308	240	22.3%	298	231	22.5%	23.5%
NOx	*g/hr*	272	232	14.8%	325	236	27.5%	321	238	25.6%	313	240	23.5%	302	231	23.3%	25.0%

THC	*g/hr*	40	29	26.9%	36	17	54.0%	33	13	60.8%	32	12	61.4%	33	13	61.5%	59.4%

APPENDIX E

PLT Emissions Results (no NH_3 dosing)

Test Points->		1	1	2	2	3	3	4	4	5	5	6	6	7	7	8	8	9	9
Speed	rpm	1500	-	1500	-	1500	-	1500	-	1500	-	1500	-	1500	-	1500	-	1500	-
Torque	N.m	21	-	42	-	66	-	83	-	118	-	151	-	176	-	192	-	213	-
Power	kW	3.3	-	6.6	-	10.4	-	13.1	-	18.5	-	23.7	-	27.6	-	30.2	-	33.4	-
Engine Exhaust temperature	ºC	131	-	146	-	165	-	179	-	207	-	238	-	263	-	282	-	306	-
CDPF outlet temperature	ºC	107	-	126	-	141	-	153	-	175	-	202	-	224	-	240	-	259	-
Exhaust gas conc.- wet																			
CO_2	%	2.0	-	2.3	-	2.7	-	3.0	-	3.6	-	4.2	-	4.6	-	4.9	-	5.3	-
CO	ppm	532	515	482	499	446	434	386	373	302	300	228	228	192	204	172	182	153	163
NO_2	ppm	67	68	76	72	86	79	86	75	82	59	73	25	67	13	61	3	52	2
NO	ppm	139	140	181	157	231	234	293	296	389	402	492	523	555	605	611	649	645	675
THC	ppm	410	-	342	-	326	-	290	-	245	-	245	-	263	-	253	-	240	-
Specific Emissions																			
CO_2	g/hr	9064	-	10115	-	11923	-	13226	-	15885	-	18503	18503	20484	-	21737	-	23422	-
CO	g/hr	152	147	137	142	126	123	109	106	85	85	64	64	54	57	48	51	43	46
NO_2	g/hr	31	32	36	34	40	37	40	35	38	27	34	12	31	6	28	1	24	1
NO	g/hr	43	43	55	48	70	71	89	90	118	122	149	158	167	183	184	195	194	203
THC	g/hr	58	-	48	-	46	-	41	-	34	-	34	-	37	-	35	-	33	-

Test Points->		10	10	11	11	12	12	13	13	14	14	15	15	16	16	17	17	18	18
Speed	rpm	1500	-	1500	-	1500	-	1500	-	1500	-	1500	-	1500	-	1500	-	1500	-
Torque	N.m	230	-	248	-	265	-	285	-	307	-	318	-	327	-	334	-	350	-
Power	kW	36.1	-	38.9	-	41.7	-	44.8	-	48.3	-	50.0	-	51.3	-	52.4	-	55.0	-
Engine Exhaust Temperature	^oC	329	-	353	-	382	-	413	-	449	-	474	-	498	-	514	-	546	-
CDPF inlet temperature	^oC	279	-	298	-	321	-	345	-	374	-	394	-	413	-	426	-	449	-
Exhaust gas conc.- wet																			
CO_2	%	5.7	-	6.1	-	6.5	-	7.0	-	7.5	-	7.9	-	8.2	-	8.4	-	9.0	-
CO	ppm	143	163	140	166	141	175	135	175	133	195	144	209	139	215	147	234	222	323
NO_2	ppm	45	2	39	2	33	2	23	2	15	2	9	2	6	2	5	2	3	2
NO	ppm	660	658	667	678	703	723	695	709	749	683	731	705	747	736	741	682	728	731
-	ppm	242	242	229	229	203	203	184	184	174	174	162	162	150	150	142	-	131	-
-																		-	-
CO_2	g/hr	24990	-	26583	-	28274	-	30353	-	32796	-	34078	-	35293	-	36349	-	38517	-
CO	g/hr	40	46	39	46	39	49	37	49	37	54	39	57	38	59	40	64	60	88
NO_2	g/hr	21	1	18	1	15	1	11	1	7	1	4	1	3	1	2	1	1	1
NO	g/hr	198	197	199	202	210	216	207	211	222	202	216	208	220	217	218	201	213	214
THC	g/hr	34	-	32	-	28	-	25	-	24	-	22	-	20	-	19	-	18	-

Test Points->	1	2	3	4	5	6	7	8	9
	% Change in Gas concentration before and after CDPF								
CO (WET)	-3.2%	3.6%	-2.8%	-3.5%	-0.5%	0.2%	6.1%	5.6%	6.6%
NO2 (WET)	1.7%	-5.6%	-7.8%	-11.8%	-27.6%	-65.2%	-80.3%	-95.4%	-95.3%
NO (WET)	0.3%	-13.2%	1.3%	1.0%	3.2%	6.2%	9.1%	6.3%	4.6%
NOx (WET)	0.7%	-11.0%	-1.2%	-1.9%	-2.1%	-3.0%	-0.5%	-2.9%	-2.8%
	% Change in specific emissions before and after CDPF								
CO	-3.2%	3.6%	-2.8%	-3.5%	-0.5%	0.2%	6.1%	5.6%	6.6%
NO_2	1.7%	-5.6%	-7.8%	-11.8%	-27.6%	-65.2%	-80.3%	-95.4%	-95.3%
NO	0.3%	-13.2%	1.3%	1.0%	3.2%	6.2%	9.1%	6.3%	4.6%
NOx	0.9%	-10.2%	-2.0%	-2.9%	-4.3%	-7.0%	-4.9%	-7.1%	-6.4%

Test Points->	10	11	12	13	14	15	16	17	18
	% Change in Gas concentration before and after CDPF								
CO (WET)	13.6%	18.7%	23.9%	29.7%	46.3%	45.6%	54.5%	59.6%	45.7%
NO2 (WET)	-95.1%	-94.7%	-93.2%	-91.2%	-88.4%	-82.7%	-70.7%	-68.8%	-35.7%
NO (WET)	-0.3%	1.7%	2.9%	2.1%	-8.8%	-3.5%	-1.5%	-7.9%	0.3%
NOx (WET)	-6.4%	-3.7%	-1.4%	-0.9%	-10.4%	-4.5%	-2.1%	-8.4%	0.2%
	% Change in specific emissions before and after CDPF								
CO	13.6%	18.7%	23.9%	29.7%	46.3%	45.6%	54.5%	59.6%	45.7%
NO_2	-95.1%	-94.7%	-93.2%	-91.2%	-88.4%	-82.7%	-70.7%	-68.8%	-35.7%
NO	-0.3%	1.7%	2.9%	2.1%	-8.8%	-3.5%	-1.5%	-7.9%	0.3%
NOx	-9.3%	-6.3%	-3.5%	-2.5%	-11.1%	-5.0%	-2.4%	-8.6%	0.1%

APPENDIX F

PLT Emission Results (with NH_3 dosing)

Test Points->		1	1	2	2	3	3	4	4	5	5	6	6	7	7	8	8	9	9
Speed	rpm	1500	-	1500	-	1500	-	1500	-	1500	-	1500	-	1500	-	1500	-	1500	-
Torque	N.m	19	-	44	-	69	-	88	-	122	-	153	-	182	-	195	-	218	-
Power	kW	2.9	-	6.8	-	10.8	-	13.8	-	19.2	-	24.1	-	28.5	-	30.6	-	34.2	-
Engine Exhaust Temperature	ºC	125	-	144	-	164	-	180	-	212	-	241	-	269	-	284	-	312	-
CDPF outlet temperature	ºC	111	-	126	-	142	-	156	-	184	-	209	-	234	-	248	-	269	-
Exhaust gas concentration - wet																			
CO_2	%	1.8	-	2.2	-	2.7	-	3.0	-	3.7	-	4.2	-	4.7	-	5.0	-	5.5	-
CO	ppm	513	489	470	472	419	413	377	372	284	288	209	221	182	186	159	168	144	152
NO_2	ppm	38	54	62	51	68	51	70	49	67	28	57	7	53	2	47	2	43	2
NO	ppm	123	189	176	176	236	243	292	298	403	406	478	517	560	600	598	630	631	654
THC	ppm	378	-	350	-	350	-	322	-	308	-	279	-	291	-	269	-	247	-
Specific Emissions																			
CO_2	g/hr	8238	-	10021	-	11967	-	13562	-	16227	-	18675	-	20904	-	22028	-	24003	-
CO	g/hr	147	140	134	135	119	117	107	106	80	81	59	62	51	52	44	47	40	42
NO_2	g/hr	18	25	29	24	32	24	33	23	31	13	26	3	24	1	22	1	19	1
NO	g/hr	38	58	54	54	72	74	89	91	121	122	144	156	168	180	180	189	189	196
THC	g/hr	54	-	50	-	49	-	45	-	43	-	39	-	40	-	37	-	34	-

Test Points->		10	10	11	11	12	12	13	13	14	14	15	15	16	16	17	17	18	18
Speed	rpm	1500	-	1500	-	1500	-	1500	-	1500	-	1500	-	1500	-	1500	-	1500	-
Torque	N.m	232	-	250	-	274	-	294	-	307	-	318	-	327	-	329	-	348	-
Power	kW	36.5	-	39.3	-	43.0	-	46.2	-	48.2	-	49.9	-	51.4	-	51.7	-	54.7	-
Engine Exhaust temperature	ºC	333	-	356	-	396	-	431	-	458	-	478	-	498	-	512	-	551	-
CDPF inlet temperature	ºC	287	-	305	-	338	-	365	-	387	-	402	-	417	-	428	-	458	-
Exhaust gas concentration - wet																			
CO_2	%	5.8	-	6.2	-	6.7	-	7.3	-	7.6	-	8.0	-	8.3	-	8.4	-	9.1	-
CO	ppm	136	143	132	146	132	147	132	151	139	149	130	151	133	161	137	169	213	256
NO_2	ppm	36	2	33	1	24	2	16	1	10	1	7	1	5	1	3	1	2	1
NO	ppm	642	677	671	656	691	704	683	669	695	689	715	660	711	649	716	609	725	575
THC	ppm	235	-	204	-	187	-	180	-	172	-	170	-	160	-	159	-	154	-
Specific Emissions																			
CO_2	g/hr	25368	-	26981	-	29314	-	31538	-	33075	-	34345	-	35505	-	36226	-	38785	-
CO	g/hr	38	40	37	41	36	41	36	42	38	41	36	41	36	44	38	46	58	69
NO_2	g/hr	17	1	15	1	11	1	7	1	5	1	3	0	2	0	1	0	1	0
NO	g/hr	192	202	200	196	205	209	202	198	205	203	211	194	209	190	210	179	210	167
THC	g/hr	32	-	28	-	26	-	25	-	23	-	23	-	22	-	21	-	21	-

Test Points->	1	2	3	4	5	6	7	8	9
	% Change in Gas concentration before and after CDPF								
CO (WET)	-4.7%	0.3%	-1.5%	-1.5%	1.5%	5.6%	2.4%	5.7%	5.9%
NO2 (WET)	41.0%	-18.5%	-24.8%	-30.6%	-58.2%	-87.8%	-96.8%	-96.2%	-96.4%
NO (WET)	54.3%	-0.2%	3.0%	2.2%	0.8%	8.2%	7.1%	5.3%	3.6%
NOx (WET)	51.2%	-5.0%	-3.2%	-4.2%	-7.7%	-1.9%	-1.9%	-2.0%	-2.7%
	% Change in specific emissions before and after CDPF								
CO	-4.7%	0.3%	-1.5%	-1.5%	1.5%	5.6%	2.4%	5.7%	5.9%
NO_2	41.0%	-18.5%	-24.8%	-30.6%	-58.2%	-87.8%	-96.8%	-96.2%	-96.4%
NO	54.3%	-0.2%	3.0%	2.2%	0.8%	8.2%	7.1%	5.3%	3.6%
NOx	50.0%	-6.6%	-5.5%	-6.6%	-11.2%	-6.5%	-6.0%	-5.5%	-5.7%

Test Points->	10	11	12	13	14	15	16	17	18
	% Change in Gas concentration before and after CDPF								
CO (WET)	5.6%	10.8%	11.9%	15.0%	7.3%	16.0%	20.8%	23.3%	19.8%
NO2 (WET)	-95.5%	-95.5%	-93.5%	-92.1%	-88.8%	-83.7%	-80.9%	-76.9%	-63.6%
NO (WET)	5.5%	-2.3%	1.8%	-2.0%	-1.0%	-7.7%	-8.8%	-14.9%	-20.7%
NO (WET)	0.1%	-6.7%	-1.3%	-4.0%	-2.3%	-8.4%	-9.2%	-15.2%	-20.8%
NOx (WET)	0.1%	-6.7%	-1.3%	-4.0%	-2.3%	-8.4%	-9.2%	-15.2%	-20.8%
	% Change in specific emissions before and after CDPF								
CO	5.6%	10.8%	11.9%	15.0%	7.3%	16.0%	20.8%	23.3%	19.8%
NO_2	-95.5%	-95.5%	-93.5%	-92.1%	-88.8%	-83.7%	-80.9%	-76.9%	-63.6%
NO	5.5%	-2.3%	1.8%	-2.0%	-1.0%	-7.7%	-8.8%	-14.9%	-20.7%
NOx	-2.6%	-8.8%	-2.9%	-5.1%	-3.0%	-8.8%	-9.5%	-15.3%	-20.8%

Protected Business Information

APPENDIX G

8-Mode Emissions results

Summary 8-Mode Test Data - before CDPF											
Test Points->		1	2	3	4	5	6	7	8	Integrated	%Change
Speed	rpm	2300	2300	2300	2300	1500	1500	1500	872	1846	-
Torque	N.m	210.9	157.9	105.7	22.2	263.8	198.9	132.2	2.4	133	-
Power	kW	92.3	69.1	46.3	9.7	75.3	56.8	37.8	0.4	49	-
Engine Exhaust temperature	°C	537.1	418.0	327.5	213.7	538.0	397.6	284.4	87.5	349	-
DOC inlet temperature	°C	461.8	365.2	288.9	188.3	438.8	334.9	244.2	82.3	300	-
Exhaust gas concentration - wet											
CO2	%	8.0	6.2	4.7	2.6	9.0	6.6	4.7	1.3	5	-
CO	ppm	167.6	174.1	311.5	734.4	190.3	155.2	164.7	308.4	269	7.1%
NO2	ppm	2.4	22.1	48.8	52.9	3.1	26.2	61.6	35.7	31	-79.9%
NO	ppm	679	525	343	85	789	627	417	72	435	-10.8%
NOX	ppm	681	547	392	138	792	653	479	107	465	-15.4%
THC	ppm	171	200	214	631	143	152	235	373	260	-
Specific emission											
CO2	g/hr	51441	40252	31002	17019	39026	28952	20811	3339	29486	-
CO	g/hr	69	72	130	305	53	44	47	52	93	6.9%
NO2	g/hr	2	15	33	36	1	12	29	10	17	-84.0%
NO	g/hr	299	233	153	38	234	189	127	13	164	-11.1%
NOx	g/hr	301	248	187	74	235	201	156	23	180	-17.9%
THC	g/hr	35	41	44	130	20	21	33	31	43	
DPM	g/hr	8.4	3.5	1.8	3.9	8.1	2.0	1.9	1.3	3.9	-88.0%

Protected Business Information

Summary 8-Mode Test Data - after CDPF										
Test Points->		1	2	3	4	5	6	7	8	Integrated
CO	%	182.2	179.1	315.4	777.0	216.6	164.7	240.0	310.5	288
NO_2	ppm	0.7	1.0	0.6	19.7	0.7	1.3	1.0	23.7	6
NO	ppm	524	493	335	92	636	596	417	72	388
NOx	ppm	524	494	335	112	637	597	418	96	394
Specific emission										
CO	g/hr	75	74	131	322	60	46	68	52	100
NO_2	g/hr	0	1	0	13	0	1	0	7	3
NO	g/hr	231	219	150	41	188	180	127	13	145
NOx	g/hr	231	220	150	54	189	180	127	20	148
DPM	g/hr	0.8	0.5	0.4	0.9	0.3	0.4	0.4	0.1	0.5