ELECTRIC DIESEL PARTICULATE FILTER DEMONSTRATION

by

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ABSTRACT

A diesel particulate filter (DPF) is highly effective at removing particulate matter (PM) from the exhaust stream. Removing the collected soot (i.e., regenerating the filter) is a more challenging problem, and for this reason a large number of diesel engines are not compatible with currently ARB-verified DPFs. This includes many older engines found in school buses.

The objective of Cleaire's ICAT project was to develop and demonstrate a product that decouples the regeneration from the engine's operating conditions through off-line electrical heating of the DPF. The ICAT project's goals were to optimize the hardware, control systems, and operational procedures to create a robust and fail safe PM control system that can be used in widespread duty cycles and on older engines.

The Horizon EPF and regenerative infrastructure performed as designed during the ICAT project and field demonstration. The chassis dynamometer testing validated the Level 3 emission reduction goal for the EPF (greater than 85% PM removal efficiency). Furthermore, the testing found that the Horizon EPF reduced the NO_2 emissions, thus providing an additional air quality benefit. Cleaire successfully met the objectives of the ICAT project and is now commercializing the Horizon EPF product.

EXECUTIVE SUMMARY

Cleaire received an ICAT grant from the ARB to develop and demonstrate an electric particulate filter (EPF) for retrofit applications on in-use diesel engines. The primary objectives of the project were to develop a robust product, design and install the necessary regenerative infrastructure, demonstrate the technology in field trials and validate the emission performance in laboratory testing.

The ICAT project was comprised of five major tasks over a one-year time frame:

1. Build prototype and regeneration emissions testing
2. Installation of regenerative infrastructure
3. Installation of EPF on demonstration vehicles
4. Field testing of technology
5. Dynamometer emission testing, final report and technical seminar

Cleaire built and tested prototype systems before the ICAT project formally began and refined the product prior to the ICAT field demonstrations and testing. The six-month field trial on a school bus operated by the Elk Grove School District (Sacramento County) provided rigorous testing of the:

- components of the EPF system
- control system algorithm that notifies the user to plug in the system (a flashing amber light)
- operator's response to the flashing amber light (to plug in the system)
- design and operation of the regenerative infrastructure
- vehicle's typical operating range (no noticeable effect from the EPF)

The EPF system and regenerative infrastructure performed as designed. Furthermore, the school district was so pleased with the vehicle's operations and the EPF's performance that it purchased and installed a total of 49 systems.

The regeneration emission testing showed no adverse emissions during the regeneration process. The chassis dynamometer testing validated the greater than 85% PM removal by the EPF. Additionally, the dynamometer testing showed a high level of NO_2 reduction from the EPF allowing it to meet Level 3+ performance.

Cleaire was able to use the ICAT project to validate that the EPF is a commercially ready Level 3+ device for wide-spread application on in-use diesel engines.

Introduction

The ICAT project accelerated the development and commercialization of the Horizon EPF diesel exhaust purifier. The tasks, goals and results of the project are detailed in this final report, which is the final element of the ICAT grant.

Innovative Technology

SYSTEM DESCRIPTION

The EPF is an emission control system that captures particulate matter emitted from an operating engine at efficiency rates above 85%. The EPF consists of an uncatalyzed silicon carbide (SiC) wall-flow diesel particulate filter, an electric heating element, an air pump, and electronic controls. The EPF replaces the existing muffler, and offers sound attenuation equal to or better than the original muffler. The electronic control system monitors exhaust backpressure and manages the regeneration process. The major components of the system are represented in Figure 1 and are described in the subsequent subsections.

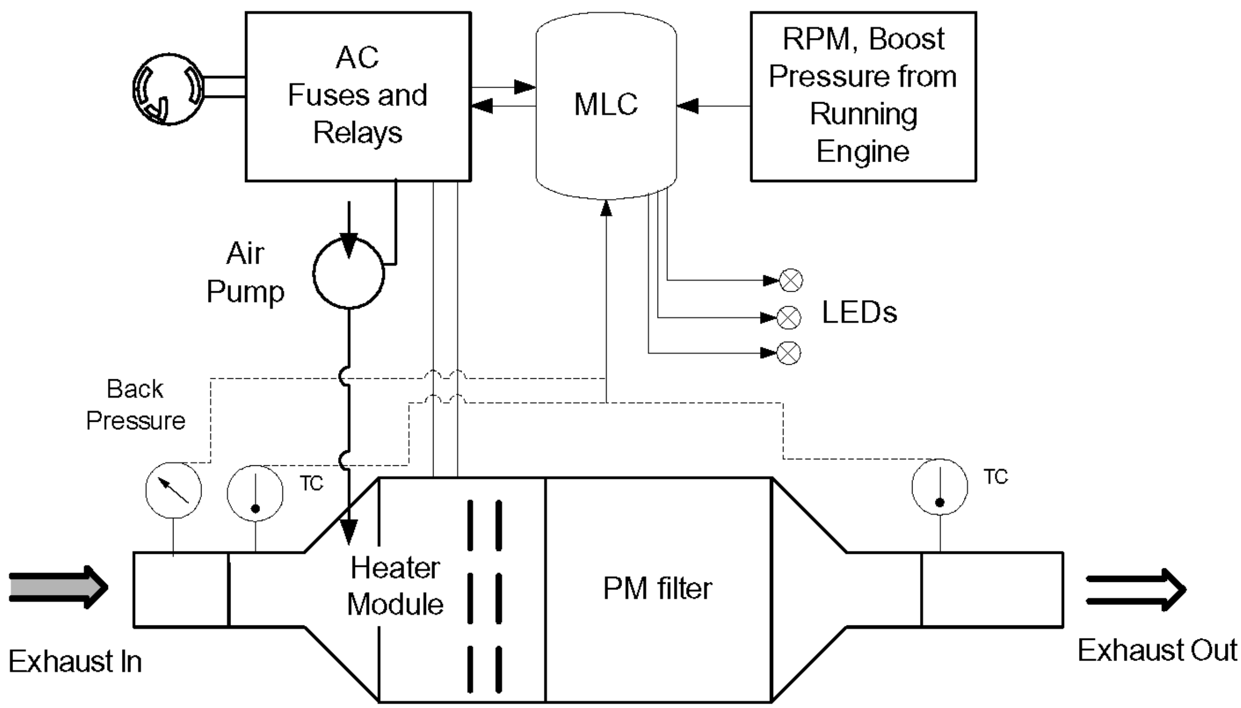

Figure 1. Horizon EPF system schematic.

All necessary hardware and controls are installed on the vehicle, requiring only off-board electric power to supply energy for the heater. When the amber LED flashes and the vehicle is parked for a period that will exceed five hours, the operator plugs the power-supply station receptacle into the EPF's power plug located on the vehicle. A starter lock-out is engaged when the system is plugged into AC power to prevent the vehicle from being started and operated while it is plugged in. Figure 2 is a schematic drawing showing where the basic system components are installed on a vehicle.

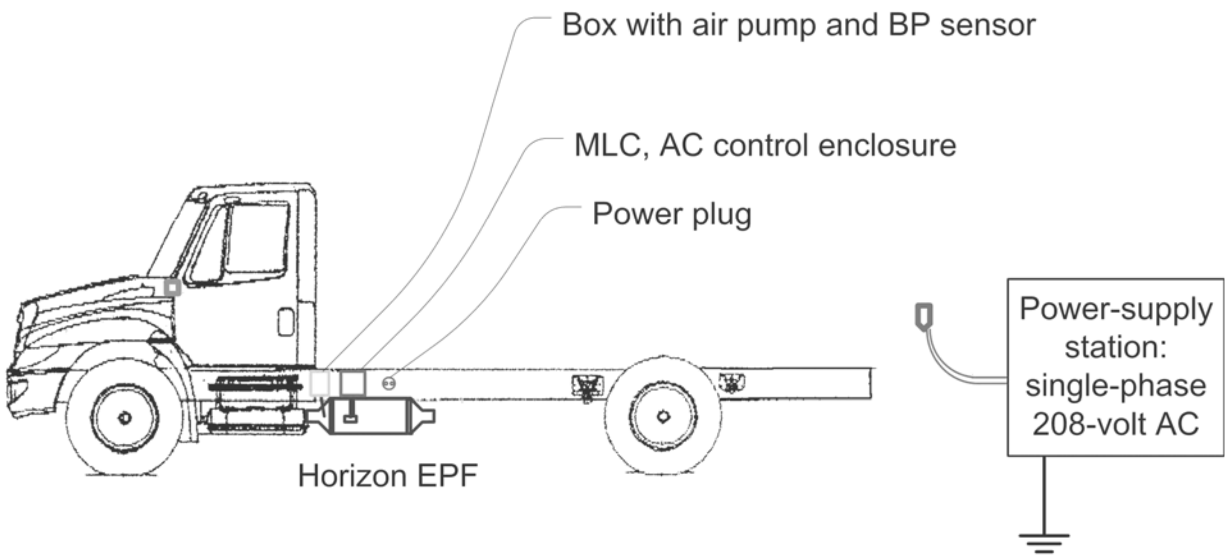

Figure 2. Horizon EPF installation schematic.

PM Filter

The EPF uses a commercially available wall-flow silicon carbide filter to capture and hold PM emitted from a diesel engine. The filtration efficiency of these filters has been extensively documented and the filters have repeatedly achieved Level 3 status in the test laboratory. The captured PM will accumulate in the filter over time as the engine is operated and must be removed or oxidized periodically (i.e., regenerated). Since the filter is uncatalyzed, fuel sulfur levels do not affect its particulate reduction performance, nor does it increase NO_2 emissions across the device (in fact, our dynamometer testing to date has shown *reductions* in NO_2 emissions).

Control System and Regeneration Process

The regeneration event is controlled by the on-board controller (MLC). The MLC indicates to the operator with a flashing amber light that a regeneration is requested based on exhaust backpressure measurements during engine operation. The regeneration is independent of any other filter conditions such as pre-heating from in-use operation. Regeneration of the EPF occurs while the engine is off and the system is connected to external grid power. The DPF is not removed from the vehicle for the regeneration process.

The regeneration process requires a heat source to raise the PM above its oxidation temperature and a source of air to allow for oxidation to occur. An electric heating element is used as the heat source and a small air pump is used to supply the air. The MLC controls the operation of these two devices.

Upon return to the designated parking space, the vehicle operator will connect the EPF to external grid power (208-volt single-phase AC). If needed, as indicated by the flashing amber light, the MLC will allow current to flow through the resistive heating element. Through convection, conduction and radiation, heat is transferred to the filter substrate, bringing it to a temperature necessary to combust or “burn-off” the captured PM. The entire regeneration process lasts five hours and is anticipated to occur at off-peak hours such as late evening or at night.

Regeneration Alert Algorithm

The MLC uses an operating timer and a histogram to determine when to alert the operator to plug in the Horizon. Whichever occurs first causes the MLC to turn on the flashing amber light. The histogram approach is illustrated in Figure 3.

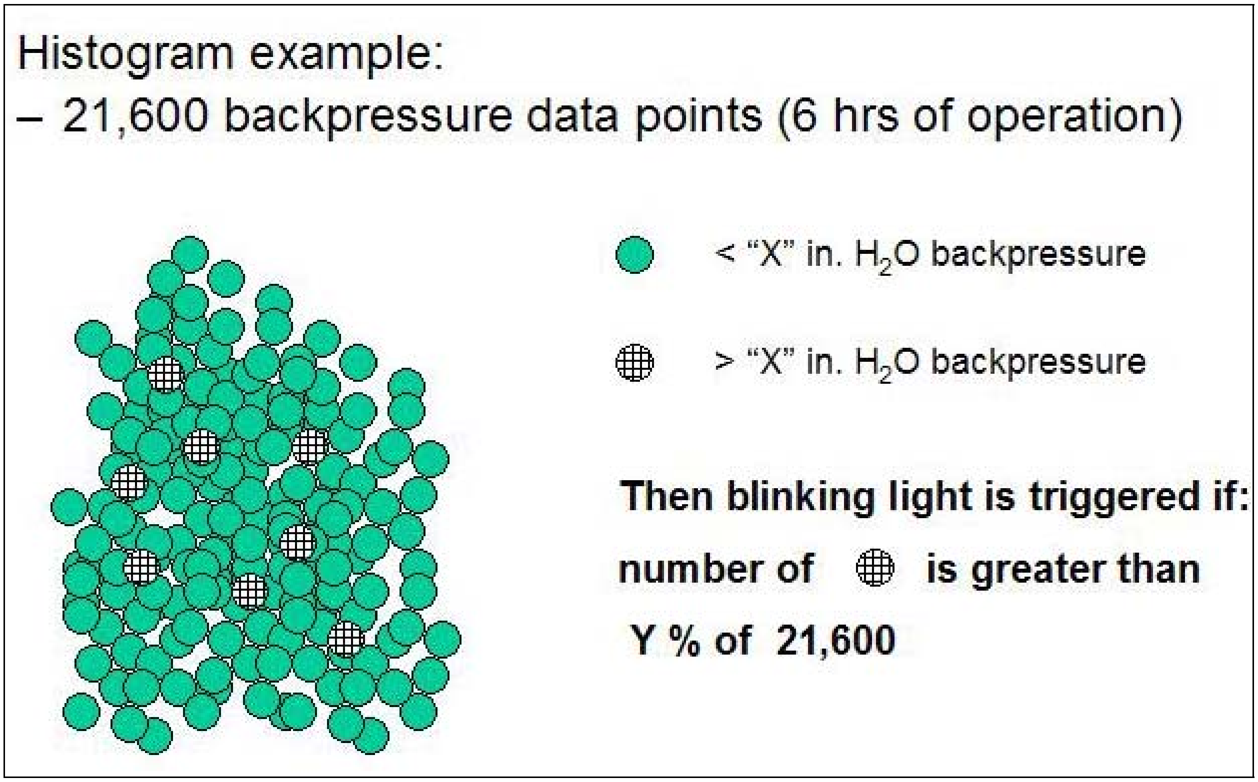

Figure 3. Representation of histogram.

The MLC keeps a running tally of backpressure data values (the tally is cleared after regeneration). Once the fraction of data points above “X” inches of water pressure goes above “Y” % of all the data points, the MLC signals the request for regeneration (flashing amber light). The values for “X” and “Y” in the histogram example are proprietary. Figure 4 provides a visual representation of the backpressure values between regeneration events.

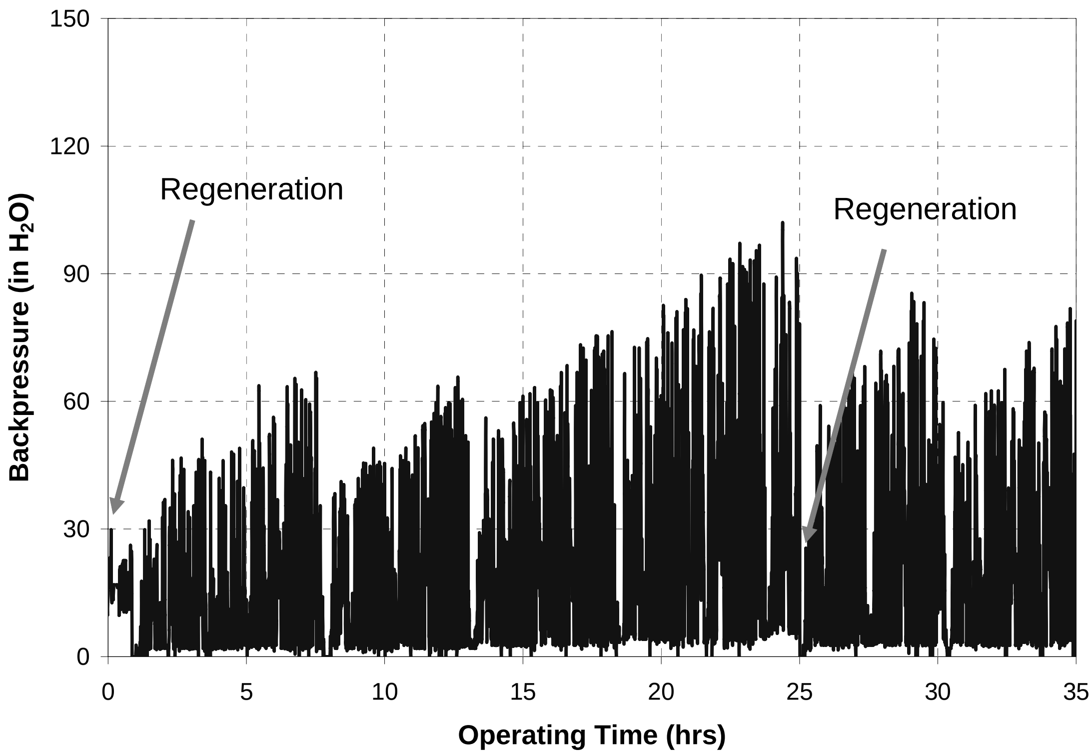

Figure 4. Backpressure data points and regeneration events.

Filter Cleaning

As with any filter system, non-combustible inorganic ash will need to be removed periodically. We anticipate that the de-ash process will be a necessary part of an annual maintenance cycle. However, more frequent de-ashing may be necessary depending on the specific engine (and its oil consumption rate) on which the EPF is installed.

TECHNICAL INNOVATIONS

The EPF's regeneration process is "active on-board, off-line" regeneration (in contrast to the typical catalyzed filter which can be classified as "passive on-board, on-line" regeneration). By decoupling filter regeneration from the vehicle's duty cycle, a much broader range of applications is possible for wall-flow PM filter technology.

Furthermore, Cleaire's MLC provides a robust control system that can not only monitor the system and control the regeneration, but provides a simple interface with the driver or operator as well as detailed data logging and diagnostic capabilities for trained Cleaire-authorized technicians.

Transforming these concepts for technical innovation into a robust product that works in real-world applications with typical operators was the main challenge and achievement of the ICAT project.

ICAT Project

The primary objective for the ICAT project was to demonstrate the Horizon EPF on a school bus under real-world conditions. This demonstration included the on-vehicle installation processes, power-supply station installation, operational robustness, customer following procedures, and the safe use of the power-supply station. In order to achieve the primary objective, a number of discrete tasks were performed including:

- Build prototype systems
- Install regenerative infrastructure (power-supply stations)
- Install Horizon EPF systems on demonstration vehicles
- Field-testing of the technology
- Test regeneration emissions
- Dynamometer emissions testing

Cleaire also performed EPF product development and verification efforts concurrently with (but outside the scope of) the ICAT project. Those results are also included in this report where appropriate.

BUILD PROTOTYPES

Cleaire performed extensive R&D testing of prototype systems before the start of the ICAT project. The development testing including testing various soot loadings in the filter before regenerating and measuring temperature profiles in the filter. Based on the development test results, the regeneration system, heaters and other system components of the initial prototypes were modified for the ICAT field trial systems.

Simultaneously with the ICAT project, Cleaire was performing field trials for a customer who wishes to remain unnamed. Based on operating experiences from ICAT and the other field trials, the commercial Horizon EPF system had a few additional minor modifications from the ICAT prototype systems.

The prototype development efforts resulted in the Horizon EPF product described in the “Innovative Technology” section beginning on page 4.

INSTALL REGENERATIVE INFRASTRUCTURE

Cleaire created specifications for the regeneration infrastructure. The field trials showed that each facility has its own limitations on power availability and its own needs regarding placement of the power-supply station. It is the responsibility of the customer and their electrical contractor to choose an infrastructure design that will conform with local codes. Nonetheless, Cleaire has worked with them to ensure that a safe and effective regeneration infrastructure is installed.

Sacramento Municipal Utility District (SMUD) installed power-supply stations (regenerative infrastructure) at their cost for Elk Grove USD as part of the ICAT project. The power-supply stations have been successfully operating as designed.

INSTALL EPF ON DEMONSTRATION VEHICLES

Cleaire installed a Horizon EPF system on a Thomas Built school bus owned by Elk Grove USD (Sacramento County). This was the primary ICAT demonstration vehicle. The bus had been repowered with a 2004 Cummins ISB prior to installation of the Horizon EPF. The results of the demonstration are discussed in the “Field Testing of the Technology” section on page 14.

Originally, Cleaire had planned to install the EPF on a mid-1970s vintage Crown school bus owned by Grant Joint Union School District. However, this installation did not occur for the ICAT project due to the configuration of the vehicle exhaust system and approval of the installation by the California Highway Patrol. Normally, the EPF would directly replace the existing engine muffler, but due to the mid-engine design of the Crown school bus, the existing muffler location was incompatible with the EPF’s mounting requirements. An alternative location on the vehicle was identified and a support bracket designed, but the approval by the CHP was not obtained in time to use this vehicle for the ICAT project. Cleaire has since streamlined the approval process with the CHP and has received approval for installation on a variety of school bus body styles and engines including a 1959 Crown school bus.

Concurrently, but outside the scope of the ICAT project, Cleaire installed and demonstrated the EPF on a Cummins West delivery vehicle with a 1988 engine and some utility vehicles operated by a customer that chooses to remain unnamed. The extreme durability testing of the Horizon EPF on the delivery truck is included below because its results provided a foundation for the field testing in the ICAT project.

Extreme Durability Prototype Testing

As part of the EPF product validation program, an EPF was installed on a Cummins West Inc (CWI) delivery vehicle. The vehicle is a Kenworth MY 1999, Class 7, 33,000-lb truck, powered by a 1988 Cummins C engine rated 250 hp at 2200 rpm. The engine and truck were chosen to simulate worst-case conditions and prove the EPF system durability on a vehicle powered by an engine older than 1994.

Experimental Configuration and Procedure

The EPF system replaces the OE muffler and has been installed in the in the same location horizontally under the truck. The EPF system has a Cleaire MLC controller, which can log system backpressure, inlet and outlet temperatures, manifold pressure and engine speed. The MLC has been setup to log at a 30-second interval. Figure 5 and Figure 6 show the truck and the installed system, respectively.

Figure 5. Test vehicle.

Figure 6. Horizon EPF installed on test vehicle.

The vehicle was retrofitted on March 10, 2005 and has been in service for deliveries in the CWI territory. The vehicle performs short and long distance deliveries with a variety of loads. The system is connected to a power-supply station to regenerate only after approximately 30 to 40 hours of engine operation. The EPF filter is removed and weighed, before and after each regeneration, to determine the removed mass.

Part of this test is that it simulates worst-case conditions in several ways:

1. The engine is a mechanically injected engine built to 1988 PM emissions standard of 0.6 g/hp/hr (versus a 1999 standard of 0.1 g/hp/hr)
2. The system is regenerated after at least 30 hours of operation have passed and not as requested by the controller
3. the captured PM mass is near or greater than the accepted limit for the EPF filter
4. exhaust backpressures exceed the engine specification
5. exhaust temperatures can be much higher than temperatures expected in typical applications

Results

The truck was operated for over 240 hours and 4500 miles. During this time the EPF was regenerated 5 times. Figure 7 shows the backpressure trace during operation. If operated according to the EPF manual the operator would have had to connect the unit to the power-supply station after one to two shifts. During this experiment the standard operating procedure was ignored. As a consequence backpressures can be seen to exceed limit of the sensor, 145-in. H_2O, after about 25 hours of engine operation.

To illustrate the severity of this application, Figure 8 shows the backpressure trace for a more typical application, a MY 2000 dump truck powered by an ISM, rated 330 hp at 1800 rpm. Although the engine operating time between regenerations is similar, backpressure readings stay below 80-in. H_2O for the entire time and the controller would not have triggered regeneration.

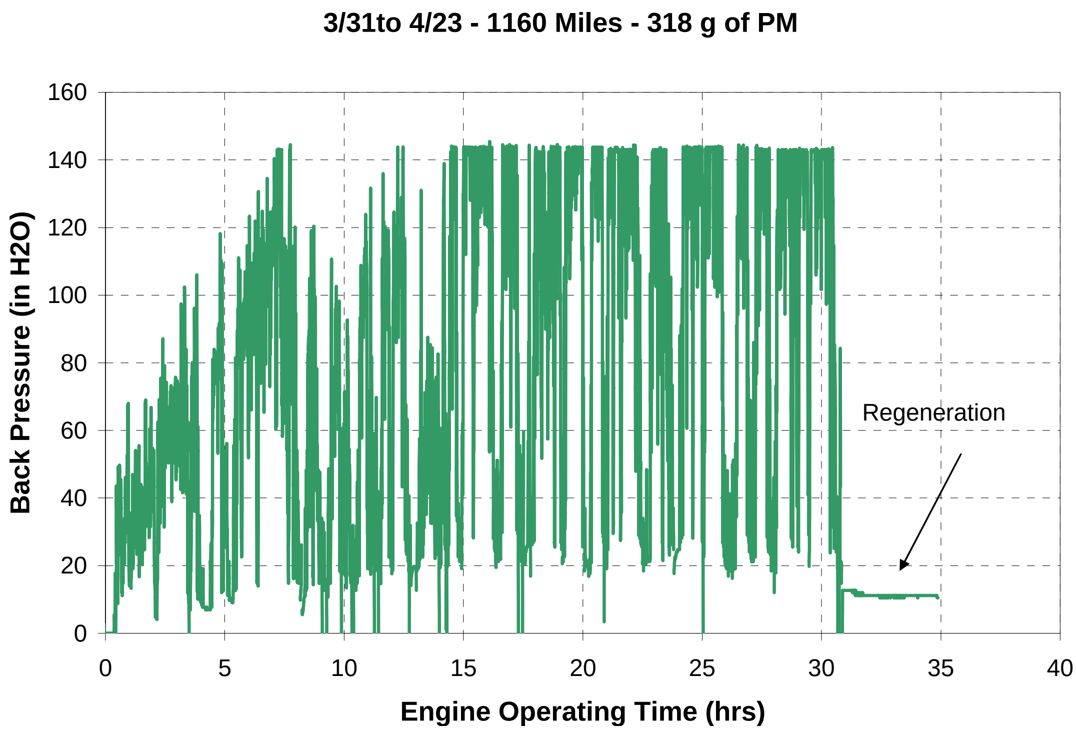

Figure 7. Backpressure trace during operation without EPF regeneration.

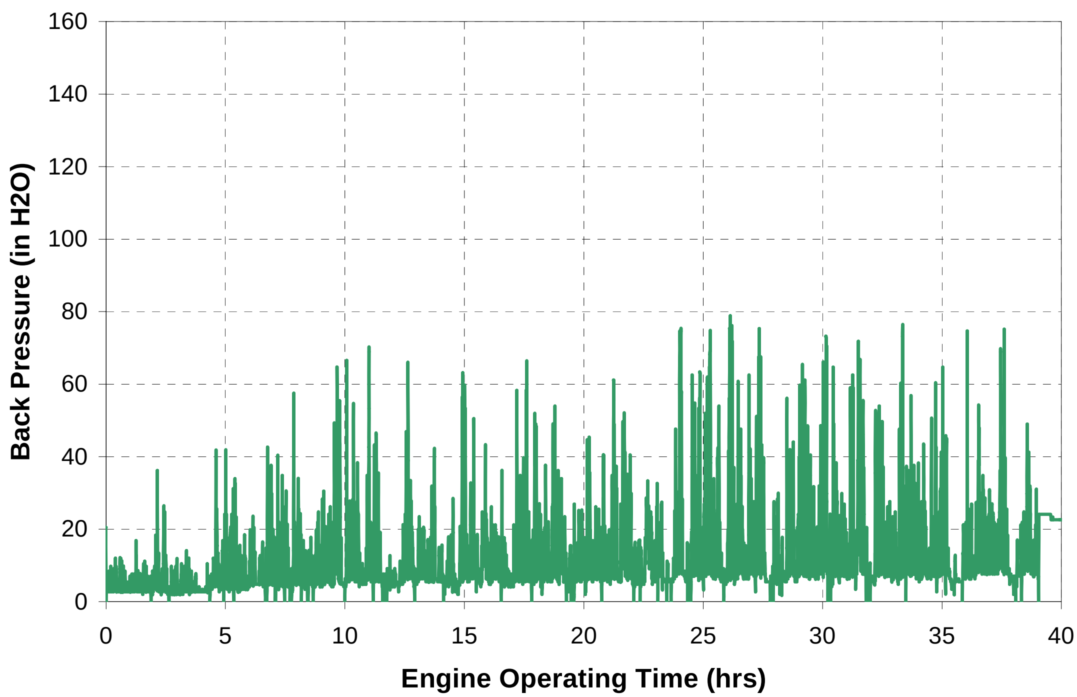

Figure 8. Backpressure trace during operation of dump truck powered by a MY 2000 ISM engine.

Figure 9, Figure 10 and Figure 11 show further backpressure traces during subsequent periods of operation. Also indicated on the Figures are the miles driven and the removed mass during regeneration. The total captured mass during this experiment has been 1573 grams over 4576 miles traveled, which leads to an average of 0.34 g/mile PM. Note that the filter mass after 240 hours of operation has increased by 18 grams. Since PM contains a variety of inorganic substances from lube oil and fuel additives mass increases over time are expected. The relative small size of this increase demonstrates the high efficiency of the electrical regeneration.

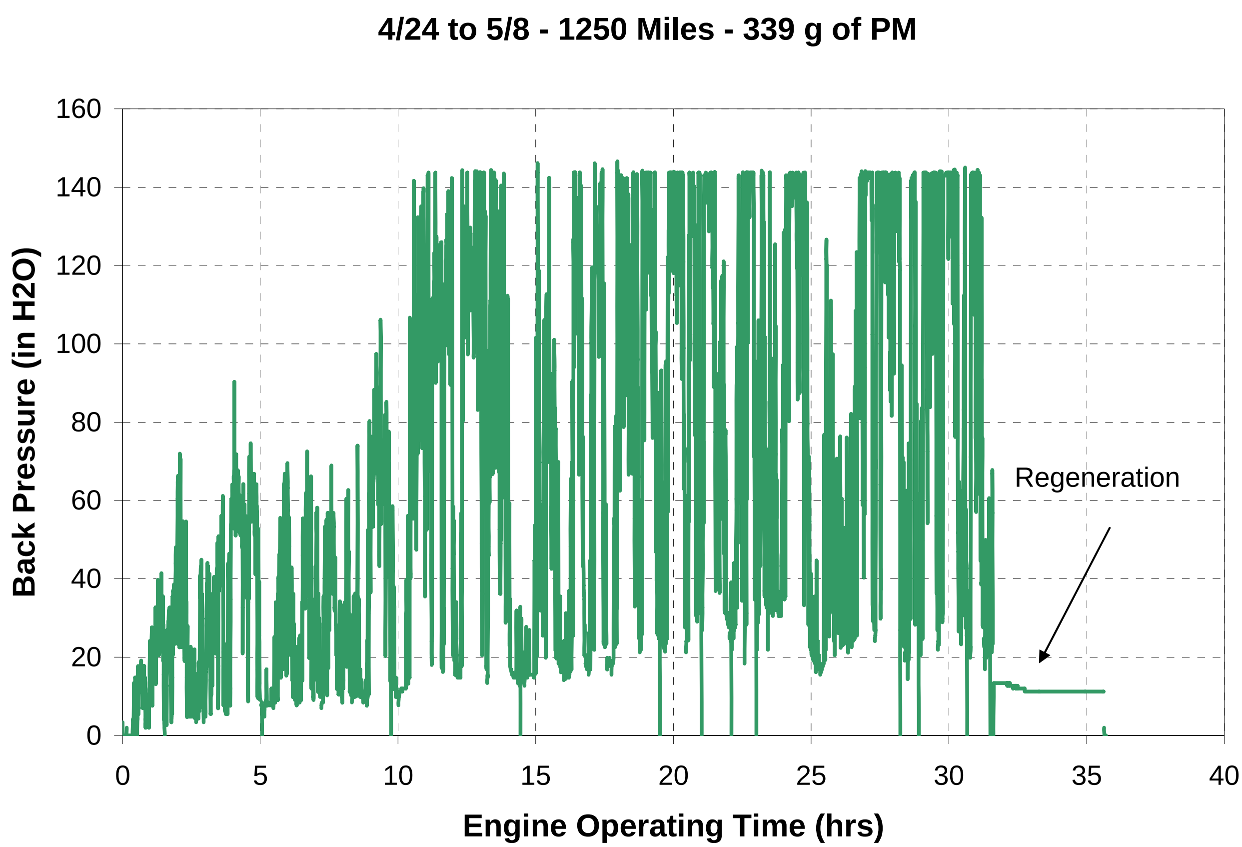

Figure 9. Backpressure trace during operation without EPF regeneration.

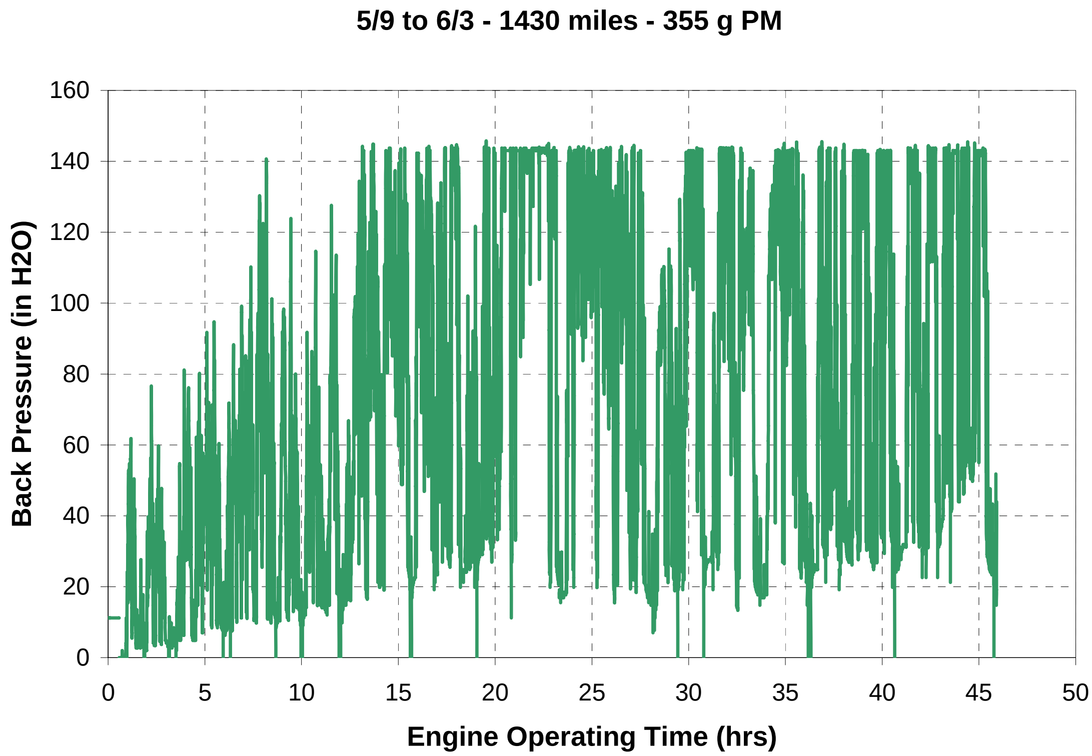

Figure 10. Backpressure trace during operation without EPF regeneration.

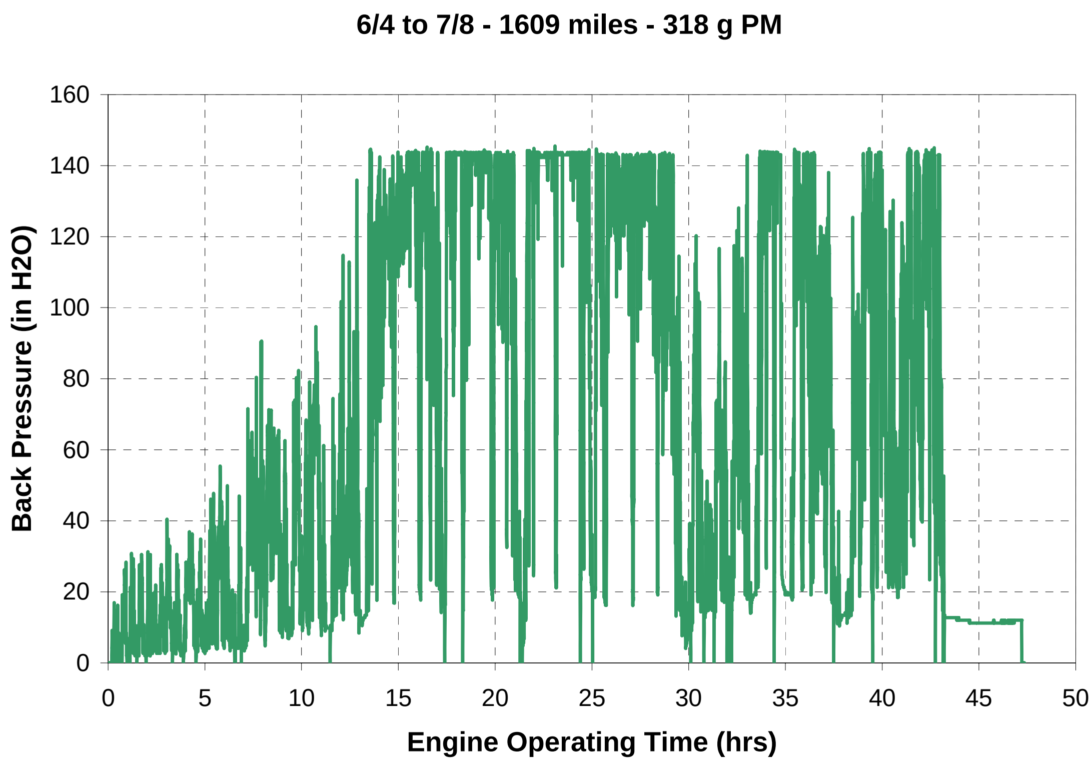

Figure 11. Backpressure trace during operation without EPF regeneration.

Conclusion

An EPF system was installed on a 33,000-lb. Class-7 Kenworth delivery truck powered by a 1988 Cummins C engine to demonstrate the systems durability. The experiment has been set up to impose worst case conditions on the system. The typical regeneration schedule is neglected and regeneration is triggered manually only with a highly loaded filter. Engine backpressures have been found to reach values exceeding 100 inches of water within 10 to 15 hours of engine operation. The vehicle was operated for over 240 hours and 4570 miles, without any noticeable loss of power or drivability. A total 1570 grams of PM has been captured.

FIELD TESTING OF THE TECHNOLOGY

The Horizon installed on the Elk Grove school bus performed as designed during the ICAT demonstration. The demonstration showed that the Horizon EPF product is robust and the operator will plug in the EPF as directed by the indicator lights. Elk Grove USD was so pleased with their ICAT demonstration unit that they purchased and installed a total of 49 Horizon EPF systems.

Elk Grove USD Demonstration

A Horizon EPF was installed on Elk Grove USD Bus number 102. The vehicle is a Thomas Built Bus, repowered with a 5.9 liter, 2004 Cummins ISB-EGR engine. The EPF was installed on the school bus to experience real-world in-use conditions:

1. The bus was used for regular daily operations as well as field trips.
2. The school district staff followed standard operating procedures for monitoring and plugging in (regenerating) the EPF.

The vehicle was retrofitted on June 7, 2005. Except for light use during the summer holiday, the bus experienced normal use during the demonstration. As instructed by Cleaire (and the Horizon EPF Owner's Manual), the Elk Grove staff pluged in the EPF to the power-supply station whenever indicated by the amber light flashing.

Results

Figure 12 shows the operating history for the school bus during the ICAT demonstration period. The Horizon EPF operated normally during the demonstration and no problems were reported by the Elk Grove School District. As shown in Figure 12, the bus operated for approximately six hours on a typical school day. The Horizon EPF accumulated over 400 operating hours and had 13 regenerations during the ICAT demonstration.

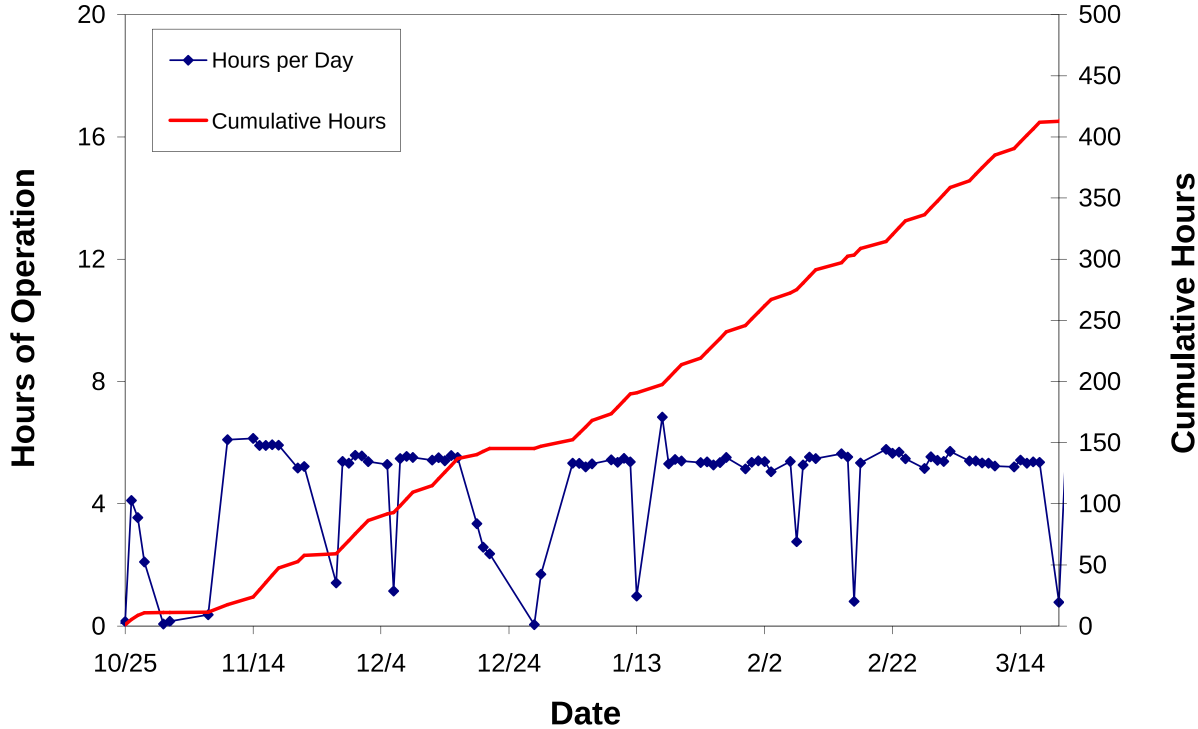

Figure 12. School bus operating history.

Conclusion

An EPF system was installed on a Thomas school bus powered by a 5.9-liter, 2004 Cummins ISB-EGR engine to demonstrate operations under real-world conditions. The MLC data log shows that the system is operating and regenerating as designed. Elk Grove USD has reported that there has been no impact on the bus's normal operations.

EMISSIONS TESTING OF THE TECHNOLOGY

Regeneration Emissions Testing

Emissions during the electrical regeneration process were measured at the California Truck Testing Services (CaTTS) laboratory in Richmond, California. One challenge of testing regeneration emissions was that an approved protocol did not exist. Cleaire developed a protocol and provided it to the ARB for review and acceptance. The end result of the testing is that regeneration emissions are negligible, especially when compared to the high rate of PM removal from the Horizon EPF or to the emissions of an operating engine.

Testing Laboratory and Procedure

The CaTTS facility is a heavy-duty vehicle laboratory designed to test trucks, buses, generators, and other heavy-duty equipment. The laboratory procedures follow 40CFR86, and it is recognized by CARB as a qualified vehicle emissions testing facility.

The laboratory has a Horiba CVS Sampler System which includes a 1500 cfm and a 3000 cfm venturi down stream of a 18" diameter dilution tunnel and a 5" secondary tunnel. During typical vehicle emissions testing, engine exhaust gases are ducted into this dilution tunnel. Gases and particulate matter (PM) are sampled in the diluted stream. PM is collected on 70mm particulate filter holders in a Horiba particulate collection system of 0–5 cfm down stream of a secondary dilution chamber.

During this EPF regeneration the emitted gas flow is les than 2 scfm. Using the standard dilution tunnel would lead to a dilution ration of approximately 1000. As a consequence the gas analysis equipment would not be able to measure the emissions accurately. Therefore the secondary dilution system, which is used for PM sample flow, has been used as the dilution tunnel with a dilution ratio of 2 to 3.

The exhaust gas analysis consists of:

- Two CO_2 infrared analyzers (one can be used for raw exhaust)
- CO infrared analyzer
- O_2 Magneto-Pneumatic Analyzer
- Two NO_x Chemiluminescent Analyzer
- THC Flame Ionization Detector

During the test cycle exhaust gases concentrations are continuously integrated such that each component can be expressed in terms of mass per test cycle.

Procedure

Emissions generated during the electrical regeneration are sampled and analyzed as described below.

1. The emissions are measured for the entire regeneration cycle of 5 hours.
2. The entire flow of emissions is ducted into a dilution chamber. The chamber has two inlets and two outlets. The second inlet port is open to the atmosphere. In the chamber, emissions and ambient air are mixed.
3. A suction pump and a sample pump are connected to the chamber outlets. The sample pump draws a sample through a gas flow meter to the gas analyzers. The suction pump draws sufficient flow through a flow meter to provide an adequate dilution ratio of ambient air to EPF emissions. The sum of the measured mass flows equals the total mass flow through the chamber.
4. Analyzer readings and mass flow meter readings are recorded at a 1Hz interval.
5. A background measurement of the ambient air is taken before and after each regeneration test.
6. The emissions are computed by multiplying the individual concentration, adjusted for average background, with the mass flow through the dilution chamber. Results are presented in terms of emitted mass per regeneration for each filter.

Figure 13 shows a schematic of the test setup.

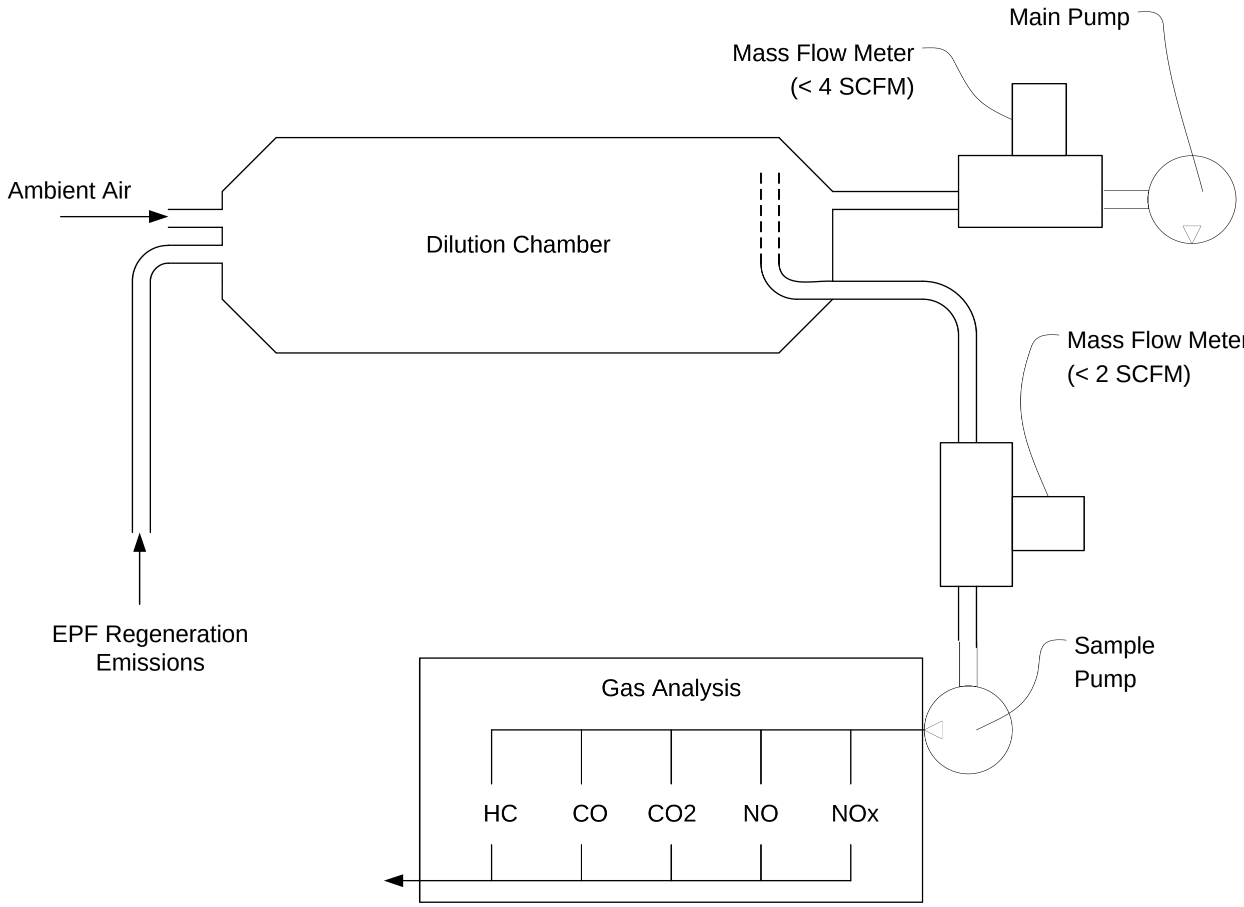

Figure 13. Schematic of Regeneration Emissions Test Setup.

Results and Discussion

After several trial runs two complete regeneration tests were conducted. Table 1 shows the emissions results for each of the regenerations. All values are in grams for the entire 5-hour regeneration cycle. Also listed are the initial EPF PM loads in grams of captured material.

Table 1. Emissions results during regeneration in grams.

	PM load	THC	CO	NOx
Test 1	109	0.00	41.90	0.03
Test 2	181	0.03	57.33	0.06

Figure 14 and Figure 15 show emission traces during the regeneration. While HC and NOx emissions are negligible, CO emissions can reach a maximum of 2400 to 3500 ppm, depending on PM load of the EPF. Although this value by far exceeds the concentration of CO in the engine exhaust of a typical diesel engine, the effluent flow rate of less than 2 scfm is in comparison so small that the total emitted mass again appears negligible. To illustrate the point consider the CO emissions of a 1997 M11 powered tractor during a NYB test cycle are 16 to 18 grams /mile. A single regeneration would be equivalent to approximately 3 miles of inner city driving. Since in use EPF systems have shown that a M11 powered vehicle operates for over 40 hours before a regeneration is triggered, the regeneration emissions result in less than 1% increase of total CO. Also important is that the current regulated CO limit for a 1997 diesel engine is 15.5 g/hp/hr. The actual certified emissions are less than 1 g/hp/hr for most engines, so that even a significant increase would not trigger a regulated limit.

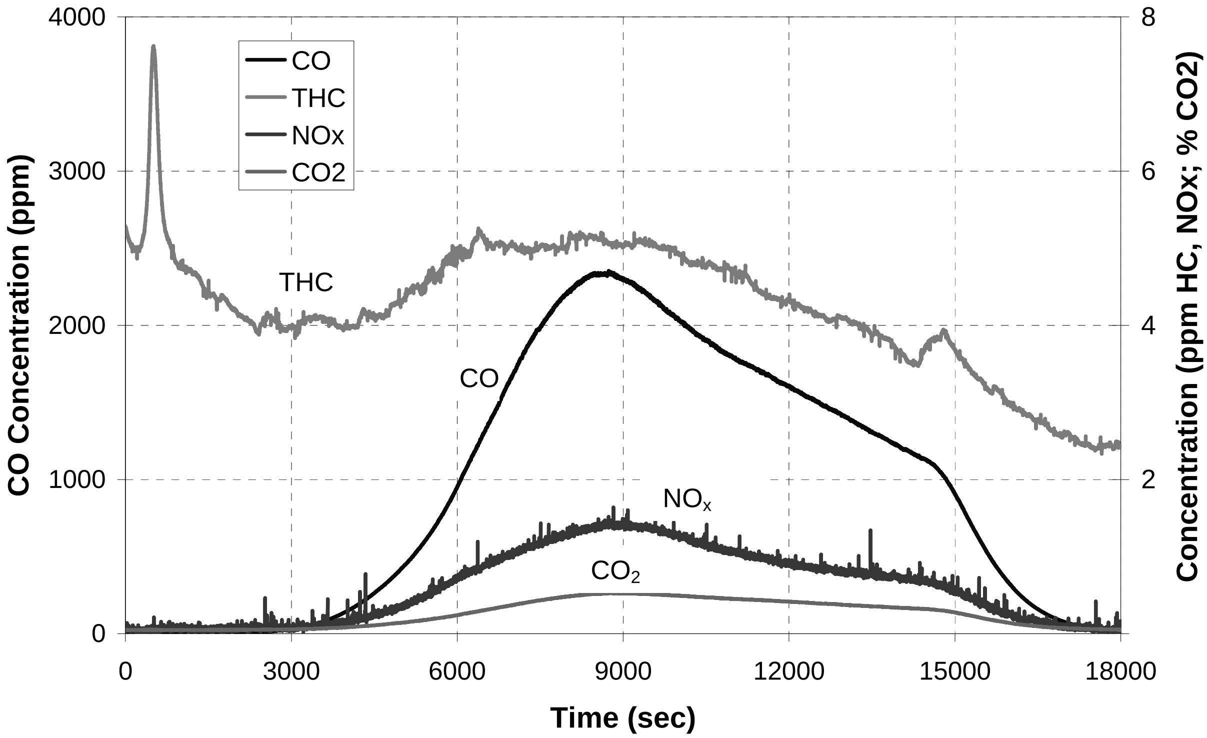

Figure 14. Emissions trace during the entire regeneration cycle of Test 1. The HC spike at the onset of the test is attributed to a spike in the ambient concentration.

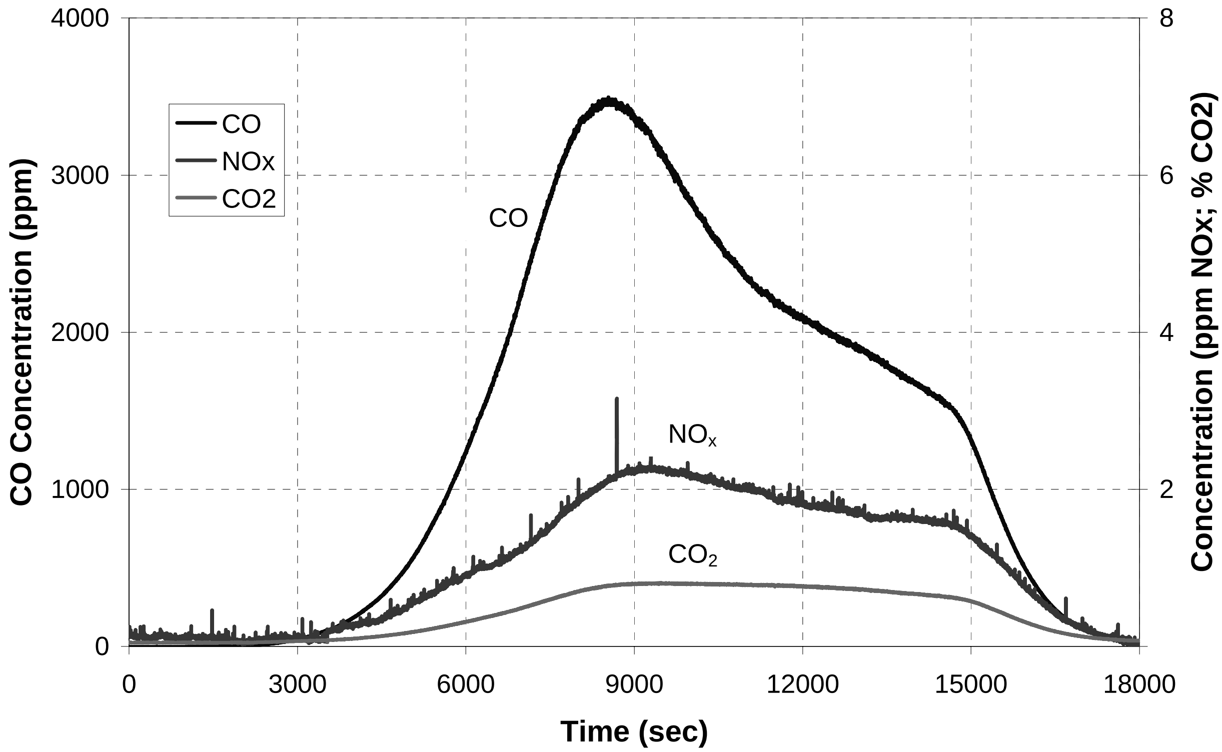

Figure 15. Emissions trace during the entire regeneration cycle of Test 2. (Unfortunately, hydrocarbon emissions data were lost for Test 2.)

Conclusion

The emissions of a Cleaire EPF system during regeneration have been measured. While HC, NOx concentrations are negligible, CO concentrations have been found to reach more that 3500 ppm dilute. The total emissions in terms of mass over the entire driving and regeneration cycle increase the mass of CO by less than 1% and are therefore well below any regulated limit .

Dynamometer Emissions Testing

The PM filter module (EPF #7 serial number) was removed from Elk Grove school bus #102 after the ICAT demonstration period had been completed. The aged PM filter was tested at the California Truck Testing Services (CaTTS) laboratory in Richmond, CA to evaluate its performance. For the performance test, a commercial Class 8 vehicle, MY 1997, was retrofitted with the PM filter (EPF #7). The vehicle is powered by a MY 1997, Cummins M11 engine rated 370 hp and a maximum speed of 1800 rpm. The Urban Dynamometer Driving Schedule (UDDS) and the New York Bus (NYB) test cycles were used to measure the EPF's emission reduction performance.

Testing Laboratory and Procedure

The CaTTS facility is a heavy-duty vehicle laboratory designed to test trucks, buses, generators, and other heavy-duty equipment. The laboratory procedures follow 40CFR86, and it is recognized by CARB as a qualified vehicle emissions testing facility.

CaTTS operates a Froude Consine 48" DC electric chassis dynamometer with tandem-axle capability and 80,000 lbs. maximum inertial mass. It is equipped with a 500 HP DC motor, governed by a CP Engineering Cadet Control system. Transient as well as steady state test cycles can be used and positive and negative road gradients can be simulated during each test.

The laboratory has a Horiba CVS Sampler System which includes a 1500 cfm and a 3000 cfm venturi down stream of a 18" diameter dilution tunnel and a 5" secondary tunnel. The exhaust gases are ducted into this dilution tunnel. Gases and particulate matter (PM) are sampled in the diluted stream. PM is collected on 70mm particulate filter holders in a Horiba particulate collection system of 0–5 cfm.

The exhaust gas analysis consists of:

- Two CO_2 infrared analyzers (one can be used for raw exhaust)
- CO infrared analyzer
- O_2 Magneto-Pneumatic Analyzer
- Two NO_x Chemiluminescent Analyzer
- THC Flame Ionization Detector

During the driving cycle exhaust gases concentrations are continuously integrated such that each component can be expressed in terms of mass per driven distance. This integration is backed by a bag sampling system which performs an actual physical integration.

Vehicle Inertia Simulation

Prior to bringing the vehicle into the laboratory, the vehicle's inertia, drag and rolling resistance are evaluated by a so called 'coast down' procedure. The vehicle is accelerated to 60 mph on a level road and allowed to coast to a halt. Deceleration rates are measured in 10 mph increments. To cancel out variations in wind and road conditions the test is repeated 3 times in either direction on the same stretch of road. The average values for the deceleration rates are input into the dynamometer controller. To simulate in-use driving conditions the tractor is pulling a trailer loaded to at least ½ of its capacity.

Note that the vehicle load changes the engine power requirement during acceleration. The higher the load the more power is required to accelerate which in turn results in elevated exhaust temperatures and higher emission levels.

Test Cycles

Once the coast down has been completed the vehicle is placed on the chassis dynamometer. The driven wheels turn the dynamometer rolls and the controller matches the vehicle inertia and coast down speeds by controlling the electric dynamometer motor.

During the test a driver accelerates and decelerates the vehicle according to a prescribed driving cycle, a transient or steady speed trace. If the deviation between the required and the actual vehicle speed is within predetermined limits, the test is considered valid. Using this procedure ensures repeatable conditions.

In this test campaign, two transient test cycles were used: the Urban Dynamometer Driving Schedule (UDDS) and the New York Bus (NYB). The UDDS cycle is the EPA chassis dynamometer equivalent to the FTP cycle which is used in engine dynamometer certification tests. The NYB is a low temperature cycle, which consists primarily of zero speed at idle interrupted by several short acceleration followed by sharp decelerations. Figure 16 and Figure 17 show the speed traces of the UDDS and NYB cycles, respectively.

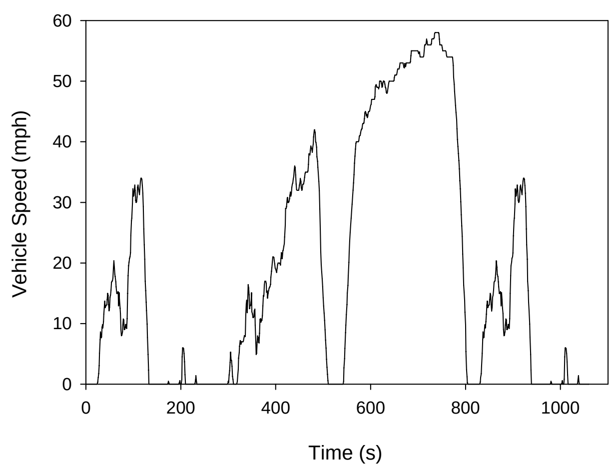

Figure 16. Time-Speed trace for the UDDS.

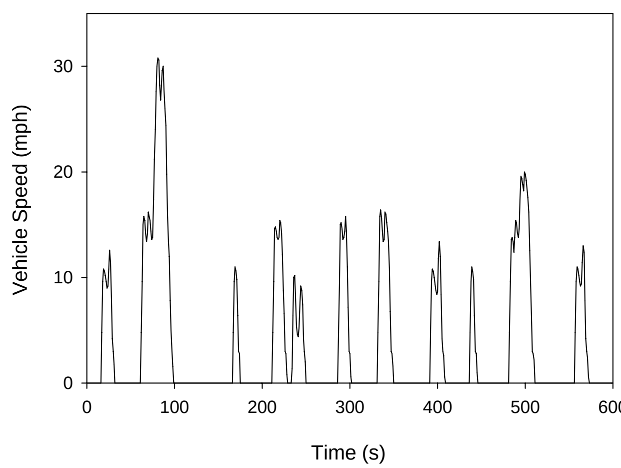

Figure 17. Time-Speed trace for the NYB.

Procedure

To establish baseline emissions, the vehicle initially tested in its original configuration, i.e., it is outfitted with the OE muffler.

Following the CFR, a complete set of tests consisting of 3 UDDS and 3 NYB tests are run consecutively with each configuration. Each test is preceded with a brief warm up of 5 minutes at a speed of 50 mph. During the test gas analysis and a PM sample are taken. The gaseous emissions are sampled at a one second interval out of the diluted exhaust and integrated over the entire driving cycle, while the PM is sampled continuously. The final emissions results are reported on a gram pre mile basis using the integrated emissions and the distance traveled during the cycle.

Once this baseline test has been completed, the EPF system is installed to replace the OE muffler and the same test protocol is repeated. CARB fuel was used during all tests.

<u>Results and Discussion</u>

Table 2 shows the emissions results summary for the baseline configuration and the EPF system. The comparison of these two results leads to the effect of the device, provided in terms of percent reduction.

Table 2. Emissions test results of key gaseous pollutants and PM. Note: All results in g/mi

Test	CONFIGURATION	THC	CO	NO_x	NO_2	CO_2	PM
UDDS	Baseline	0.672	3.889	18.53	1.596	2148	0.394
UDDS	Baseline	0.646	3.698	17.61	1.655	2144	0.372
UDDS	Baseline	0.632	3.786	17.85	1.650	2160	0.400
	Average, Baseline	**0.650**	**3.791**	**17.99**	**1.634**	**2151**	**0.389**
UDDS	EPF #7	0.570	5.112	18.58	0.186	2228	0.036
UDDS	EPF #7	0.350	5.110	19.08	0.423	2220	0.033
UDDS	EPF #7	0.404	5.080	18.42	0.515	2216	0.038
	Average, with device	**0.441**	**5.101**	**18.69**	**0.375**	**2221**	**0.036**
	Effect of Device	**-32.1%**	**34.5%**	**3.9%**	**-77.0%**	**3.3%**	**-90.8%**
NYB	Baseline	3.335	14.23	39.90	3.895	4915	1.270
NYB	Baseline	2.583	14.41	38.77	3.311	5015	1.287
NYB	Baseline	2.467	14.96	37.86	2.603	4920	1.356
	Average, Baseline	**2.795**	**14.53**	**38.85**	**3.270**	**4950**	**1.304**
NYB	EPF #7	0.188	15.84	38.05	0.931	4999	0.185
NYB	EPF #7	1.715	15.84	37.44	0.000	4977	0.132
NYB	EPF #7	1.568	15.56	37.05	0.021	4895	0.211
	Average, with device	**1.157**	**15.748**	**37.51**	**0.317**	**4957**	**0.176**
	Effect of Device	**-58.6%**	**8.4%**	**-3.4%**	**-90.3%**	**0.1%**	**-86.5%**

During the UDDS cycle, PM emissions were reduced by over 90%. The device did not significantly affect NOx and CO2 emissions. CO emissions were increased by 35%, HC emissions were reduced by 32%, and NO2 emissions were reduced by 77%.

During the NYB cycle, PM emissions were reduced by over 86%. The device did not significantly affect NOx and CO2 emissions. CO emissions were increased by 8.4%, HC emissions were reduced by 58.6%, and NO2 emissions were reduced by 90%.

Note that the PM emission reductions for both the UDDS and NYB meet CARB Level 3 criteria. The increase in CO from the EPF is not significant because of the relatively low emissions of CO from the diesel engine (approximately 10% of the certification level).

The EPF achieved greater than 85% PM removal efficiency for both test cycles which was the emission reduction goal of the ICAT project. The EPF also *reduced* NO_2 emissions by a significant amount as illustrated in Figure 18.

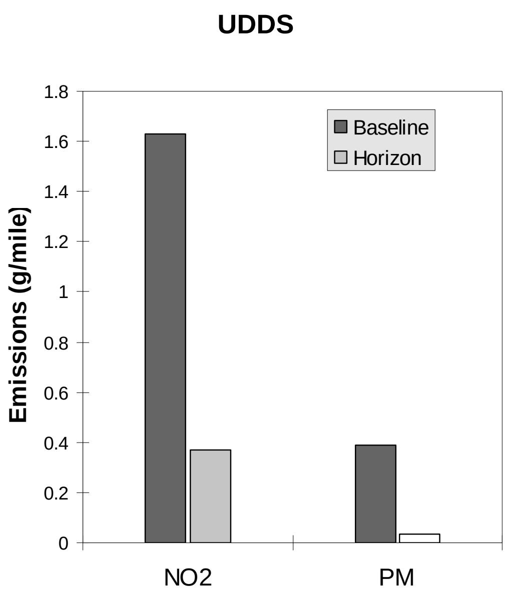

Figure 18. NO_2 reduction by Horizon EPF.

Status of the Technology

Cleaire submitted the ICAT pre-proposal for the EPF in the spring of 2004. That action began a series of events, which resulted in the Horizon EPF being developed, verified and commercialized sooner than Cleaire originally anticipated.

Cleaire received ARB verification of the Horizon EPF in December 2005. Cleaire is in the process of expanding the Horizon EPF verification for additional engine families and for minor part changes. Cleaire's distributor, Cummins West, is marketing the Horizon and is receiving positive response from a number of customers. Elk Grove USD was very pleased with the results of their ICAT demonstration. They have since purchased and installed a total of 49 Horizon EPF units.

Cleaire has envisioned a number of variants to expand the Horizon EPF product line to expand its applicability and provide greater operating flexibility to the customer.