

Development of Partial Filter Technology for HDD Retrofit

Todd Jacobs, Sougato Chatterjee, Ray Conway, and Andy Walker
Johnson Matthey ECT

Jan Kramer, Klaus Mueller-Haas
Emitec Inc.

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ABSTRACT

Diesel oxidation catalyst and particulate filter technologies are well established and their applications are well known. However, there are certain limitations with both technologies due to their inherent technical characteristics. Both technologies get 75-90% reduction of HC and CO. A typical oxidation catalyst can be applied to almost any heavy duty diesel application and achieve 20 to 30% reduction in PM mass but no significant reduction in the number of PM particles. On the other hand, diesel particulate filters are very effective at removing >90% of the particles by mass and >99% by number. Unfortunately, passive DPF technology cannot be applied to all applications since the filter regeneration is limited by engine out NO_x to PM ratio as well as exhaust temperature. For this reason, particulate filters can not universally be applied to older "dirtier" engines with high PM emissions. This creates a technology gap for a passive device that can be successfully applied to old, high PM emission engines to achieve significant reduction in both PM mass and PM number.

This paper will discuss the development of a passive PM control device referred to as a partial filter technology or PFT. This device combines an oxidation catalyst with a unique filter technology that can reduce PM by up to 77%. The new filter material combines the attributes of a flow through substrate with those of a wall flow filter to collect some but not necessarily all the engine out soot and thus provide PM reduction without leading to filter plugging. Due to the flow through characteristics, excess soot beyond filter capacity is not collected in the PFT and thus the exhaust is able to continue to flow without a significant increase in back pressure. The PFT system also utilizes the NO₂:C reaction used by passive diesel particulate filter systems to oxidize a portion of the soot and passively regenerate the filter. In addition, the filter does not accumulate significant amounts of lube oil ash and this may minimize the need for a periodic ash cleaning maintenance.

Engine bench emission testing with this system has shown PM reductions ranging from 77% for fresh (de-greened) system to 63% for an aged system along with >90% HC and CO reductions. On-road operational data collected on various model year applications over a two year period has shown stable back pressure since installation. In addition, no adverse operational or maintenance issues were noted which can be attributed to the installation of the PFT system.

This paper describes the development and testing of this passively regenerating partial filter technology.

INTRODUCTION

Diesel engines have proven their durability in use across a wide spectrum of applications, notably public transport, commercial goods delivery and municipal utility applications. Because the heavy duty diesel engine is so long lived, dependable, and economically rebuilt, it tends to remain in service for a very long period of time. As a result, older engines which emit a higher concentration of regulated emissions (PM, HC, CO, NO_x) remain in service long after emission standards become more stringent. The increasing evidence, indicating that emissions from diesel engines may be harmful to human health and air quality, has moved the California Air Resources Board (CARB) to create regulations requiring PM reduction from existing diesel vehicles by retrofitting with emission control devices. In this process, CARB has recommended three classifications for such PM reduction devices [1]. Level I devices are defined as such that reduce PM by >25%. DOCs are example of Level I devices. Level II devices are defined as such that reduce PM by greater than 50% while Level III systems are ones that reduce PM by greater than 85%. Diesel particulate filters are examples of Level III devices. Therefore based on system definition, Level II devices fall in between DOC and DPF for PM reduction performance.

It has been well documented that DOC and DPF are able to significantly reduce the amount of PM, HC, and CO emitted from diesel engines [2, 3]. Generally the DOC is applicable to most engines without major

concern for exhaust temperature and emission levels; however its effect is limited for PM reduction because it reduces the PM mass by primarily oxidizing soluble hydrocarbons that are present in PM and not soot [4,5]. In this process, DOC does not significantly reduce the total particle count. On the other hand, a DPF is extremely effective at reducing total PM, both in mass and particle number [2,3]. As a typical example, a passively regenerating CRT[®] diesel particulate filter system combines a DOC with a bare wall flow filter and in this way eliminates over 90% CO, HC and PM while continuously regenerating the filter. But the retrofit application of such a passive DPF system is limited by the exhaust temperature and the engine out NO_x to PM ratio.

The significant gap in particulate emission reduction between a DOC (Level I) and a DPF (Level III) shows the need for an intermediate device (Level II) that is able to operate successfully on a wide range of engines while reducing PM by at least 50%. A system that combines the attributes of a flow thru DOC and the trapping characteristics of the DPF would be ideally suited as a Level II PM reduction device. In addition, if the system can operate with both ULSD and LSD fuel, it will be even more beneficial.

This paper describes the development and performance of the PCRT[™] filter system, which is a Level II partial filter technology (PFT) for PM reduction. This system combines an oxidation catalyst with a unique filter technology that can reduce PM by up to 70%. The new filter material combines the attributes of a flow through substrate with those of a wall flow filter to collect some but not necessarily all the engine out soot and thus provide PM reduction without leading to filter plugging. This PFT system uses the patented CRT[®] operational principle, where NO₂ is created prior to the filter and it is then utilized to oxidize soot captured by the particulate filter [6]. However, in the case of the PFT system, instead of a wall flow filter, a specialized foil and metal fleece filter substrate is used, that combines the ability to trap soot particles with the benefits of a flow through design.

The objective of the PFT project was to develop a cost effective Level II PM reduction system capable of reducing PM by amounts > 50% and HC/CO by > 60% in a modular, easily maintained package. Emission reduction results from this development will be presented in this paper. The results are from engine dynamometer test cell work using a variety of engines operating over the US FTP test cycle. In addition, extensive field trial data on a variety of applications will be presented to demonstrate the durability of the system.

EXPERIMENTAL

The development of the PFT filter system consisted of engine testing at test facilities in the United States, Canada, and Europe. Field trials were carried out in

California and Pennsylvania. Details about the PFT system, test engines, test facilities and test procedures are discussed in this section.

SYSTEM DESCRIPTION

The PFT system is a modular design incorporating inlet, catalyst, filter and outlet modules (Figure 1). The PFT device is comprised of two primary sections. The first section comprises a diesel oxidation catalyst similar to a CRDPF [2] system, where the necessary oxidation steps are carried out. The soot collection and combustion process is completed in the second section, which contains the unique flow through filter element. The catalyst section contains an oxidation catalyst consisting of a ceramic honeycomb substrate coated with a proprietary highly active platinum group metal. Aside from oxidizing a portion of the NO for soot combustion, the catalyst also oxidizes CO, HC and the SOF portion of the PM [2,3].

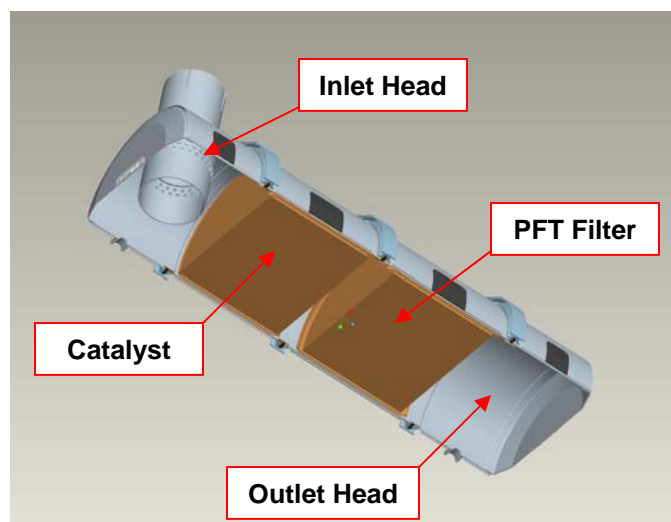


Figure 1: Modular PFT System

The PFT filter element is fabricated in a flow through monolithic configuration. Figure 2 shows a cut-away diagram of the filter section. The exhaust flows through metallic foil (channel) that is stamped along its length creating a ramp or “shovel” which creates a tortuous path for the exhaust. The wall between the channels is made up of a porous sintered metal fleece material compressed between metal foils. The shovels in the channels force a part of the exhaust to redirect through this metallic fleece material which traps a portion the soot. The remaining exhaust flows out through the other end of the channel similar to a flow through substrate. The soot trapped in the fleece material is combusted by the NO₂ generated by the upstream catalyst and thus the filter is regenerated, allowing for additional soot collection. Details of NO₂:C oxidation can be reviewed in other papers [6,7]. However, if such a situation arises where filter regeneration is hindered and the fleece reaches a saturation point with collected soot, this substrate will not plug up similar to a wall flow filter. In this case, all of the exhaust is able to flow relatively

unimpeded past the shovels and out through the other end of the channels, similar to a flow through substrate.

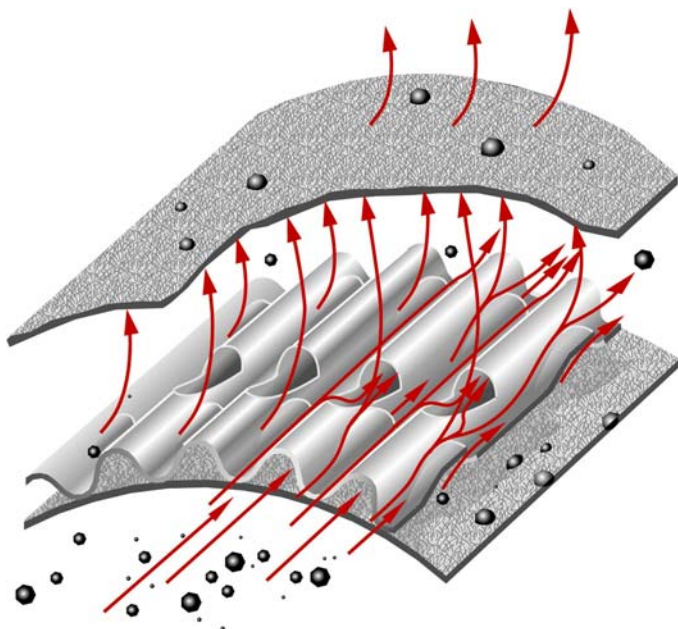


Figure 2: Foil substrate with “Shovels” forcing soot into the sintered metal fleece material

The catalytic coating on the DOC was applied using standard coating processes onto a 400 cells/in² cell density ceramic substrate. The filter section of the PFT consists of a proprietary metallic foil/fleece design with a cell density of 200 cells/in². The size of the DOC and PFT are specific to a given application. The catalyst section is sized to produce sufficient NO₂ to combust the soot collected in the filter. The filter is sized to provide low operating back pressure and high soot trapping efficiency.

LABORATORY TEST ENGINES

Table 1 shows the engines, catalyst/filter volumes used, and engine out emissions in laboratory testing. A 1998 Caterpillar 3126 was tested in March – April 2004 at Environment Canada. A 1991 Cummins N14 and 1989 Cummins 6CTA8.3 were tested at Southwest Research Institute in March – June 2005.

Test Cell Engines			
Model	Caterpillar 3126	Cummins N14	Cummins 6CTA8.3
Emissions Standard	1998 US HDD (FTP)	1991 US HDD (FTP)	1989 US HDD (FTP)
Size (l)	7.2 L	14 L	8.3 L
Type	4 stroke	4 stroke	4 stroke
Power	250hp	350hp	240hp
Config/ Cyl	Turbo / 6 Cyl	Turbo / 6 Cyl	Turbo / 6 Cyl
Controls	Electronic	Electronic	Mechanical
Cat Volume (L)	8.44	8.44	8.44
Filter Volume (L)	16.42	8.21 and 16.42	8.21
Engine Out Emissions g/bhp-hr (ULSD 9 ppm S)			
NO _x	3.80	4.48	4.71
HC	0.24	0.30	0.53
CO	1.34	1.85	1.21
PM	0.07	0.149	0.362
Engine Out Emissions g/bhp-hr (LSD 347ppm S)			
NO _x	3.73	5.45	4.69
HC	0.16	0.26	0.57
CO	1.23	1.87	1.22
PM	0.09	0.153	0.363

Table 1: Engines used in laboratory testing for PFT development

FUEL

Two diesel fuels were used in emission testing, an ultra low sulfur diesel (ULSD) with a nominal sulfur level of 10 ppm, and a type - 2D low sulfur diesel with approximately 350 ppm sulfur. The 2D fuel is an emissions grade diesel and the ULSD fuel meets 2007 EPA diesel fuel specifications. Table 2 details fuel specifications.

Item	ASTM Method	Specifications	
		2D	ULSD
Cetane #	D613	46.4	44.0
Distillation Range			
IBP, F	D86	358	362
10% point, F	D86	410	400
50% point, F	D86	499	489
90% point, F	D86	590	602
EP, F	D86	646	665
Gravity, API	D287	36.23	36.27
Total Sulfur	D5453	347	9
Hydrocarbon composition:			
Aromatics (min.), %	D1319	29.4	28.3
Parafins, Naphthenes, Olefins %	D1319	1.2	0.8
SFC Aromatics, wt%	D5186	31.6	31.4
PNA, wt%	D5186	7.4	8.0
Flashpoint (min), F	D93	149	156
Viscosity, centistokes	D445	2.53	2.42

Table 2: Specifications of Diesel fuel used

EMISSIONS TESTING AND TEST FACILITIES

TESTING AT ENVIRONMENT CANADA

US FTP engine dynamometer testing was completed on the 1998 Caterpillar 3126 at Environment Canada in Ottawa Canada in April 2004. The emission testing was conducted in the Heavy-Duty engine emissions laboratory of the Emissions Research and Measurement Division. The exhaust gas sampling system in this laboratory is designed to measure the true mass of both the gaseous and particulate emissions in the exhaust of the heavy-duty diesel engine that is tested. These values are obtained using a large double-dilution critical flow venturi (CFV) continuous volume sampler (CVS) (Figure 3). Coupled to the dilution tunnel was a secondary dilution tunnel, which draws out a constant volume of diluted exhaust and dilutes it again (double dilution), thereby conditioning the sample and enabling particulate collection in accordance with accepted test procedures. The flow rate in the main tunnel during emissions testing was a nominal 2200 scfm.

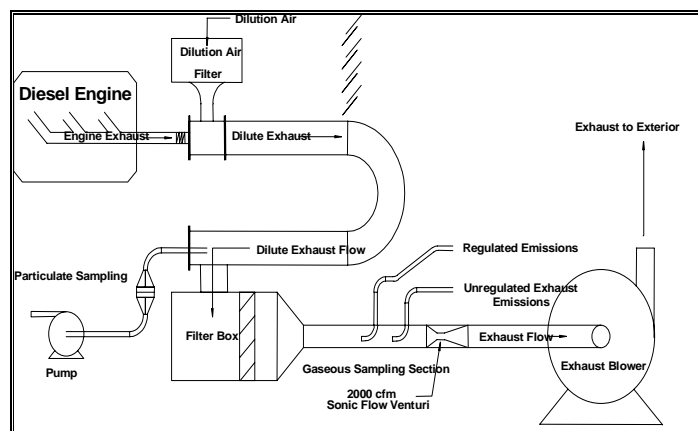


Figure 3: Test cell at Environment Canada

A continuously integrated analytical system was used for determining the THC and NO_x emissions during the testing. This system continuously draws a sample of the dilute exhaust through a heated probe, heated filter, and heated sample line to the heated Flame Ionization Detector (for THC) and the heated Chemiluminescence instrument (for NO_x) during the course of the test. The analyzers then measure and report the concentrations for every second during the testing. The heated components used in this system were maintained at 191 degrees Celsius. Similarly, continuous measurements of CO and CO₂ concentrations were taken throughout the engine duty cycle. This was performed with two separate Non-Dispersive Infrared (NDIR) detection analyzers.

The dynamometer used at Environment Canada was a 500 hp electric D.C. motor with regenerative power absorption.

TESTING AT SOUTHWEST RESEARCH INSTITUTE

US FTP engine dynamometer testing was completed on the 1991 Cummins N14 and the 1989 Cummins 6CTA8.3 at Southwest Research Institute located in San Antonio Texas in DEER cell #11 from March – June 2005.

The experimental setup shown in Figure 4 was used to measure full flow dilute exhaust emissions over cold-start and hot start transient cycles using test procedures given in 40 CFR, Part 86, Subpart N.

Measurements included quantifying total hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO_x), nitric oxide (NO), and particulate matter (PM). The total hydrocarbons were measured using continuous sampling techniques with a heated flame ionization detector (HFID). The NO_x and NO levels were measured continuously using two separate chemiluminescence analyzers, with NO₂ expressed as the difference between NO_x and NO levels.

The PM level for each test was determined using dilute sampling techniques that collected particulate matter on

a series-pair of 90mm Pallflex™ T60A20 filter media. Each pair of particulate filters was weighed before and after sampling to establish mass accumulated for the given emissions test. In addition, some PM analysis was carried out by SwRI using the extraction and filter weight loss technique to determine the SOF content in the PM.

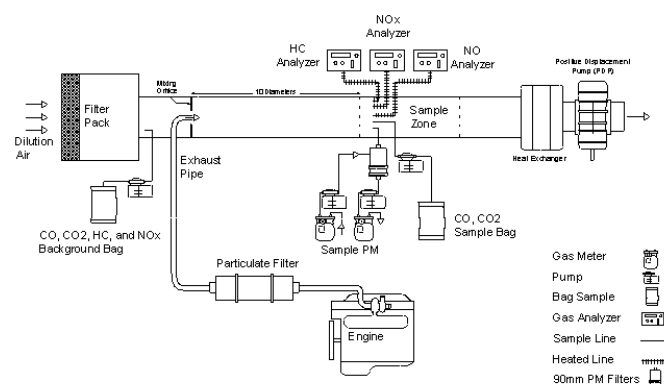


Figure 4: DEER test cell #11 at SwRI

All testing was completed using the United States Federal Test Procedure (US FTP). Figure 5 shows the US FTP transient cycle.

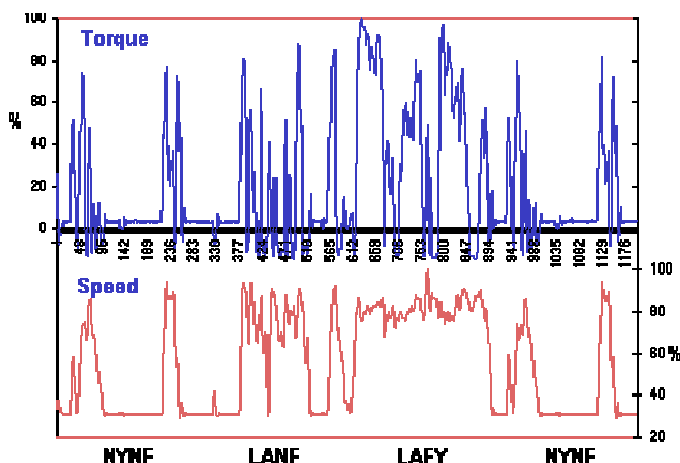


Figure 5: US FTP transient cycle

FIELD INSTALLATION AND TRIAL

Two separate field trials were carried out to evaluate the PFT filter system. One trial started in California on refuse collection trucks operating with ULSD and the second one was in Upper Darby, PA. (a Philadelphia suburb) on a school bus operating on #2 low sulfur diesel.

The California field trial consisted of 5 various model year refuse collection trucks operating throughout the Los Angeles basin. The majority of driving for these trucks is completed on city streets, however some freeway driving is part of the daily cycle as well. Two types of collection trucks were used in the trial. Overhead loaders collect refuse from commercial

dumpsters. A roll-off loader delivers empty refuse containers and picks up full containers (Figures 6 and 7). All the vehicles were operating on ULSD.



Figure 6: Overhead refuse collection truck



Figure 7: Roll-off container hauler



Figure 8: International FE300 school bus

The Upper Darby field trial consisted of a single 37.5 foot International FE300 school bus (Figure 8) powered by an International DT466 190hp engine operating on city streets picking up and dropping off children. This vehicle was operating on #2 low sulfur diesel (LSD).

Table 3 details the vehicles involved in both field trials.

California Refuse Trial with ULSD				
Model Year	Engine	Chassis	Catalyst Volume (L)	Filter Volume (L)
1988	CAT 3208T 250hp	White Expeditior	8.44	16.42
1989	Mack E7 300hp	Mack	8.44	16.42
1993	Volvo TD-73 250hp	White Expeditior	8.44	16.42
1993	Mack E7 300hp	Mack	8.15	19.12
1995	Volvo VE-7	Volvo White	8.44	16.42
Upper Darby School Bus with LSD				
2001	Intl. DT466 190hp	Intl. FE300 37.5'	8.44	16.42

Table 3: Details of the field trial vehicles.

RESULTS AND DISCUSSIONS

The following will be discussed in this section: PFT system characterization, emission testing results at Environment Canada and Southwest Research Institute test cells with the engines operating on ULSD and LSD fuels, and field trial performance of the PFT system.

The primary goals of the system development testing included:

1. Understanding PM trapping efficiency of the PFT system
2. Understand durability of the system as it ages
3. Understand the effect of fuel sulfur level on system performance

ENGINE DYNAMOMETER TEST RESULTS

Two separate rounds of engine dynamometer testing were completed. The first one was at Environment Canada on a 1998 Caterpillar 3126 250hp in March - April 2004. The second set of testing was carried out at Southwest Research Institute during April – June 2005 on a 1991 Cummins N14 350hp engine and a 1989 Cummins 6CTA8.3 240hp engine. Testing was completed with the engines running on ULSD and LSD fuels. Test results for each type of fuel are discussed separately in the following sections.

All testing was completed using 10.5x6 – 400 cpsi pre-catalysts (8.4L) and 10.5x6 – 200 cpsi filters (8.21L each). In certain cases, two 10.5x6 filters were installed in series, creating a 10.5x12 filter (16.42L). This is referred to as a "dual" filter system. PFT systems were tested either after test cell de-greening (24 hrs. of OICA cycle) or following prolonged field aging (3600 hrs). Sample configurations and aging details are provided in the following sections. For each type of fuel, the same catalyst formulation was used for both de-greened and field aged DOCs. However, separate DOC formulations were used with the PFT systems depending on type of fuel used during testing (ULSD and LSD).

Emissions Testing Results with ULSD Fuel

Table 4 details tested system configuration on the three test engines running on ULSD fuel. Emission testing was first carried out with the pre-catalyst to understand the PM removal efficiency of the DOC. Then the PFT system (pre-catalyst plus PFT filter) was tested to obtain a total PM reduction figure. In all cases, the same catalyst formulation was used with each engine tested.

	PFT System Configuration		
	De-greened [DOC + Dual Filters in Series]	De-greened [DOC + Single Filter]	Field Aged [DOC + Single Filter]
1998 CAT 3126 250hp	X	-	-
1991 Cummins N14	-	X	X
1989 Cummins 6CTA8.3	-	X	X

Table 4: PFT system configurations for testing with ULSD fuel

1998 Caterpillar 3126

The Caterpillar 3126 engine was first tested with dual filters in series, as shown in Table 4, in March 2004 at Environment Canada. Testing was carried out with ULSD (<15 ppm S) fuel. Single filter testing was not carried out on this engine. Prior to testing, the PFT system (DOC plus flow through filter) was de-greened for 24 hours using the OICA cycle.

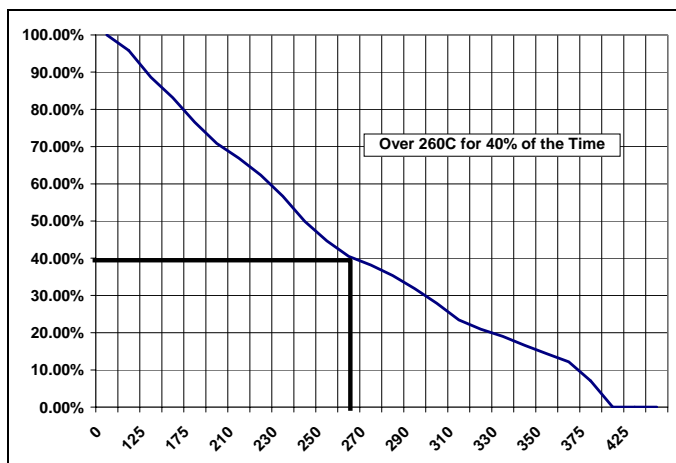


Figure 9: Average exhaust temperature profile of 3 hot FTP cycles on Caterpillar 3126 engine

The emission testing involved three repeat HDD FTP hot tests in each configuration. Cold FTP testing could not be carried out. Figure 9 shows the average exhaust temperature profile during 3 hot FTP cycles on the Caterpillar 3126 engine with the dual filter PFT system. Temperature was measured at the inlet of the PFT. Exhaust temperature appeared reasonably warm and exceeded 260°C for more than 40% of the operational cycle.

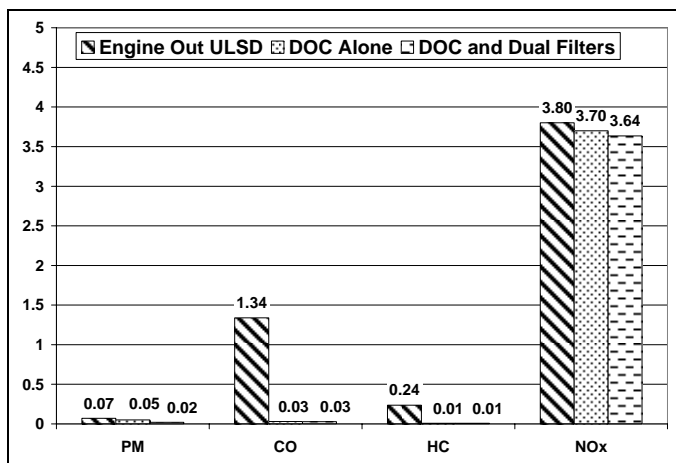


Figure 10: Emission test results (g/bhp-hr) on 1998 CAT 3126 with de-greened DOC and de-greened PFT system using ULSD fuel

Figure 10 shows the emission test results from the CAT 3126 engine testing. Results are presented as an average of 3 hot FTP emission tests. The test configurations were engine out emissions, DOC out emissions and PFT system out emissions in g/bhp-hr

with the engine operating with ULSD fuel. It can be seen that significant PM reductions were achieved with both the DOC and with the PFT system.

Figure 11 details the emission reductions as a percentage of the baseline engine out emissions. On the Caterpillar 3126 engine, the DOC alone produced 30% PM reduction. In comparison, the PFT system provided 72% PM reduction, signifying an additional 42% PM reduction by adding the flow through filter. CO and HC were both reduced by greater than 95% with both the DOC and the PFT system.

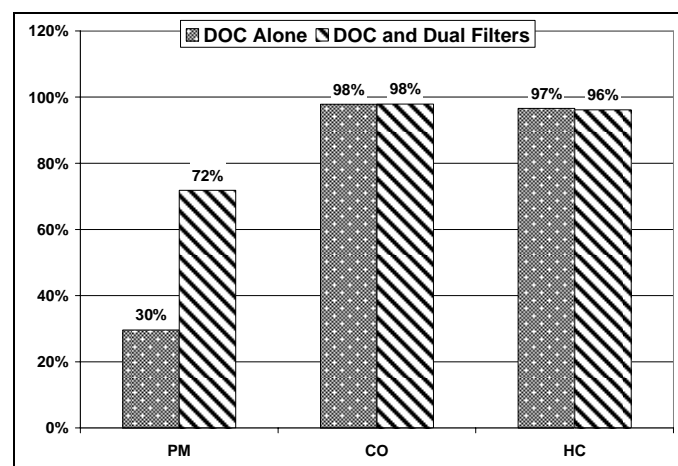


Figure 11: Emission reductions with de-greened DOC and de-greened PFT system using ULSD fuel on CAT 3126

Another round of engine dynamometer emission testing with PFT systems was carried out at Southwest Research Institute in San Antonio, Texas. The objective was to compare emissions reduction performance between a single and a dual filter configuration. In addition, field-aged PFT system testing was also carried out to compare the performance of de-greened and field aged PFTs.

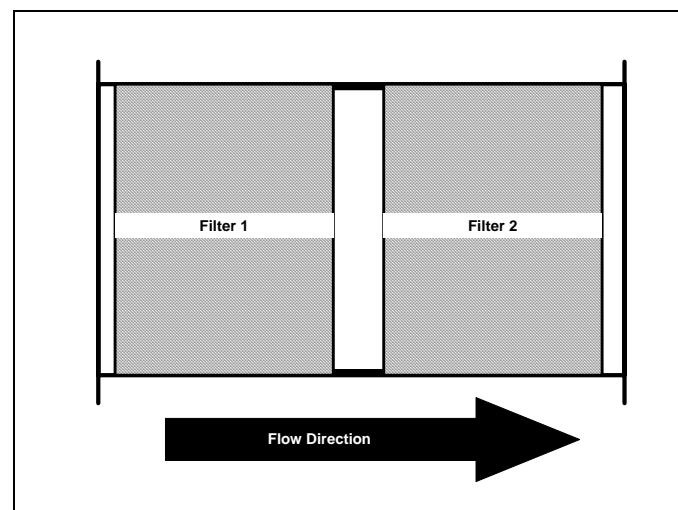


Figure 12: PFT system dual filter module configuration

For this testing, the aged PFT system was retrieved from one of the trucks operating in the California refuse truck field trial. The catalyst and dual filter modules were originally installed on a 1993 White/Expeditor powered by a 250hp Volvo TD-73 engine (Truck FL44). The system accumulated over 3600 hours of stable operation before removal for this testing.

The dual filter module was separated into 2 individual single filter modules. Figure 12 shows a dual filter module with the filters in series. For test purposes, the front filter (filter 1) was removed and used in all testing. Testing was carried out on a 1991 Cummins N14 and a 1989 Cummins 6CTA8.3 in April – June 2005. De-greened and aged single filter systems were tested with the engines running on both ULSD fuel.

1991 Cummins N14

A single 10.5x6 – 400 cpsi DOC and single 10.5x6 200 cpsi flow through filter were tested on the 1991 Cummins N14-330E engine. The N14 was a 14L engine rated at 350hp @ 2100rpm and 1440lb-ft of torque @ 1200rpm (S/N 11635538). Both de-greened and aged systems were tested on this engine. De-greened system was prepared by aging a fresh DOC and PFT filter using the OICA cycle for 24 hours. No sample preparation was required for the aged parts. The aged parts were tested as removed from the vehicle. The testing involved HDD FTP Cold and Hot test cycles. Results are presented both as average of hot tests and as a composite of one cold and three hot test cycles.

Figure 13 shows the exhaust temperature profile during the FTP testing on the N14. The temperature was measured at the inlet of the PFT. This temperature profile is again, an average of 3 hot FTP cycles. The exhaust temperature of this engine was only above 230°C for 40% of the operational cycle, which was significantly less (apprx. 30°C) than the previously tested Caterpillar 3126 engine. ,

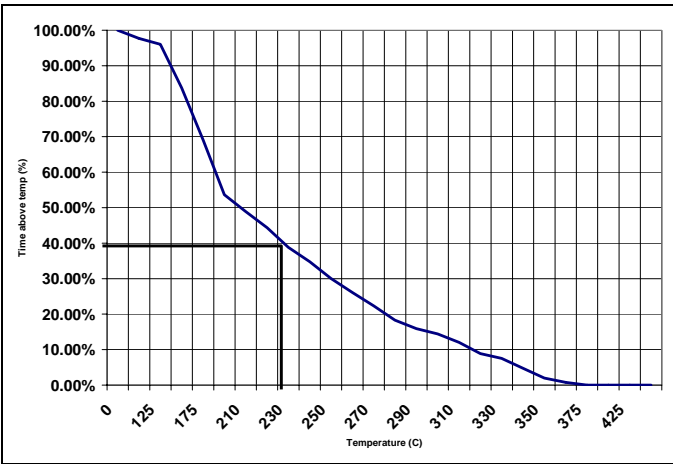


Figure 13: Average exhaust temperature profile of 3 hot FTP cycles on the Cummins N14 engine

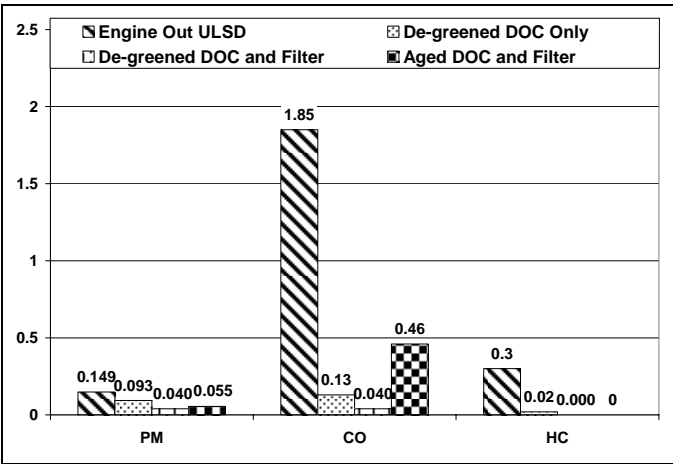


Figure 14: Emission test results (g/bhp-hr) for FTP Hot tests with DOC and PFT systems on 1991 Cummins N14 using ULSD fuel

Figure 14 quantifies the emissions from the N14 engine as engine out, de-greened DOC out, de-greened PFT system out and aged PFT system out, with the engine operating on ULSD fuel. These are average of 2 - 3 FTP hot test results only. As with the Caterpillar 3126, it can be seen that significant PM reductions were achieved with both the de-greened DOC and with the de-greened PFT system. In addition, the aged PFT system also showed significant PM reduction.

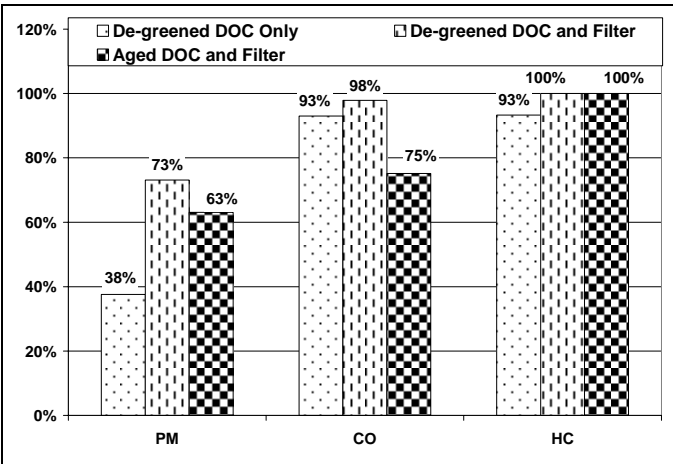


Figure 15: Emission reductions during FTP hot tests on 1991 Cummins N14 with DOC and PFT systems using ULSD fuel

Emission reductions with the DOC and the PFT systems on the N14 engine during FTP hot tests, are shown in Figure 15. These results indicate that a 73% PM reduction was achieved with a de-greened PFT system using a single filter while 63% PM reduction was observed with an aged PFT system, also using a single filter. However, the de-greened DOC alone produced 38% PM reduction on this engine. In addition, the de-greened system converted >95% of the HC and CO. The aged system showed some reduction in CO conversion (75%) but no such reduction for HC conversion.

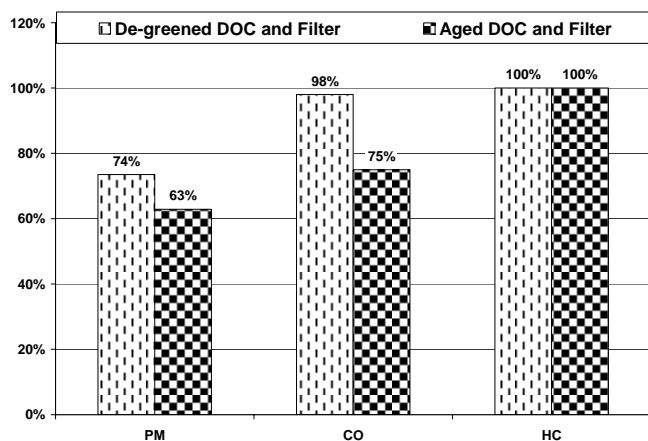


Figure 16: Emissions reductions during FTP composite testing on 1991 Cummins N14 with different PFT systems using ULSD fuel

In Figure 16, emissions reductions with the de-greened PFT and the field aged PFT on the Cummins N14 engine are presented for FTP composite testing (weighted average of 1 cold and 3 hot tests). It can be seen that the emission reductions remain consistent when the FTP composite results are compared to the FTP hot tests shown in Figure 15. PM reduction was up slightly to 74% versus 73% with the de-greened system while the aged system remained at 63%. CO and HC reductions did not change from the hot test average to the composite average.

It is well understood that, the PM reduction exhibited by a DOC on a diesel engine is mostly due to the oxidation of the soluble organics or SOF [3, 4, 5] from the engine out PM. The engine out PM analysis of the Cummins N14 showed about 50% SOF content during FTP hot tests. This explained the 38% PM reduction observed with the DOC on this engine, even though the exhaust temperature profile was much lower than the Caterpillar 3126. Furthermore, this high efficiency DOC used with ULSD fuel in this PFT system is also very efficient and durable for overall SOF removal. This was clearly demonstrated by the 93% and higher HC removal observed in these tests with either de-greened or aged PFT system. Therefore, it can be expected that the DOC in the PFT system provided a consistent PM removal through oxidation of the SOF.

The overall PM reduction in a PFT system is the cumulative effect of PM reduction on the DOC and PM reduction on the flow through filter. These test results signified that a de-greened single PFT filter produced an additional PM reduction of approximately 35% on this engine, while the same with an aged filter was about 25%. It can be inferred that this additional PM removal observed with the flow through filter in the PFT systems was primarily due to the trapping of the inorganic carbon (soot) component of the PM (since the DOC efficiency appears to remain unaffected with aging) [5]. Based on this testing, it appears that a single 10.5x6 flow through

filter in the PFT is capable of 25 – 35% soot trapping depending on the aging condition.

These results indicate an apparent loss in trapping efficiency when a de-greened system is compared to an aged system. It may be speculated that depending on oil consumption and ash content of the oil, ash accumulation on the flow through filter substrate (inside the sintered metal fleece material) may reduce the soot trapping efficiency. This has been clearly observed with such field aged filter systems [8]. Due to the inherent design of the flow through filter, where only a fraction of the flow will be forced through the fleece for filtration, the amount of accumulated ash can limit such filtration area and thus reduce soot trapping efficiency. This inherent design, on the other hand, also prevents filter channel blockage even when ash is deposited.

Besides the regulated emissions, NO and NO₂ emissions from the different PFT systems were also analyzed during the FTP tests. With the high efficiency DOC used in the PFT for ULSD testing, it is expected that the NO₂ concentration in the exhaust will be significantly increased. Accordingly, comparing the NO₂/NO_x ratios between the engine and the de-greened PFT, the latter showed 40 – 45% increased (absolute) NO₂/NO_x ratio. The field aged PFT system showed about 30 – 35% increased (absolute) NO₂/NO_x ratio compared to the base engine. These results suggested that since the PM reduction efficiency of the PFT system is noticeably lower than a CRDPF, a lower efficiency DOC can probably be used in the PFT system and thus the NO₂/NO_x ratio can be reduced.

1989 Cummins 6CTA8.3

PFT systems, comprising a single 10.5x6 – 400 cpsi DOC and single 10.5x6 – 200 cpsi flow through filter, were tested on a 1989 Cummins 6CTA8.3 (S/N 44370295) engine rated at 240 bhp @ 2200 rpm and 680 lb-ft torque @ 1400 rpm. The de-greened and the aged PFT systems used for this testing were the exact same parts previously tested on the 1991 Cummins N14 engine. No additional sample conditioning was carried out. It should be noted that this engine was rebuilt prior to these emission testing. The testing involved HDD FTP Cold and Hot test cycles. Results are presented both as average of Hot tests and as a composite of one Cold and three Hot test cycles.

The exhaust temperature profile during the FTP cycle with this engine is shown in Figure 17. Similar to the CAT and Cummins N14 engines, this profile is an average of 3 hot FTP tests. The exhaust temperature observed was over 270°C for 40% of the cycle. This temperature profile was slightly higher (10°C) than the 1998 Caterpillar 3126 and significantly higher (40°C) than the 1991 Cummins N14.

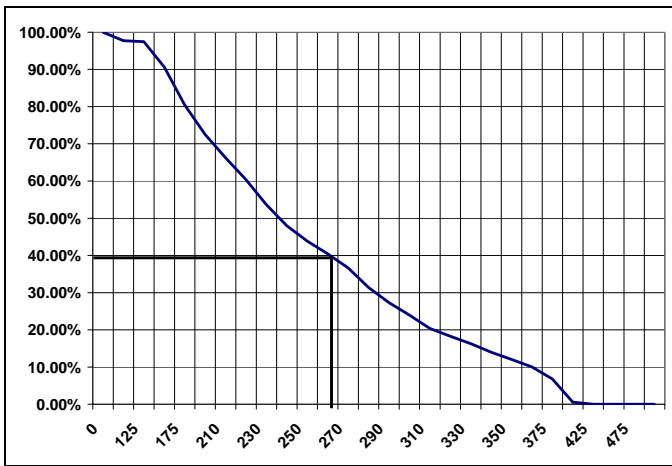


Figure 17: Average exhaust temperature profile of 3 hot FTP cycles on a 1989 Cummins C8.3 engine

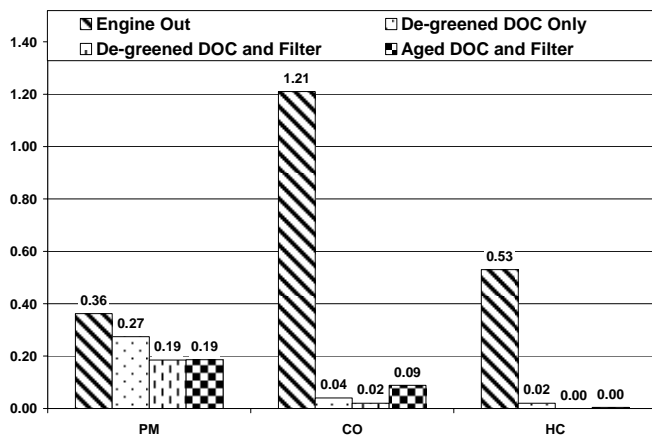


Figure 18: Emission test results (g/bhp-hr) for FTP Hot tests with DOC and PFT systems on the 1989 Cummins C8.3 using ULSD fuel

Engine out emissions along with emissions from de-greened PFT system and aged PFT system for the Cummins C8.3 engine are presented in Figure 18. This is shown as an average of three FTP hot test cycles.. Again, it can be seen that the partial filter system significantly reduced the PM mass when compared to the baseline engine out figure.

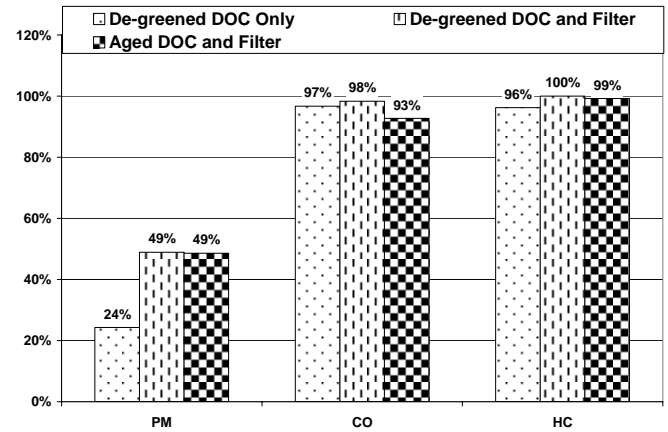


Figure 19: Emission reductions during FTP hot tests on 1989 Cummins C8.3 with DOC and PFT systems using ULSD fuel

The results in Figure 19 demonstrate that close to 50% PM reduction was possible using both de-greened and aged single filter PFT systems, even when tested on this older, higher emission engine. Again, these results are based on average of three hot FTP tests. In addition, both CO and HC conversions were >90% with both the de-greened and the aged systems on this engine.

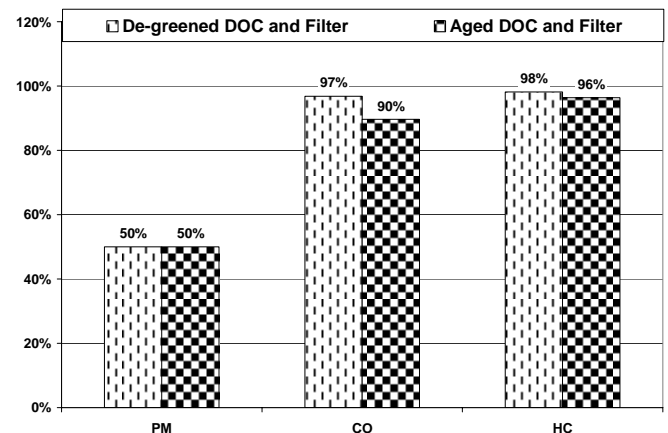


Figure 20: Emissions reductions during FTP composite testing on 1989 Cummins C8.3 with different PFT systems using ULSD fuel

Figure 20 shows the emissions reductions for FTP Composite (1 cold and 3 hot cycles) test cycle with the de-greened and the aged PFT systems on the C8.3 engine. Under composite testing, PM reduction with the PFTs increased to 50%. However, CO and HC reductions were maintained at and above 90%.

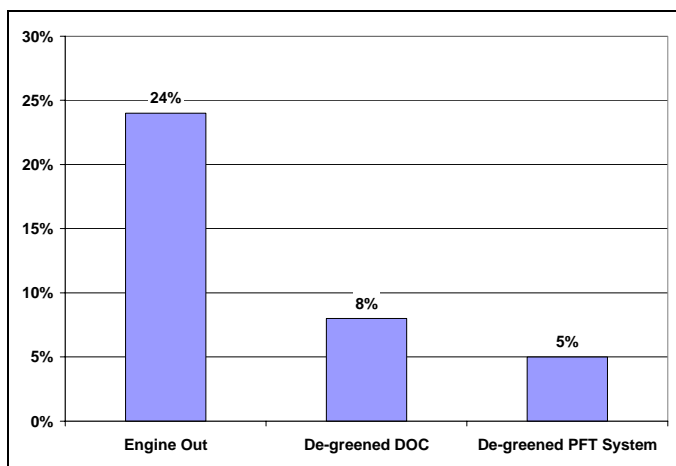


Figure 21: SOF contribution to total PM mass as tested on the 1989 Cummins C8.3 engine with ULSD fuel

Comparing the performances between the DOC and the PFT systems under FTP Hot tests, it can be seen that the DOC produced 24% PM reduction while the flow through filters produced an additional 25% PM reduction (49% total for PFT). The flow through filter contribution increased to 26% (total 50%) under FTP composite. The C8.3 engine-out PM analysis showed that it contained about 24% SOF (Figure 21), most of which was removed by using the DOC alone. In comparison to the N14, the much higher exhaust temperature profile appeared to have contributed towards this increased efficiency for SOF removal in the C8.3. The PM analysis also showed that there was almost no difference in the SOF content of the PM after the de-greened DOC and after the de-greened PFT. These results clearly demonstrated that while the PM reduction by the DOC was primarily due to SOF removal from the PM, the additional PM reduction by the flow through filter was due to the inorganic soot removal. Again, this points to about 25 - 26% soot capture and removal efficiency for the single 10.5x6 flow through filter. Interestingly, the reduction in filter performance is not seen with the aged filter on the C8.3 engine. This may indicate slightly better performance of the PFT system (NO_2 & soot burn) with the smaller C8.3 engine compared to the larger M11 engine, since the same exact PFT was used on both. This might have also been affected by some ash loss during the previous tests with the N14.

As with the N14 engine, NO and NO_2 emissions from the different PFT systems were also analyzed during the FTP tests. When the NO_2/NO_x ratios between the engine and the de-greened PFT are compared, the latter showed 35 - 40% increased (absolute) NO_2/NO_x ratio. The field aged PFT system showed about 20 - 25% increased (absolute) NO_2/NO_x ratio compared to the base engine. These results are slightly less than the results gathered from the N14, however they still suggest that since the PM reduction efficiency of the PFT system is noticeably lower than a CRDPF, a lower efficiency DOC can probably be used in the PFT system and thus the NO_2/NO_x ratio can be reduced.

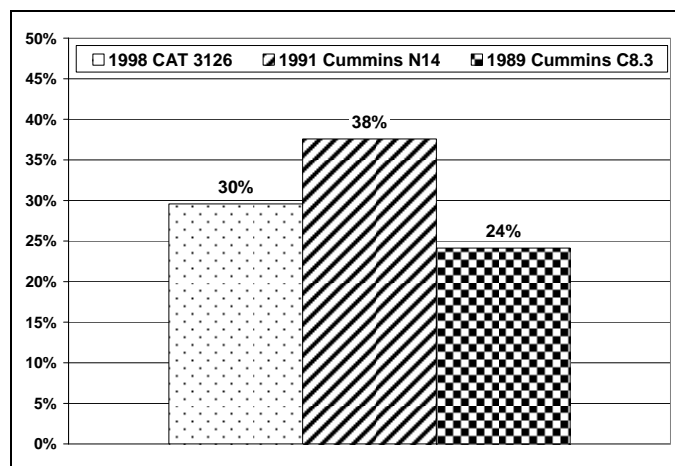


Figure 22: PM reductions with the de-greened DOCs on all three engines using ULSD fuel

Figure 22 summarizes the PM reductions observed with the de-greened DOCs on the three test engines as an average of hot FTP test cycles. As discussed, PM reduction with the DOC was highest on the Cummins N14 followed by the Cat 3126 and then the Cummins C8.3. These results also signified that the SOF portion of the PM was highest for the Cummins N14, followed by the Cat and then the Cummins C8.3. PM analysis from the N14 and the C8.3 supported this analysis.

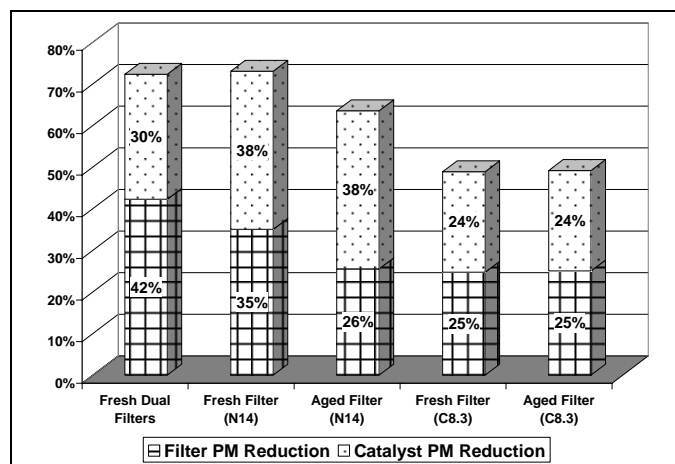


Figure 23: Catalyst and PFT Filter contribution to PM reduction shown over hot FTP test cycles

Figure 23 shows the contributions of both the DOCs and the flow through filter modules to the overall PM reduction for all three engines. The results are an average of 2 - 3 hot FTP test cycles. The Caterpillar engine is shown using a de-greened dual filter system and the Cummins engines are shown using both de-greened and aged single filter systems. Based on these results, it appears that a single filter element traps between 25% and 35% by mass of the soot particles, depending on the aging condition. By comparing the de-greened dual and single filter testing, it appears that a dual filter module contributes 42% (soot trapping) to overall PM reductions which represents a 17% increase in PM trapping efficiency compared to the single filter results.

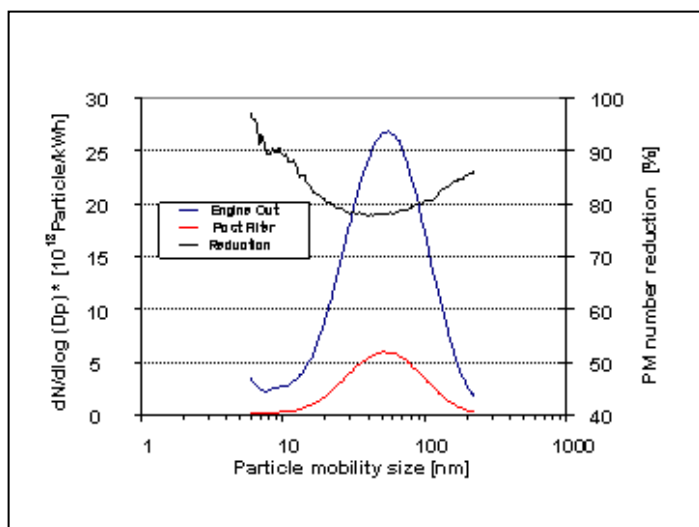


Figure 24: Particle size reduction with PFT filter system on MAN engine

In addition to the PM mass reductions presented in this paper, the partial filter system also appears to reduce PM particle number across different size ranges. Results published by E. Jacob of the MAN Group during the Wien Engine Symposium April 2005 [9] showed significant particle reductions across the entire size range. This data was collected using a EURO III MAN engine running on ULSD fuel (nominal 9ppm S) configured with a catalyst volume of 4.32 L and filter volume of 8.36 L. Figure 24 shows total particle number reduction between 75% and 90%. Rothe et al. [10] suggested that particles smaller than 10nm consist mainly of hydrocarbon or sulfuric acid droplets and that particles in the 60nm range consist of the actual soot particles which may also contain condensed hydrocarbons, sulfuric acid, and oil ash particles. Figure 24 clearly shows better than 75% conversion of particles in the 60nm size range. This data shows that the partial filter significantly reduces the number of particles as well as the mass of the PM. Further studies are being carried out to better understand reduction in total particle count.

Emissions Testing with #2 LSD Fuel

As mentioned earlier, emission testing was also completed on all three engines with PFT systems, while using commercially available #2 LSD fuel ($\approx 350\text{ppm S}$). A sulfur-tolerant and lower sulfate make DOC was used in this PFT system along with single or dual flow through filter substrates. All PFT systems were tested following 24 hrs of degreening. Table 5 details the test configurations.

A PFT system with dual filter module was tested on the 1998 Caterpillar 3126 engine at Environment Canada. Both the Cummins N14 and C8.3 were then tested with single filter modules at Southwest Research Institute. Only de-greened systems were tested. Aged system testing with LSD fuel was not completed because a properly LSD fuel aged system was not available at the time of testing. In addition, separate DOC only test

results were not available, hence complete PFT system PM reductions are shown. Only FTP Hot test results are presented here for LSD fuel testing.

	PFT System Configuration	
	De-greened [DOC + Dual Filters]	De-greened [DOC + Single Filter]
1998 Caterpillar 3126	X	-
1991 Cummins N14	-	X
1989 Cummins C8.3	-	X

Table 5: PFT system configurations for testing with LSD fuel

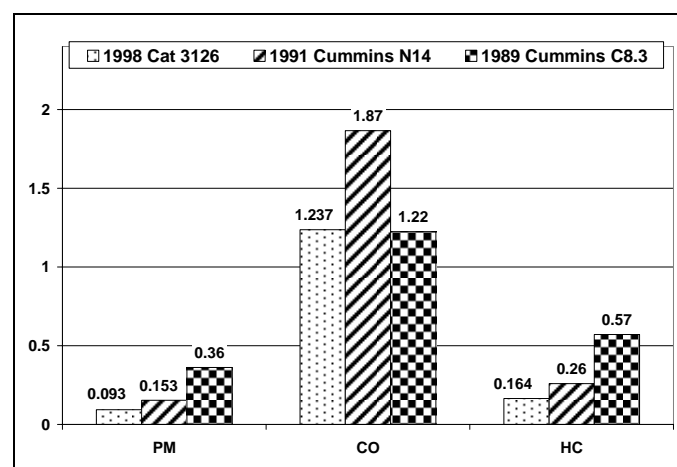


Figure 25: Engine out emissions (g/bhp-hr) using LSD fuel on all three test engines

Figure 25 shows the engine out emission levels in g/bhp-hr from all three engines. The results are reported as average of three hot FTP tests. Cold tests were not carried out in these cases. As expected, the PM mass increased due to the sulfur in the fuel when compared to the results gathered during the ULSD testing. However, the exhaust temperature profiles did not change with the change of fuel on these engines.

Figure 26 shows the emissions in g/bhp-hr after the partial filter systems were tested on all three engines using LSD fuel. PFT systems on all three engines showed significant PM, CO, and HC reductions when compared to engine out emission levels.

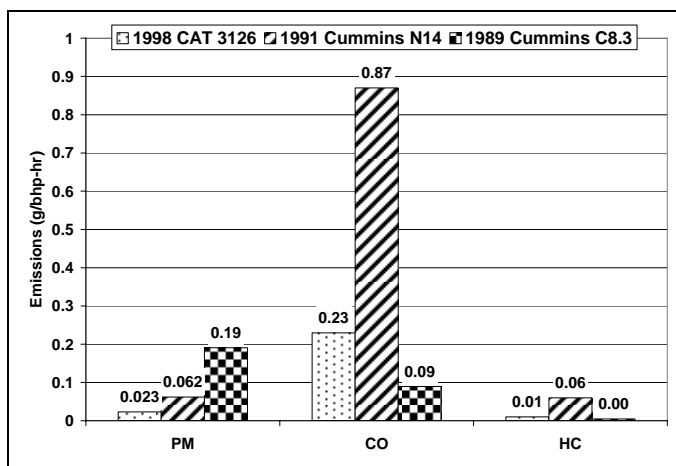


Figure 26: Emissions (g/bhp-hr) results with de-greened PFT systems on all three engines, using LSD fuel

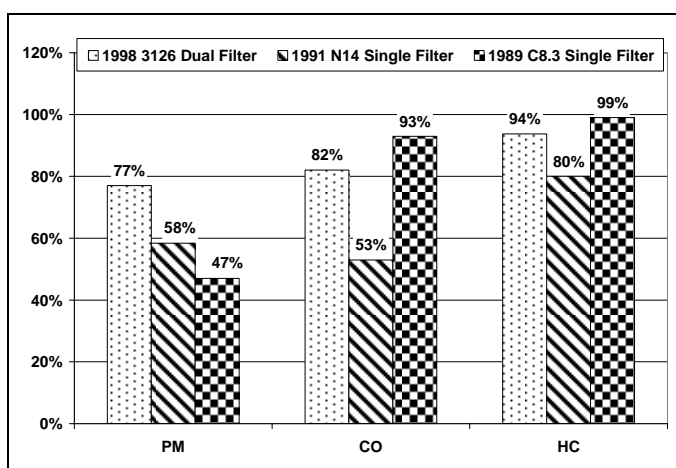


Figure 27: Emission reductions with de-greened PFT systems on all three test engines, using LSD fuel

Figure 27 shows the emission reductions achieved on all three engines. Once again, it can be seen that the partial filter system is capable of reducing the PM significantly when compared to the engine out levels, even with LSD fuel. If we assume that the filter maintains an approximate trapping efficiency of 26% (similar to results gathered during ULSD testing) we see that the DOC contribution is reduced for LSD fuel testing on these engines. This is to be expected because the catalyst formulation with LSD fuel is not as active due to the sulfur tolerance requirement. PM was reduced between 47% and 77%. The lowest PM reduction was with the single filter on the C8.3 engine which was also the case with the ULSD fuel. This appears to be due to the lower SOF content of the engine-out PM and hence reduced PM reduction with the DOC alone. On the other hand, highest total PM reduction was observed with the dual filter PFT system on the Cat 3126 engine.

CO emission was reduced between 53% and 93% with PFT systems on these engines. HC emission was reduced by > 80% in all cases. Results also indicated that the CO and HC conversion with LSD fuel and the PFT systems were related to the engine exhaust temperatures. Highest CO and HC conversions were

obtained with the C8.3 engine which also showed the highest exhaust temperature profile (40% > 270°C). The PFT on the Caterpillar engine showed the next best CO and HC conversion and it also showed intermediate temperature profile (40% > 260°C). Finally the Cummins N14 with the coldest temperature profile (40% > 230°C) showed the lowest CO and HC conversion. It should be noted that this effect was not observed with ULSD fuel when all three systems showed very high CO and HC conversions. This appears to be due to the use of lower efficiency, sulfur tolerant DOC. This trend may also hold for NO₂ generation with this DOC for filter regeneration. Unfortunately, the effect of field aging with LSD fuel could not be evaluated in the engine test cell, but field trial results are discussed below.

FIELD TRIALS

Two field trials were initiated to demonstrate system durability using dual filter modules. The first, started in August 2003 on trash haulers running on ULSD, is based in the Los Angeles, California area. The second, started in November 2004 on a school bus running on LSD, is based in the Philadelphia, Pennsylvania area. Table 6 details the field trial participants.

California Refuse Trial with ULSD Fuel					
Model Year	Engine	Chassis	Vehicle Number	Catalyst Volume (L)	Filter Volume (L)
1988	CAT 3208T 250hp	White	FL27	8.44	16.42
1989	Mack E7 300hp	Mack	1525	8.44	16.42
1993	Volvo TD-73 250hp	White	3191	8.44	16.42
1993	Mack E7 300hp	Mack	FL44	8.15	19.12
1995	Volvo VE-7	Volvo White	FL7	8.44	16.42
Upper Darby School Bus Trial with LSD Fuel					
2001	Intl. DT466 190hp	Intl. FE300 37.5'	17	8.44	16.42

Table 6: Field trial system details

ULSD Fuel Field Trial

The California Refuse Hauler Demonstration program (referenced in this paper previously) contained five trash trucks operating in the Los Angeles, California area running on ULSD fuel. The trucks are based north of Los Angeles and operate throughout the basin collecting commercial and construction waste.

The refuse trucks transport waste to a transfer facility where they are off-loaded and returned to collection service. This program utilized dual filters in series in two

diameters, 10.5" and 11.25". All filters retained a standard length of 6", creating an effective substrate length of 12". All of the trucks were equipped with a datalogger that continuously monitored system back pressure and exhaust temperature.

The on-road exhaust temperature varied from vehicle to vehicle, however in all cases it was typically between 100 and 450C. Figures 28 and 29 represent the lowest (Truck 3191, 1993 Mack E7 300hp) and highest temperature (Truck FL44, 1993 Volvo TD-73 250hp) profiles observed in this trial.

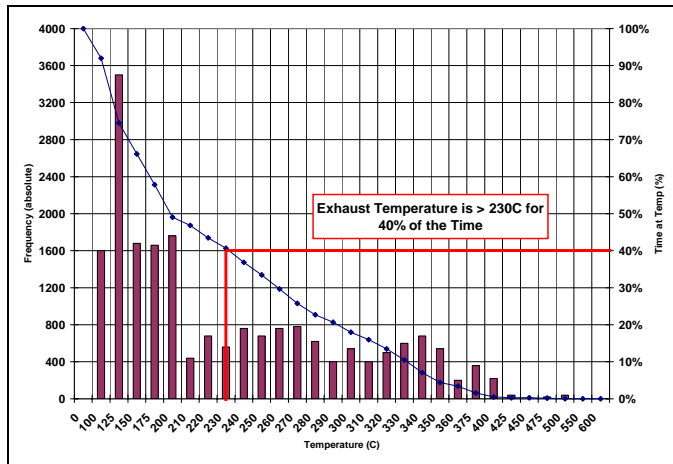


Figure 28: Exhaust temperature profile for Truck 3191 with 300 hp 1993 Mack E7 engine

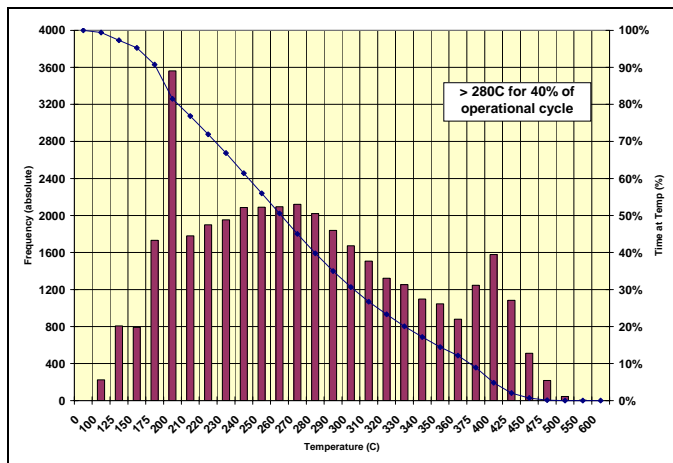


Figure 29: Exhaust temperature profile for Truck FL44 with 250 hp 1993 Volvo TD-73 engine

In both cases, stable exhaust back pressure was observed over the course of the field trial. Figure 30 shows stable peak on-road back pressure between 6.5 and 7.5 in Hg observed on truck 3191. This truck was equipped with dual 11.25 x 6 filters in series. While the peak on-road back pressure was slightly higher than typically expected with a wall flow DPF, no operator complaints such as low engine power or additional maintenance were noted during the trial.

The exhaust back pressure distribution for truck 3191 is shown in Figure 31. This data indicates that while the

peak back pressure may be high, the distribution is quite low (exceeding 2.75 in Hg less than 10% of the operation time) and very reasonable for a vehicle in daily service.

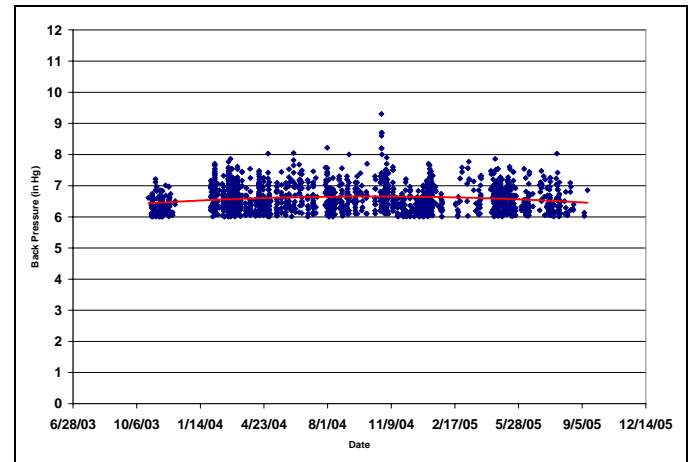


Figure 30: Peak on-road back pressure with PFT on Truck 3191 with 300 hp 1993 Mack E7 engine

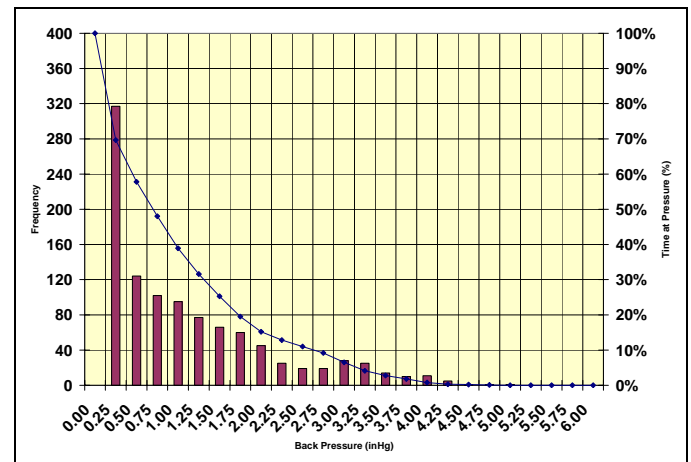


Figure 31: Exhaust back pressure distribution with PFT on Truck 3191 with 300 hp 1993 Mack E7 engine

Figure 32 shows the peak on-road back pressure for truck FL44. Truck FL44 used dual 10.5 x 6 filters in series. The peak on-road back pressure was stable between 6 and 7 in Hg. It's also interesting to note the spike in peak back pressure in May 2004 shown in Figure 32. This represented an incident when the engine fuel pump failed causing very high engine out soot conditions and hence the increase in the back pressure. It is important to note that even though the peak back pressure increased during this incident, the filter did not plug. The back pressure returned to normal immediately after repairs were made to the engine. There was no long term negative effect to the filter as evidenced by the emission testing carried out at Southwest Research Institute. This indicates that the substrate is very robust in the event of such engine upset condition.

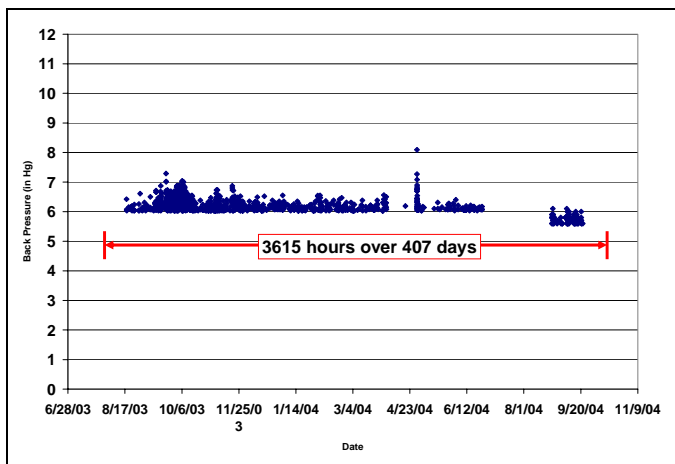


Figure 32: Peak On-road Back pressure with PFT on truck FL44 with 250 hp 1993 Volvo TD-73 engine

Figure 33 shows the back pressure distribution of truck FL44. It has a very similar back pressure profile when compared to 3191. The exhaust back pressure with this PFT system exceeded 2.6 in. Hg for less than 10% of the operating time.

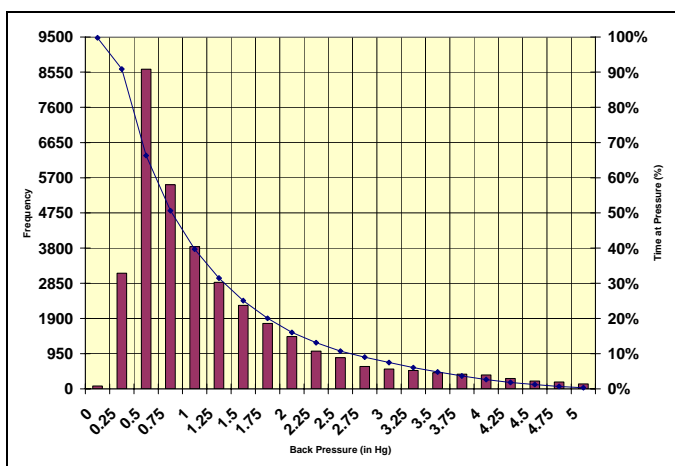


Figure 33: Back Pressure distribution, Truck FL44

It should be noted that even though these field trials were carried out with dual filter modules, based on the more recent engine test cell work, it will be preferable to use single filter systems. It appears that the additional PM reduction added by the second filter is not required to achieve > 50% PM reduction with the PFT system, therefore the additional cost and presumed higher back pressure incurred with a second filter can not be justified. Independent of the single versus dual filter configurations, the stable back pressure shown by the field trial vehicles indicates that the partial filter system regenerates continuously, thereby minimally impacting vehicle performance and maintenance requirements.

LSD Fuel Field Trial

The Upper Darby school bus field trial was initiated to demonstrate durability of the PFT system with an engine operating on commercially available #2 LSD fuel. The bus operates in a congested area of the suburbs of

Philadelphia, PA picking up and dropping off children. It also transports high school sports teams to events as well as other special class functions. This system has accumulated over 900 hours in 14 months service.

Peak on-road back pressure from this PFT application is shown in Figure 34 indicating very stable operation over time even though the exhaust temperature profile is very cold as shown in Figure 35 (> 210C for 40%). Please note that the gap in data from June through September 2005 is due to summer break when the bus did not run and not due to a mechanical repair taking the bus out of service. A typical CRDPF would most likely plug at these lower exhaust temperatures showing the value of this system when being applied to difficult duty cycles.

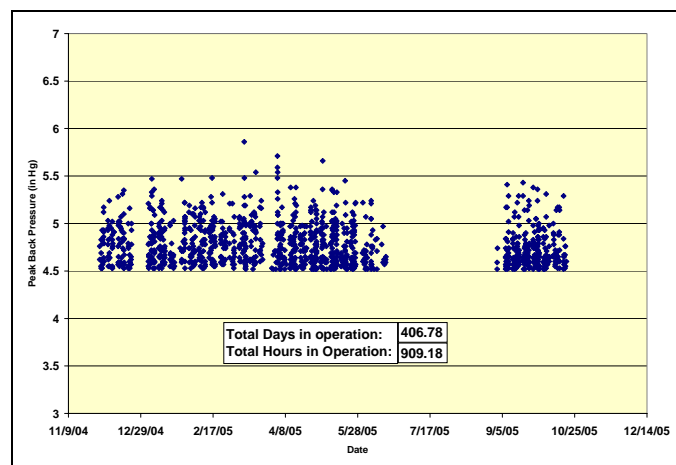


Figure 34: Peak On-road Back Pressure Upper Darby School Bus #17 with LSD Fuel

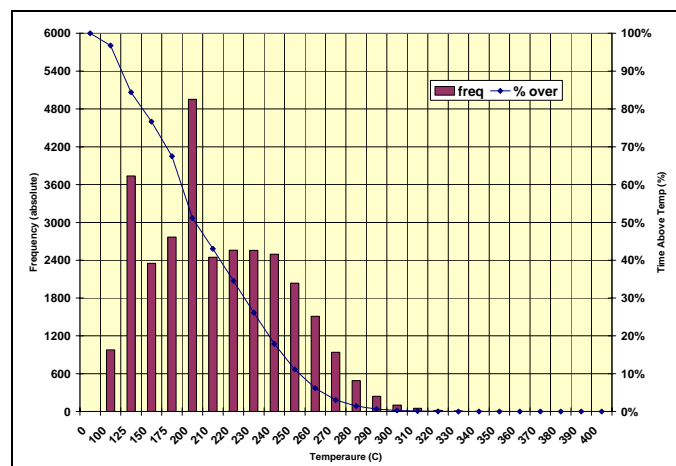


Figure 35: Exhaust temperature profile for Upper Darby School Bus #17

Besides the Upper Darby school bus, two transit buses with 1991 Mercedes OM 366 engine and 2001 International DT 466 engine are also operating with the PFT system and LSD fuel in Mexico City. These have been operating without any issues since September 2005.

The stable results from the school bus application and the transit buses may indicate that long term operation

on fuels with a sulfur level up to 350 ppm is possible with the partial filter system. These applications may include off-road as well as on-road. However, further field trials with LSD fuels will have to be carried out as well as field aged systems will have to be tested to clearly establish the durability of the PFT system with LSD fuel.

CONCLUSION

The results of the multiple field trials and engine test cell testing on the 1998 Caterpillar, the 1991 Cummins and 1989 Cummins engines indicate the following:

- PM mass reductions of up to 77% are possible when retrofitting existing diesel powered vehicles with ULSD and a PFT system
- Greater than 90% CO and HC reductions are possible when retrofitting existing diesel powered vehicles with ULSD and a PFT system
- It is possible to achieve >50% PM reduction with a single filter element in the PFT system in retrofit applications with ULSD fuel
- Current filter design allows greater than 45% PM reduction, when tested in a de-greened condition with commercially available #2 LSD fuel
- The stable back pressure observed on the different model year vehicles with varying exhaust temperature profiles indicated the good durability of the PFT system across a wide range of applications. However, the durability with LSD fuel needs to be confirmed through additional testing.
- The robust design of the partial filter is resistant to engine upset conditions causing very high PM out emissions
- The design allows easy retrofit on a variety of heavy duty diesel engines.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the following for their contribution to this work:

The staff at Environment Canada and Southwest Research for performing the engine test cell testing and emission analysis.

The California Air Resources Board for sponsoring the California Refuse Truck Field Trial.

Crown Disposal Company and Foothill Waste Reclamation for participating in the California Refuse Truck Field Trial.

Upper Darby School District for participating in the field trial.

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