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Naval Facilities Engineering Command

ENGINEERING SERVICE CENTER
Port Hueneme, California 93043-4370

TECHNICAL REPORT
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DIESEL ENGINE AIR EMISSIONS
REDUCTION TECHNOLOGIES
ESTCP Project Number: WP-0404
FINAL REPORT

by

Norman Helgeson
David Trueblood
Bruce Holden
Jason Jack
Gene Griffin

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Norman Helgeson
Bruce Holden
Gene Griffin
NAVFAC Engineering Service Center

David Trueblood
Cummins, Inc.

Jason Jack
United States Army Aberdeen Test Center

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LIST OF ACRONYMS

ATC	Aberdeen Test Center
B20	20 Percent Biodiesel by Volume, 80 Percent Petroleum Diesel by Volume
BAT	Best Available Technology
CAA	Clean Air Act
CARB	California Air Resources Board
CBD	Central Business District Transient Driving Cycle
CCR	California Code of Regulations
CFR	Code of Federal Regulations
CSF	Catalyzed Soot Filters
DENIX	Defense Environmental Network & Information Exchange
DNPH	Dinitrophenylhydrazine
DOC	Diesel Oxidation Catalyst
DoD	Department of Defense
DPF	Diesel Particulate Filter
ECM	Engine Control Module
EGT	Exhaust Gas Temperature
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
ESW	Environmental Solutions Worldwide, Inc.
Fed EPA No. 2	Low Sulfur No.2 Diesel Fuel That Met pre 2006 EPA On-highway Requirements
g/bhp-hr	Gram Per Brake Horsepower Hour
GC/MS	Gas Chromatography/Mass Spectroscopy
GC/FID	Gas Chromatography/Flame Ionization Detector
g/mile	Gram per Mile
HAP	Hazardous Air Pollutant
HC	Hydrocarbon
HPLC/UV	High Performance Liquid Chromatography / Ultraviolet
KPa	Kilo-Pascals
NDIR	Non Dispersive Infrared
NAVFAC ESC	NAVFAC Engineering Service Center
NMHC	Non-Methane Hydrocarbon
NOx	Nitrous Oxide Chemical Compounds

LIST OF ACRONYMS (Continued)

NORAD	North American Air Defense Command
NREL	National Renewable Energy Laboratory
PAH	Polycyclic Aromatic Hydrocarbon
PM	Particulate Matter
ppm	Parts Per Million
RPF	Robust Particulate Filter
TEG	Temperature of Exhaust Gas
THC	Total Hydrocarbon
UCR	University of California, Riverside
ULSD	Ultra Low Sulfur Diesel
VOC	Volatile Organic Compounds

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ABSTRACT

This report summarizes the results of a three-year project lead by the NAVFAC Engineering Service Center (NAVFAC ESC) to demonstrate the potential of two diesel engine exhaust gas treatment devices in reducing diesel engine particulate matter (PM) emissions. These devices, which are installed in the engine's exhaust system, are designed to trap engine PM emissions and periodically, chemically oxidize the soot through a process termed "regeneration". The project was sponsored by the Environmental Security Technology Certification Program with additional funding provided by Cummins, Inc. One of the tested devices, the ESW, Inc. Particulate Reactor, uses only the heat of the engine for regeneration, while the other, the Cummins, Inc. Robust Particulate Filter, also included the capability for direct fuel injection into the filter to provide additional heat. The demonstration results were that the ESW product reduced PM emissions by 50 percent, as expected, while the Cummins filter had significant performance issues which resulted in the suspension of its development as a commercial product.

1.0 INTRODUCTION

1.1 Background

Diesel engines are widely used throughout the Department of Defense (DoD) for powering tactical and non-tactical vehicles and vessels, off-road vehicles and equipment, engine-generator sets, aircraft ground-support equipment, and a variety of other applications. Although diesel engines are known to emit several types of pollutants into the atmosphere, human health concerns regarding the penetration of the small particulate matter into the deeper regions of the lungs have greatly increased interest in diesel PM emissions in the recent past. PM emissions are regulated as a criteria pollutant by the National Ambient Air Quality Standards established by the Clean Air Act (CAA).

Although most regulations are directed at the certification of new diesel engines, increasingly, emphasis is being placed on in-service engines. In California, the Air Resources Board (CARB) has issued PM control regulations requiring the retrofit of school buses, garbage trucks, off-road and on-road vehicles. To address these compliance requirements, many exhaust gas treatment devices are coming onto the market, but the selection of the optimal one (which also must meet the approval of applicable regulatory bodies) is dependent upon several factors that must be evaluated for each application.

This project demonstrated two diesel engine exhaust gas treatment devices believed to have the potential for assisting the DoD in meeting applicable PM regulatory requirements. In both cases, the technology consists of a high-temperature filter designed to remove the PM from the exhaust stream. The difference between the two filter designs involves the filter pore size and thus their ability to capture the PM emissions (50 percent vs. 85 percent PM reduction), as well as their method for regeneration. Both filters include the ability for in-use regeneration, the difference is the fact that one is regenerated passively, using only the heat of the engine, while the other is actively regenerated using direct fuel injection into the filter. These two technologies were tested on 8 DoD operated diesel engines at three DoD sites; ATC, Camp Pendleton and Cheyenne Mountain Air Force Station. The test periods varied from a few months to over one year.

1.2 Objectives of the Demonstration

The primary objectives of this project are to demonstrate that the two tested technologies will be capable of reducing diesel engine PM emissions by at least 50 percent, and demonstrate that these technologies are sufficiently robust to provide years of trouble-free service. In addition to these primary objectives, other objectives included significant reductions in carbon monoxide (CO), hydrocarbon (HC) and hazardous air pollutant (HAP) emissions, maintaining vehicle fuel economy and drivability, and finally demonstrating the ease of installing the technologies.

For the Environmental Solutions Worldwide, Inc. (ESW) Particulate Reactor technology, all emissions reductions, drivability, installation and reliability performance objectives were met. For the Cummins, Inc. Robust Particulate Filter (RPF), installation and reliability performance

objectives were not met. The emissions control performance objectives for the RPF device were not measured since the other performance objectives were not met.

1.3 Regulatory Drivers

Mobile-source diesel emissions are regulated by both Federal (40 CFR 86, 89) and California (13 CCR Chapter 3) equipment and vehicle standards. Those standards are applied to equipment and vehicles at the time of manufacture. In the last nine years, the Environmental Protection Agency (EPA) has pursued a program to dramatically tighten these regulations. This is illustrated in Table 1.1 below, which shows the 2007 EPA on-road heavy-duty engine standards, along with the year 2000 and 2004 standards. Likewise, the EPA has pursued a program to dramatically tighten the regulations for non-road diesel engines. These regulations, unlike their on-road counterparts, are based on the size of the engine with larger engines having tighter standards.

Table 1.1
Current and Future EPA Emissions Regulations [g/bhp-hr]

		2000 Standard (g/bhp –hr)	2004 Standard (g/bhp –hr)	2007 Standard (g/bhp –hr)	Phase-In by Model Year*			
					2007	2008	2009	2010
Diesel Fleet	NO _x	4.0	N/A	0.20	25%	50%	75%	100%
	HC	1.3	N/A	0.14				
	NMHC + NO _x	N/A	2.4	N/A				
	CO	15.5	15.5	15.5	100%	100%	100%	100%
	PM	0.10	0.10	0.01	100%	100%	100%	100%
* % represent percent of applicable vehicles sold within the calendar year that must meet the 2010 EPA emissions standards								

The 2007 heavy-duty highway diesel engine standards will reduce PM emissions by about 98 percent relative to the 1990 baseline emissions level and by 90 percent relative to the 2000 baseline. Significant nitrous oxide (NO_x) and non-methane hydrocarbon (NMHC) reductions are also required for 2004 and later engines. However, because these emission decreases do not affect in-use diesel engines, the full benefit of that change will take more than 20 years to achieve. In an effort to achieve the emissions reduction benefits sooner, several states have proposed regulatory strategies to reduce emissions for existing (in-use) engines.

In October 2000, CARB finalized their *Risk Reduction Plan to Reduce Particulate Matter Emissions from Diesel-Fueled Engines and Vehicles*. The California plan calls for the use of low-sulfur fuels as well as the installation of engine exhaust after-treatment on in-use engines for on-road, non-road, portable, and stationary applications. Otherwise, new replacement engines will be required. Of particular importance to the DoD is their recent regulation that requires off-road diesel powered vehicles to be retrofitted or replaced by the end of 2010.

In 2001, Texas enacted regulatory changes to reduce emissions from diesel engines. The Texas plan included a comprehensive set of incentive programs. The plan includes: 1) The Retrofit and Repower Incentive Program for On-Road and Non-Road High-Emitting Engines; 2) The New Purchase and Lease Incentive Programs for Light-Duty and Heavy-Duty On-Road Vehicles; and 3) Clean diesel fuel requirements which include limitations on aromatics and sulfur in commercial diesel fuels.

Stationary-source diesel emissions are regulated by state and local regulations. Currently, most regulations only limit NO_x, CO, and opacity. However, CARB recently proposed guidance that, if adopted by local air districts, would require the reduction of HAP emissions by reducing PM emissions.

1.4 Stakeholder/End-User Issues

The purchase of diesel filters represents a significant and many times unplanned cost to government diesel-powered equipment and vehicle fleet managers. These managers are faced with a multitude of choices in meeting current and proposed new regulations for reducing diesel PM emissions. Unfortunately, many of the commercial products available to address this problem are not suitable for common DoD engine duty cycles. Other products, although effective, may not meet government needs for maintainability and durability. Government decision makers therefore need an independent, informed resource such as the results from this project to assist them with the selection of appropriate diesel engine emissions control technologies.

2.0 TECHNOLOGY DESCRIPTION

2.1 Technology Development and Application

Two newly developed technologies to reduce diesel engine PM emissions were demonstrated in this project. One of the two technologies is currently commercially available for retrofit use. The second was planned for use with new vehicles for the 2007 model year. A modification of the latter filter is being demonstrated here as a retrofit device. The use of either in commercial fleets is limited due to their short time in the marketplace. Descriptions of the technologies are provided in the paragraphs below.

2.1.1 ESW Particulate Reactor

The ESW filter is a newly developed diesel engine high-temperature exhaust gas treatment filter designed to reduce diesel engine PM emissions. Normally, the filter is installed in place of the muffler. Although the technology is currently commercially available, its use in commercial fleets is limited due to its short time of exposure in the marketplace.

The ESW diesel oxidation catalyst filtering technology was developed to reduce PM emissions by up to 60 percent. This is twice the reduction of traditional diesel oxidation catalysts (DOCs), but lower than the 90 percent reduction possible with a diesel particulate filter (DPF) such as the RPF device. While traditional DOCs reduce CO, HC and the soluble portion of the PM emissions, the ESW filter also catalytically oxidizes a portion of the black (inorganic) carbon emissions. This reduction is accomplished by use of a proprietary flow-through low backpressure filtering process with large pore sizes where the filter media is coated with the catalyst material. In the filter, the collected engine exhaust soot is periodically oxidized. This occurs when the filter is heavily loaded with soot and a high engine exhaust temperature occurs. No additional heat source is required to initiate this regeneration process.

The ESW filter has been certified by CARB as a Level II diesel emissions control device. Diesel filters certified at this level have been verified to reduce PM emissions by at least 50 percent. A photograph of the filter media is shown in Figure 2.1.

The ESW filter was developed for both the new and retrofit diesel engine market for engines that do not maintain high exhaust temperatures for significant portions of their duty cycles and for applications where a > 85 percent reduction in PM emissions (i.e., CARB Level III certification) is not required. It was designed primarily for new off-road equipment as well as for the retrofit of existing on-road vehicles. This technology is suitable for use with current EPA approved off-highway diesel fuel containing < 500 ppm of sulfur. Its performance will, however, improve when on-highway ultra low sulfur diesel (ULSD) containing <15 ppm of sulfur is used.



Figure 2.1
ESW Particulate Reactor Cut-away

Although the ESW filter does not offer a performance level equivalent to the RPF, a Level III emission control filter, it does offer several economic and technological advantages. Once in full commercial production it is expected that the ESW filter will be priced approximately 25 percent less than Level III emission control devices for similar applications. Further reducing ESW filter lifetime costs is the fact that no scheduled maintenance is required, it is a completely passive filter requiring no computer, other controls or utilities. It is also a much more robust filter than almost any Level III device and will be able to withstand many of the harsher, clogging environments that DoD equipment is typically subjected to. Finally, ESW filters will self-regenerate at lower engine load conditions than most Level III filters.

2.1.2 Robust Particulate Filter

Cummins has developed the RPF to reduce PM emissions from diesel engines by up to 90 percent. The RPF system, as shown in Figure 2.2, was designed for and commercially used in 2007 new Cummins engines. The RPF system consists of four major parts: a catalyzed soot filter (CSF), a DOC, a fuel injection system, and the electronic control system. The CSF removes PM from the exhaust gases using a wall-flow filtering process with very small pore sizes (a schematic of a CSF is shown in Figure 2.3). Periodically, high exhaust temperatures from either a highly-loaded engine or caused by fuel injected directly into the exhaust (a.k.a. dosing), causes the soot accumulated on the catalyzed surface of the CSF to oxidize. This process, producing CO and Carbon Dioxide (CO₂), is termed “regeneration.” The DOC installed upstream from the CSF catalytically oxidizes the CO and HC species in the exhaust as well as the soluble portion of the PM emissions to CO₂ and H₂O. The fuel injection system periodically injects fuel into the exhaust system upstream of the DOC where, at adequate temperatures, the injected fuel is also oxidized to provide sufficient thermal energy to the CSF to cause the soot to oxidize and regenerate the CSF. The proprietary electronic control system determines when, and

if, the fuel injection system will be activated. This determination is made by using a differential pressure measurement from across the CSF as well as by other proprietary engine operational parameters.

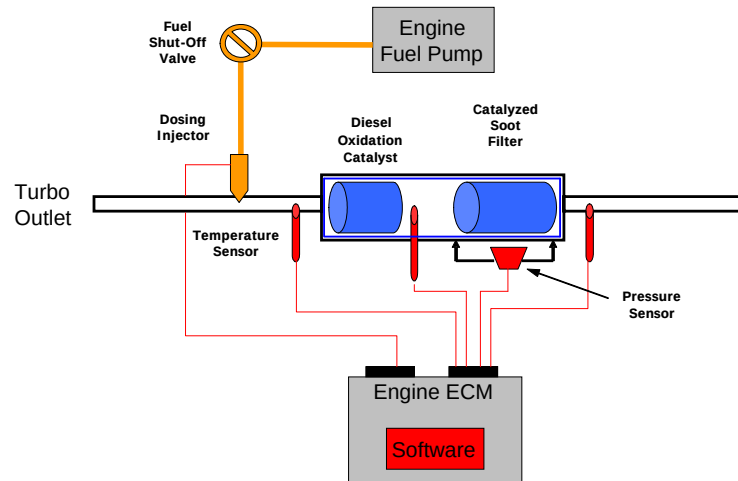


Figure 2.2
Robust Particulate Filter

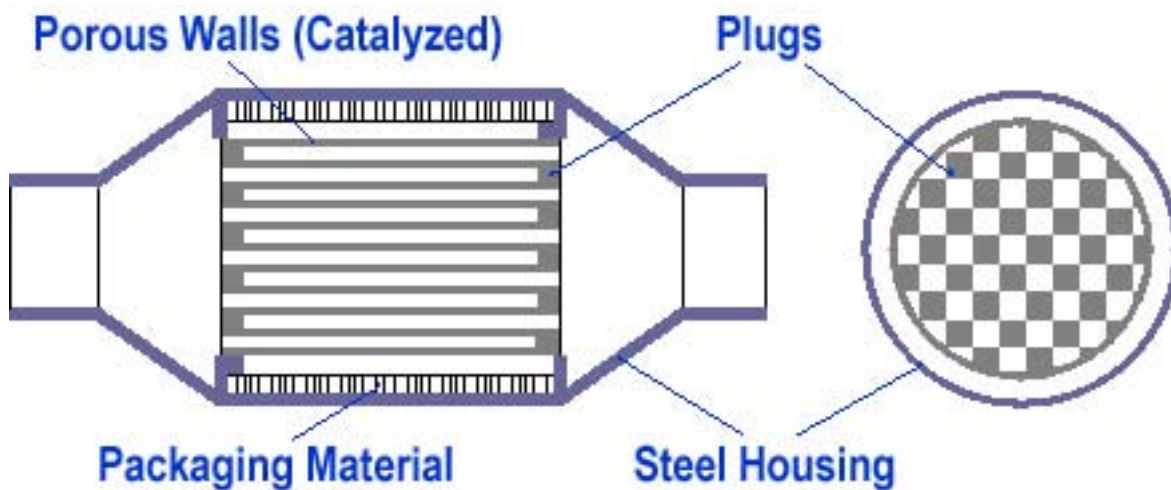


Figure 2.3
Catalyzed Soot Filter.

The RPF technology was developed for the new diesel engine market, although for this project it was used for retrofit applications. It was designed primarily for on-road vehicles that, by virtue of the exhaust gas temperatures, do not maintain sufficiently high exhaust temperatures during their duty cycles to provide satisfactory “passive” regeneration of the filters. An advantage of this filter, compared to competing technologies, is that it is suitable for use with current EPA approved off-highway diesel fuel containing up to 500-ppm of sulfur. However, the technology’s performance improves when fuels with lower sulfur levels are used. This technology represents the next generation of the CSF that was demonstrated in a previous ESTCP project (see Reference 1). In that project, it was found that a passive CSF is appropriate only in a very limited number of applications where the engine has high exhaust temperatures for a significant portion of its duty cycle.

2.2 Previous Testing of the Technologies

2.2.1 ESW Particulate Reactor

Cummins Engine Company has satisfactorily completed ‘hot’ rig/shaker (off engine/vehicle) testing, engine dynamometer testing, and vehicle field-testing on the ESW filter. Rig testing is the term used to describe off-engine testing, and shaker testing involves mounting a component or sub-system on a shaker table that vibrates in one or more axis (vertical, axial or radial) at loads and frequencies determined to be common and critical to the application in which the component or sub-system will be used. The term ‘hot’ means that the component was heated to operating temperature by running hot air through it to simulate exhaust gas conditions.

Engine dynamometer testing of the ESW filter consisted of system performance and mechanical development tests. Emissions tests were conducted on two engine families: the 5.9 liter Cummins B Series and 7.3 liter Navistar T444E engine, using low sulfur (less than 350 ppm) diesel fuel. These tests showed PM reductions greater than 50 percent by mass. Listed below is a summary of the specific engine performance and mechanical development testing performed by Cummins.

1. Soot loading tests to correlate soot loading to exhaust back pressure
2. Balance point testing to provide a measure of the temperature where the soot being produced by the engine is equal to the amount of soot being oxidized in the filter.
3. Uncontrolled regeneration tests. Uncontrolled regeneration is started by a high oxidation rate of soot collected in the reactor that results in excessive temperatures in the device. If there is excessive soot in the reactor, rapid oxidation of it (combustion) can lead to damage to the reactor.
4. Deterioration factor test. This consists of extended testing to simulate actual in-service use with exhaust emissions measured periodically. The emissions data is then run through a model that calculates a deterioration factor.

In addition to the above described rig and engine test cell testing, the ESW filter also underwent extensive field-testing beginning in 2003. Seventeen engines in both on- and off-road applications were fitted with an ESW filters and used for the field-testing. Off-road applications

included a John Deere diesel powered generator and a Cummins QSK19 powered crane. On-road field-testing included a pickup and delivery vehicle, 10 school buses, 2 Mack refuse trucks and 2 transit buses.

2.2.2 Robust Particulate Filter

During a previous ESTCP project (see Reference 1) performed by the NAVFAC Engineering Service Center, as well as in other demonstrations, passive soot filters have been extensively tested in both engine test cells and on numerous test vehicles. The active RPF represents the latest generation of the CSF technology. The initial field-testing of a passive CSF technology was conducted in 1998 on eight urban buses operated by the New Jersey Transit Authority. Those results showed CSF lifetimes of greater than one year (>100,000 miles) and PM emissions reductions of greater than 80 percent. Some soot filter failures were also noted during this program, indicating the need for manufacturing improvements, the importance of monitoring the condition of the soot filter and performing routine maintenance. Those tests were followed by the others reported in Reference 1 which demonstrated both (a) the importance of knowing the exhaust temperature histories from the diesel engines, and (b) the wide range of these histories that apply to DoD diesel engines.

To illustrate the effectiveness of a soot filter in reducing the total PM mass, Figure 2.4 shows two sample filters from a double dilution tunnel system installed on the exhaust pipe of a diesel engine placed in an engine test cell. The clean filter was installed downstream from a CSF, while the black filter was placed in an exhaust system without a CSF installed. The measured results are shown in Table 2.1.

Because of the limited applicability of the passive CSF technology, Cummins developed the RPF technology as their primary strategy for meeting the year 2007 new heavy-duty diesel engine PM emissions limits. Internal Cummins testing of this technology began in 2004 and continued through the fall of 2006. This extensive testing program consisted of bench/rig testing, engine test cell testing and on-road vehicle testing. Validation testing for 2007 engine applications was divided into both sub-system (controls, DOC, fuel doser, and particulate filter) and total system performance testing. The total system performance testing consisted of active regeneration testing, back pressure mapping and performance measures, full load endurance testing, 1,500 hour start/stop cycle testing, accelerated aging/life tests, noise testing, complete thermal fatigue analysis, as well as summer and winter field testing using Cummins-operated heavy-duty trucks.



Figure 2.4
Effectiveness of a CSF in Reducing Total Particulate Mass

Table 2.1
Engine and CSF Emission Data for EPA Transient
Cycle Using a C8.3-275 Hp Transit Bus Engine

<i>Emission</i>	Total Particulate	Soluble Organic Fraction	Total Hydrocarbon	Carbon Monoxide
Engine-out (g/bhp-hr)	0.09	0.05	0.18	0.69
CSF-out (g/bhp-hr)	0.02	0.01	0.05	0.21
Reduction (%)	80	78	70	70

2.3 Factors Affecting Cost and Performance

This project will demonstrate two technologies that provide at least a 50 percent reduction in PM emissions. They can be expected to compete in over-lapping market segments, will have somewhat different prices, and although both will provide 50 percent PM reduction the RPF

device is expected to do better than this. We would also expect that systems providing less performance will be less expensive. In general, the costs for diesel emission control technologies are primarily driven by duty cycle, engine size, system complexity (e.g., needed control modules), number of similar applications, and the presence and quantity of precious metals such as Platinum (Pt).

Although, in general, the technology purchase costs will increase with engine size and increased engine duty cycle, the system costs will not be directly proportional to capacity. The reason is that there is a fixed design cost for each new application. This design cost may be very significant where the market is only a small number of engines. As the market for similar engines increases, the design cost per engine will become significantly less.

Since the effectiveness of the diesel oxidation process is temperature dependent, the average and maximum engine exhaust temperature caused by the load on the engine will affect the type of filter that can be deployed and the total system cost. To a lesser extent the climate in the area where the engine is operated will have an effect. In general, engines with high exhaust temperatures or used in hot climates will require less precious metals.

The technology operating costs are driven by maintenance costs and any fuel penalty caused by the technology. The soot filter contained in the RPF will require periodic cleaning to remove the accumulated ash that will plug filter pores. This cleaning operation will require that the filters be temporarily removed from the vehicle. The cleaning period will be dependent on the duty cycle and hours of use on the engine as well as the sulfur level in the fuel. Along with oxidizing the CO and HC emissions, the Pt catalyst will also convert fuel sulfur compounds into particulate sulfates, a form of ash.

Use of these technologies is also expected to result in a reduction in fuel economy. In the worst case, this reduction is expected to be less than 2 percent. Where possible, fuel use differences were measured as part of the demonstration. In general, it was expected that engine applications with lower exhaust temperatures will experience a greater fuel penalty.

Except for the fuel penalty, neither of the technologies selected for testing was expected to materially affect overall engine performance. It was not expected that engine operators would notice any operational differences except for reductions in black exhaust smoke. Since the PM control capabilities of the technologies are different, their performance cannot be directly compared. Instead, they must be measured against user needs and life-cycle costs.

2.4 Advantages and Limitations of the Technology

The ESW technology demonstrated a minimum 50 percent reduction in PM emissions while the RPF system was designed for a 90 percent reduction. This is an improvement over a DOC that only reduces the PM emissions by 30 percent. The DOC removes only the soluble organic soot compounds whereas the demonstrated technologies also reduce a portion of the soot's black carbon.

For potential users, the ESW filter offers the advantage of being commercially supported by a major diesel engine manufacturer. Several of the competing technologies, such as the microwave regenerated soot filter, have been independently developed and supported by small private startup companies. The ESW technology also offers the advantage of requiring no engine operator actions and of being suitable for use for a wide range of applications. Based on its poor performance in this demonstration, Cummins has decided not to make the RPF device a commercial product for the retrofit market; therefore, this report will provide no further discussions of its advantages and limitations.

The ESW technology has been designed to meet the CARB Level II requirement. Given this design, the technology is expected to compete in those vehicle (on- or off-road) retrofit and new off-road and stationary engine market segments where both the user and the applicable air pollution regulatory agency would be satisfied with a 50 percent reduction in PM emissions. Unlike some competing technologies, the ESW technology is suitable for use with low sulfur fuel. It does not require the use of ULSD.

The major cost categories for diesel engine emissions treatment technologies are: the purchase cost, the installation cost, maintenance, and the operating costs. The primary cost driver for the ESW unit is the use of precious metal in the catalyst that is used to assist in burn-off of accumulated soot and regeneration of the filter. This cost, although significant, is comparable to those for competing diesel aftertreatment technologies.

The primary limitations on the use of the ESW technology are the engine duty cycle and the fuel sulfur level. In order to provide PM reductions over a long period of time the ESW filter periodically needs to regenerate itself by causing the soot collected to be oxidized to CO₂ by a catalytic oxidation process. To initiate the oxidation, a high exhaust temperature excursion is required, although in the tests conducted in this project that temperature excursion was extremely modest. To ensure proper operation, ESW recommends that the engine operates with an exhaust temperature above 300°C for 7 percent of the duty cycle.

Like the engine exhaust temperature, the fuel sulfur level also limits the applicability of this technology. During the oxidation reaction on the catalyst, fuel sulfur compounds are oxidized into solid sulfates, a form of ash. Since the ESW filter is a CARB Level II certified device, the pore size of the catalyst will allow the majority of this ash to simply pass through into the atmosphere whereas a Level III filter, such as the RPF device, would retain this ash and need to have it periodically removed in order to maintain low filter back-pressures. Within these limits the ESW is designed to be applicable for fuels having sulfur levels < 500 ppm.

3.0 DEMONSTRATION DESIGN

3.1 Performance Objectives

The performance objectives in this demonstration project for each filter tested are shown in Table 3.1.

Table 3.1
Performance Objectives

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance Objective Met?
Quantitative	Backpressure	20-34 kPa of backpressure	Yes
	CO emissions reduction	60% reduction	ESW – Yes RPF – Not Measured
	Fuel Economy	No greater than 2% decrease	ESW – Yes RPF – Not Measured
	HC emissions reduction	60% reduction	ESW – Yes RPF – Not Measured
	PM emissions reduction	50% reduction	ESW – Yes RPF – Not Measured
	HAP emissions reduction	50% reduction	ESW – Yes RPF – Not Measured
Qualitative	Drivability	Maximum one driver report of drivability issue	ESW – Yes RPF – Yes
	Installation	8 hours per installation	ESW - Yes RPF – No
	Reliability	Maximum one breakdown caused by pollution control device	ESW - Yes RPF – No

3.2 Selecting Test Sites/Facilities

DoD test sites were selected to provide a broad array of DoD on-highway vehicles. Also important to the test site selection process was their proximity of the test vehicles to project personnel. A primary consideration in the selection of the test units was the vehicle operating

profile. Here emphasis was placed on vehicles that normally operated at medium to high load levels with long operating times. Secondary considerations included ease of installation of the pollution control hardware, and the number of similar units in the DoD inventory.

A total of eight vehicles at three test sites were selected for demonstrating the ESW and RPF device. Since one engine may be operated under different conditions (e.g., different driving routes) compared to the rest of a fleet, duplicate engine applications were included where possible. Test sites, an identification of the proposed demonstration units, and the technology installed on each demonstration unit are shown in Table 3.2.

Table 3.2
Diesel Powered Vehicles to be Demonstrated

Demonstration Site	Vehicle	Control Technology
Marine Corps Base, Camp Pendleton, CA	Ford L9000 Truck Thomas Bus International 7600 Truck Ford F Series Stake Truck	Robust Particulate Filter Robust Particulate Filter ESW Particulate Reactor Robust Particulate Filter
Cheyenne Mountain Air Force Station, CO	Thomas Bus Thomas Bus	ESW Particulate Reactor ESW Particulate Reactor
U.S. Army Aberdeen Test Center, Aberdeen Proving Grounds, MD	Ford F350 Pickup Truck Navistar 4700 Panel Truck	ESW Particulate Reactor Robust Particulate Filter

3.3 Test Site/Facilities History/Characteristics

The demonstration vehicles were located at the DoD facilities described below:

Marine Corps Base, Camp Pendleton, CA is the site of the Corps' largest amphibious assault training facility, encompassing 17 miles of Southern California coastline and 125,000 acres. The base has a population of nearly 40,000 Marines and Sailors. As such, nearly every type of equipment in the Marine Corps inventory is located at this facility. As a functioning training command, the equipment is used almost daily for training and transportation purposes. The trucks and bus selected for the demonstration are used primarily for trips between various Marine Corps and Navy training activities within Southern California as well as for on-base use. Many of the vehicle trips were through the California desert, a very hot and dry environment.

Cheyenne Mountain Air Force Station, Colorado Springs, CO, is buried 2,000 feet under Cheyenne Mountain at an elevation of over 7,000 feet. The facility is situated in underground tunnels that were bored out of the mountain. The air station is a top-secret combat operations center formerly known as the North American Air Defense Command, or NORAD. The station contains equipment that provides warning of missile or air attacks against North America and

can serve as the focal point for air defense operations in the event of an attack. The station's mission is to provide Canadian and U.S. National Command authorities with accurate air, space, missile and nuclear detonation information. The major units of the station are the North American Aerospace Defense Command, U.S. Space Command, and Air Force Space Command. To access the main operational areas diesel powered vehicles are used in the underground tunnels. Exhaust from these vehicles is the major source of contamination for the facility's air handling system. The Thomas buses selected for the demonstration are used to transport workers down the main access tunnel.

U.S. Army Aberdeen Test Center (ATC), Aberdeen Proving Grounds, MD, is an east coast temperate-climate proving ground encompassing 57,000 acres of land and water. It is the DoD's lead test center for land vehicles, guns and munitions, and live-fire vulnerability and lethality testing. After more than 80 years ATC has developed into a world-class, all-purpose test center operating as an outdoor laboratory. The comprehensive array of capabilities, unique facilities, simulators and models at ATC, combined with an experienced scientific and technical workforce, enable testing and experimentation on items ranging from components to entire systems. To support its testing mission, many of the diesel vehicles used by the DoD are found on Aberdeen Proving Grounds. The Ford F350 pickup truck selected for the demonstration is used primarily to support the long distance transport of oversized equipment. The Navistar 4700 Panel Truck is primarily used to support on-post weapons testing.

3.4 Present Operations

All eight vehicles tested during this demonstration are operated by various DoD activities in support of their DoD missions. These vehicles utilized diesel engines supplied by various manufacturers between the model years 1992 to 2003. None of the test engines selected were previously equipped with aftermarket air pollution control devices. Some of the engines proposed for the demonstration produced visible soot during operation, making them especially desirable candidates for retrofit of pollution control devices.

3.5 Pre-Demonstration Testing and Analysis

A recently completed NAVFAC Engineering Service Center lead ESTCP project (see Reference 1), surveyed diesel-powered equipment and vehicles at representative Air Force, Air National Guard, Army, Marine Corps, and Naval activities. This survey identified 85 different commonly operated DoD diesel engines. The eight demonstration engines chosen for this demonstration were selected from those 85 diesel applications plus additional engines added to the fleet since completion of that survey.

That previous work included an evaluation of the engines to determine whether they would be suitable candidates for retrofitting with soot filters. The suitability evaluations were based on estimated engine duty cycles, number of similar applications, age of the engines, miles driven (hours of use), and ease of filter installation. Twenty-two (22) engine applications (of the 85) were identified as possible candidates for filter retrofit and from them a single unit from each of

the 22 application classes was then instrumented and tested for a three-week period to establish actual hours of use (miles driven), and average and maximum exhaust temperatures. From those results eight vehicles were selected for demonstrating PM emissions reduction using a “passive” CSF. Two portable tactical generators were also selected for demonstrating PM reduction with a catalyzed “active” soot filter. The results of the demonstration showed that the “passive” soot filters reduced PM emissions by greater than 90 percent, but that their potential applications were limited by their need for periodically high exhaust temperatures. Results for the “active” filter showed a 62 percent reduction in PM emissions, but provided the advantage that they were compatible with diesel exhaust streams of lower temperatures. Complete results from that study are available in Reference 1.

Those tests demonstrated the importance of exhaust temperature histories in successfully applying soot filters to diesel engines. Therefore, to verify that the exhaust temperature profiles of the selected test vehicles for this study would meet the minimum requirements of the technologies to be demonstrated; all the demonstration vehicles except for the Thomas bus at Camp Pendleton were instrumented and tested for a one to two-week period to monitor their exhaust gas temperature (EGT) histories. Those tests included the measurement of hours of vehicle use as well as average and maximum EGTs. The project team did not instrument the Camp Pendleton Thomas bus since sufficient data was already available for it from the previous ESTCP project (see Reference 1). The composite pre-test results for exhaust temperatures for the selected test vehicles are shown in Table 3.3.

The right hand column of Table 3.3 shows the manufacturer’s guideline for fraction of operational engine time that the exhaust temperature should be above the indicated temperature for the installed filter to successfully regenerate itself during normal operations. The guidelines are of two standards: (a) 7 percent of the time above 300°C, and (b) 8 percent of the time greater than 250°C. The former standard applies to the ESW filter. As the ESW is a “passive” filter (i.e., no thermal augmentation is provided to the thermal energy of the exhaust gas for regeneration of the filter), a somewhat hotter exhaust gas temperature is specified by the filter manufacturer. The latter standard (for the RPF device) reflects that some additional fuel is injected into the exhaust stream during certain parts of the operational cycle to boost the exhaust stream temperature and provide a better opportunity for filter regeneration. Because this thermal boost (fuel injection) is available, the demand for a hot exhaust gas temperature coming from the engine is less.

The second-to-last column shows the actual fraction of time that the exhaust temperature was, from field measurements, determined to be greater than the manufacturers’ guidelines. These temperatures were satisfactory for all vehicles except for the Thomas buses at Cheyenne Mountain Air Force Station. However, the decision was made to proceed with those tests in spite of this questionable indicator for satisfactory operation. Unfortunately, for the Ford F350 pick-up truck at ATC, the recorded preliminary EGT measurements were not reflective of the vehicle’s normal duty cycle. Therefore, the results have not been included.

Table 3.3
Pre-demonstration Testing Results

Application	Engine Type	Actual % of Time Above Required Temperature	Recommended % of Time Above Required Temperature
Camp Pendleton			
Ford L9000 Truck	Caterpillar 3306	8% of Time Above 250°C	8% of Time Above 250°C
Thomas Bus	Caterpillar 7.2L	Not Tested	8% of Time Above 250°C
International 7600 Truck	Caterpillar C12	10% of Time Above 300°C	7% of Time Above 300°C
Ford F Series Stake Truck	Cummins C8.3-250	40% of Time Above 250°C	8% of Time Above 250°C
Cheyenne Mountain Air Force Station			
Thomas Buses (2)	Cummins 5.9L	5% of Time Above 300°C	7% of Time Above 300°C
ATC			
Ford 350 Pickup Truck	Navistar 7.3L T44E	N/A*	7% of Time Above 300°C
Navistar 4700 Panel Truck	Navistar 7.3L T44E	22% of Time Above 250°C	8% of Time Above 250°C

*This vehicle's normal reported duty-cycle was not captured during the test period; however, operating personnel provided an assessment that the exhaust gas stream was sufficiently hot to provide satisfactory filter regeneration.

3.6 Testing and Evaluation Plan

The following sections discuss the field installation, testing and evaluation of the ESW and RFP filter technologies.

3.6.1 Demonstration Set-Up and Start-Up

The project team installed the pollution control technologies on each of the eight demonstration vehicles selected. The installations were performed in such a manner that the engines could be restored to their original configuration at the completion of the test periods. The retrofit pollution control devices were installed in place of the existing exhaust mufflers. The installations also included installing the required instrumentation for measuring exhaust temperatures and pressure

drops across the filters, and where required, controllers (Filter Electronic Control Module). Because of the complexities of the RPF device, their interactions with engine operations, and the need to periodically inject fuel into the exhaust stream, additional sensors to measure a great deal of engine data were also installed for these applications.

On-board data loggers were used to store the collected data. It was expected that each filter installation could be completed in one to two days and that all eight installations would be completed within a two-month period. All installation work was accomplished at each of the operator's facilities. It was originally anticipated that little or no maintenance of the pollution control technologies would be required during the demonstration period. This expectation was realized with the ESW filter, but not for the RPF.

3.6.1.1 ESW Particulate Reactor

Installation of the ESW filter was fairly straight-forward, and they were installed within approximately one work-day. Several photos of the installations are shown in Appendix A. The installation consisted of removing the current muffler, installing the canned catalyst in its place, and connecting the pressure and temperature sensors to the system data logger. The sensors were set to record temperatures at the inlet and outlet of the catalyst bed and pressure at the inlet to the catalyst (engine exhaust back pressure). Once these components were installed, the vehicles were put back into service.

3.6.1.2 Robust Particulate Filter (RPF)

Installation of the RPF device was a much more complex operation than for the ESW filter, and the efforts needed to adjust the RPF device for satisfactory field operation was also much greater (see Appendix A for photographs of the RPF installations). The RPF installations consisted of replacing the current muffler with the canned DOC and DPF, adding a fuel dosing system (fuel pump, fuel injection tubing and nozzle, fuel shut-off valve, mass air flow meter, engine boost pressure sensors, and an exhaust throttle valve for thermal management of the exhaust gas stream), and a filter electronic control module. Many of these components, in addition to the catalyst, are shown in Figure 3.1. A filter fuel pump is not shown, but if a commercial retrofit package were to be developed, the fuel source could be taken directly from the high pressure side of the engine fuel pump. A separate, low-pressure Racor fuel pump was used for fuel injection into the RPF for these tests.

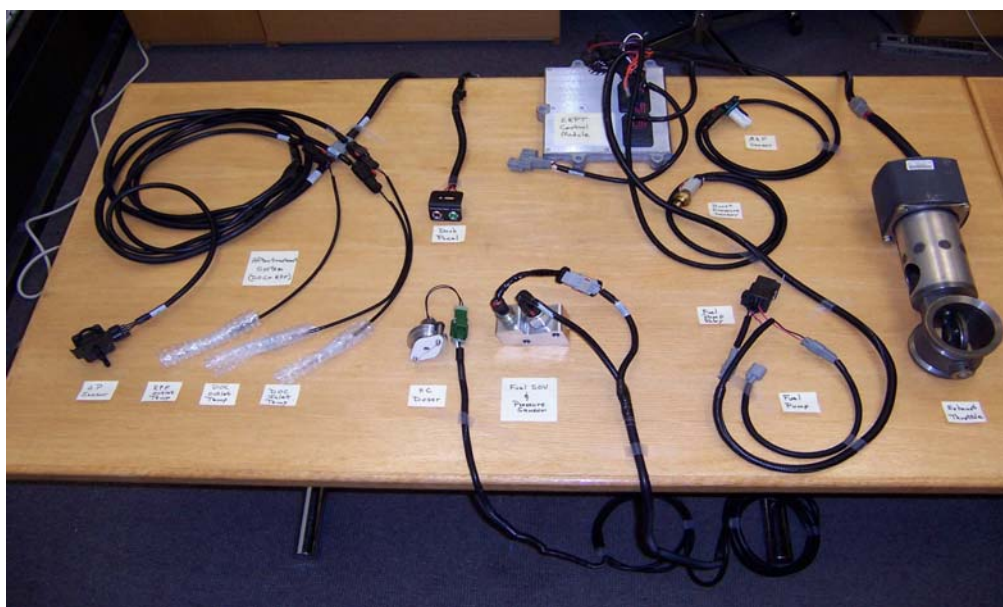


Figure 3.1
Layout of RPF Components

Note: (The RPF installed for these tests was not yet a commercially-ready system for retro-fit to in-use vehicles. Rather, it was a first-generation, retro-fit developmental unit of the RPF technology developed by Cummins Engine Co. for use with its 2007 engines. Therefore, it was felt that it also had high promise for retro-fit applications. The filter elements (a DOC and CSF), themselves, were well developed for use on new vehicles, and the specific controls and instrumentation needed for the coordinated operation of these elements with new engines was in final development. But “active filters” capable of Level III performance (> 85 percent reduction of particulate emissions) require a substantial amount of control coordination between the filter engine control module (ECM) and the engine ECM. This coordination is possible when designed into the system for new vehicles, but extremely difficult when trying to retro-fit RPF devices to vehicles in the field having different model years, different manufacturers, and different engine ECM designs. Prolonged efforts were made by Cummins personnel to meet this challenge and to develop alternative RPF control strategies that would be successful as retrofit for each of the chosen test vehicles. But this adaptation meant design, calibration, and installation of new untried RPF components that were being used for the first time. This contributed to field installation problems, calibration problems, delays in the filter installation, and finally difficulties in maintaining some of the filters operational).

The installation of the four RPF systems took from 12 to 16 hours, each, to complete. This time may be reduced somewhat in a commercial retrofit scenario because the RPF unit would be manufactured to fit in the same space as the existing muffler. Also, the ECM would have to be provided in such a way as to accommodate a range of engines and ECMs that would be encountered in a retro-fit scenario and a technician with experience gained from many such installations would be doing the work. In the present case, the schedule of the demonstration did

not allow for custom fitting the catalyst to the different vehicles and developmental, non-specific hardware was used. Pictures of the four RPF installations are included in Appendix A.

3.6.2 Period of Operation

The demonstration period lasted approximately one and one-half years, from March 2005 until October 2006. It was anticipated that the installation of all control devices would be accomplished by the summer of 2006, providing all devices with a year's field-test evaluation. However, working installations of some units was not completed until the summer of 2006 so that actual field-test periods ranged from over a year to several months.

3.6.3 Amount/Treatment Rate of Material to be Treated

The exhaust stream to be treated varied with the engine horsepower being delivered by each unit during its operational cycle. The full load exhaust flow rate of the smallest unit selected for the demonstration was approximately 1,000 cubic feet per minute at 260-370°C. The largest unit had an exhaust flow rate of approximately 2,500 cubic feet per minute at a temperature of 430 °C.

3.6.4 Operating Parameters for the Technology

During the demonstration period, each of the test engines was operated using its normal duty cycle; each pollution control technology was continuously operational during engine operation. Since each of the demonstration engines had a different operating duty cycle, a range of engine operating conditions was experienced during the demonstrations. In general, a goal of test operations was that the installation of a pollution control device would be transparent to engine operators who would not be aware that they were using an engine that had been modified with the control device. The pollution control technologies had been designed to minimize their effects on engine performance, and changes in engine noise, fuel economy and power were also expected to be minimal.

Instrumentation was installed to monitor the performance of the pollution control devices and the engines on portable data loggers. Exhaust pressures and temperature data were recorded for the filters as well as engine parameters. The project team periodically collected and reviewed the data to verify that both the test engines and filter control hardware were operating satisfactorily.

3.6.5 Experimental Design

3.6.5.1 Operational Data

The demonstration consisted of installing the pollution control devices on eight selected DoD engines and operating those engines under normal conditions for approximately one-year test-

periods. The purpose of the tests was to gather field data to address both the qualitative criteria of drivability, installation, and reliability of the filters and the quantitative criteria of filter back-pressure, effect on fuel economy, and emissions reductions. The actual number of engine and filter operating parameters that were monitored were different for the two filters, and exceeded those originally planned. This excess data (mainly for the RPF) was recorded to provide the best opportunities for understanding how well the filters were performing during testing and for helping to diagnose operational problems if or when they occurred.

The temperature history of the exhaust gases is a primary indicator of the engine's duty cycle and is also a good indicator of the adequacy of the thermal energy of the exhaust stream for providing satisfactory regeneration of the filters. It was carefully monitored. The inlet filter pressures were also recorded as a function of time. For the ESW filter, minimum, average, and maximum temperatures and pressures were determined from this data. The recorded pressures (filter back-pressure) were the primary indication of the condition of the filter and whether they were being properly regenerated (a high pressure drop would indicate excessive build-up of soot in the filter and unsatisfactory filter regeneration). Ambient temperatures were also recorded. Data loggers were programmed to collect data as frequently as necessary, but not so often as to overload the logger memories between down-loadings of the data. The ESW data was logged at a rate of one data set every 5 minutes and the RPF data was logged at a rate of one data set every 5 seconds. A Johnson Matthey CRTdm data monitor was used to collect the exhaust temperature and pressure data for the ESW systems and doubled as a system monitor. For the RPF systems, a Cummins designed and assembled data logger was used to collect the exhaust temperature and pressure data. Approximately monthly, on-site checks of the filters were made to ensure that data was being collected and that all hardware was operating properly. In some cases the data was down-loaded by on-site operating personnel and transmitted electronically to the project team.

Many additional system parameters were recorded by Cummins to monitor status and performance of the RPF device and engines. The data recorded included: temperature of exhaust gas (TEG) entering the DOC; TEG exiting the DOC and entering the DPF; TEG leaving the DPF; the dosing rate of fuel being added to the exhaust gas stream for increasing its temperature; dosing fuel pump on/off; dosing fuel pressure; engine intake manifold pressure; exhaust throttle valve position; mass air flow frequency (from which air mass flow was calculated by the filter ECM), and the filter pressure-drop needed for calculating soot loading of the filter.

3.6.5.2 Emissions Testing

Air emissions testing results show that emissions vary with a number of parameters, the most important being the engine operating conditions. The emissions testing conditions are therefore chosen to duplicate expected cycle operating conditions as closely as possible for comparison to other similar applications. To do this, vehicle emission testing is normally performed with the vehicle placed on a chassis dynamometer using one or more driving cycles that have been developed to simulate common applications. For this project, the Central Business District (CBD) transient cycle was used by both NREL and UCR to test one of the Cheyenne Mountain Air Force Station buses since this cycle somewhat matches its actual driving cycle. These bus emissions were also tested using a custom transient cycle developed by NREL that matched the actual driving cycle of these buses as determined using a data-logger. Air emissions results from this testing have been reported in the form of emission factors as grams per mile (g/mile) or grams per brake horsepower hour (g/bhp-hr) as is customarily reported in the scientific literature.

Plans were made for making air pollution emissions measurements for the regulated pollutants CO, HC, NO_x and PM for two demonstration engines (one using an ESW filter and one using an RPF device). Emissions testing for HAP emissions was planned for one engine using an ESW filter. Measurements for the ESW filter were made at NREL on one of the Cheyenne Mountain Air Force Station buses. For the RPF, the Camp Pendleton Thomas bus was to be used. This work was cancelled, however, because difficulties were encountered in maintaining the RPF devices operational in the field.

3.6.6 Product Testing

See Section 3.6.5.

3.6.7 Demobilization

Once field-testing was completed, all of the pollution control devices were removed from the vehicles. The RPF devices were returned to Cummins, Inc. for a post-use analysis consisting of a visual inspection. The exhaust systems were restored to their pre-demonstration condition. All of the data loggers were returned to Cummins.

3.7 Selection of Analytical/Testing Methods

Air pollution emissions testing of a Cheyenne Mountain Air Force Station bus was performed by both NREL and UCR at the NREL laboratory located in Denver, Colorado. This testing was performed using analytical testing instrumentation listed in Table 3.4. Although each testing organization employed similar analytical testing instrumentation and utilized similar analytical testing procedures specified in federal or recognized standard publications, they each have unique testing capabilities in terms of the types of tests that they could perform. These unique capabilities have been fully exploited by this project.

For the testing of regulated pollutants (CO, HC, NO_x and PM), emissions testing analytical test methods approved by the EPA, and found in the Code of Federal Regulations (CFR), were used. Specifically, testing was performed using the methods contained in 40CFR86 for control of emissions from new and in-use highway vehicles and engines. The detailed emissions test procedures for diesel engines are found in 40CFR86, Subpart N – *“Emission Regulations for New Otto-Cycle and Diesel Heavy-Duty Engines; Gaseous and Particulate Exhaust Test Procedures”* and more specifically in paragraph 86.1310-2007 *“Exhaust gas sampling and analytical system for gaseous emissions from heavy-duty diesel-fueled engines and particulate emissions from all engines.”*

For the non-regulated emissions, the analysis methods are not found in the CFR. Instead these analyses were performed using industrial specifications and methods that are referenced in the scientific literature. For example, the speciated C1-C12 volatile organic compounds (VOCs)

were determined using a Society of Automotive Engineers method developed by the automotive and petroleum industries (see Reference 2).

To detect gaseous air emissions, an infrared analyzer was used to measure CO and CO₂, a heated probe and flame ionization detector was used to measure HC's, and a chemiluminescence analyzer was used to measure NO_x. Characterization of gaseous HAP compounds, including the Mobile Source Air Toxics identified in Table 3.5, was performed by UCR using Gas Chromatography (GC) where the samples were collected on DNPH cartridges. Portable versions of these instruments were available and employed for field measurements. The mobile instrumentation included the same type of analyzers, except for the NO_x sensor. The mobile NO_x sensor was a solid-state zirconia sensor.

Table 3.4
Test Methods and Analysis of Exhaust Emissions

Instrument/Method	Measurement	Sample Duration	Lower Quantifiable Limit (Expressed in terms of fundamental measurement)
Pierburg NDIR	CO ₂ , CO	1 s	50 - 500 ppm
California Analytical Instruments/Flame Ionization Detection	THC, CH ₄	1 s	10 - 30 ppm
California Analytical Instruments/Chemiluminescence	NO, NO ₂	1 s	10 ppm
Various/Filter*	PM _{2.5} Mass and Chemistry-	0.25 - 2 hrs	Various
Tedlar Bag/GC-FID	VOC's (C ₂ - C ₁₂)	0.25 - 2 hrs	10 ppb C
DNPH Cartridges/Shimadzu HPLC/UV	Aldehydes and Ketones	0.25 - 2 hrs	0.02 ug/mL

*Includes Teflon and quartz media for mass, metals, ions, elemental/organic carbon and PAHs by GC/MS on extracts from filters.

Table 3.5
Partial List of EPA's Recognized Mobile Source Air Toxics

Acetaldehyde	Ethylbenzene	Poly Organic Matter (PAHs)
Acrolein	Formaldehyde	Styrene
Benzene	n-Hexane	Toluene
1,3-Butadiene	Naphthalene	Xylene

The measurement of PM emissions is more difficult and consisted of mass measurements as well as chemical and physical characterizations of the particles. Mass measurements were made by collecting particulate on a filter media and weighing the media before and after exposure to the exhaust. For these measurements, it was critical that the CFR methods be applied with respect to

the having an upstream classifier to remove the large particles and that the filter face temperature was maintained at 47°C +/-5°C. Chemical characterization of the PM involved chemically testing the particles collected on quartz filter media for elemental and organic carbon.

To collect emissions samples and make measurements, UCR utilized their mobile heavy-duty testing laboratory (test trailer). A schematic of the trailer is shown in Figure 3.2. The UCR mobile laboratory dilutes the whole exhaust stream and utilizes the constant volume sampling concept of measuring the combined mass emissions of Total Hydrocarbon (THC), NO_x, Methane (CH₄), CO, CO₂ and PM. Additionally, a bag for proportional sampling for sample integration is used for HC, NO_x, CO, and CO₂ measurement. The mass of gaseous emissions is determined from the sample concentration and total flow over the test period. The mass of particulate emissions is determined from a proportional mass sample collected on a filter and the total flow over the test period.

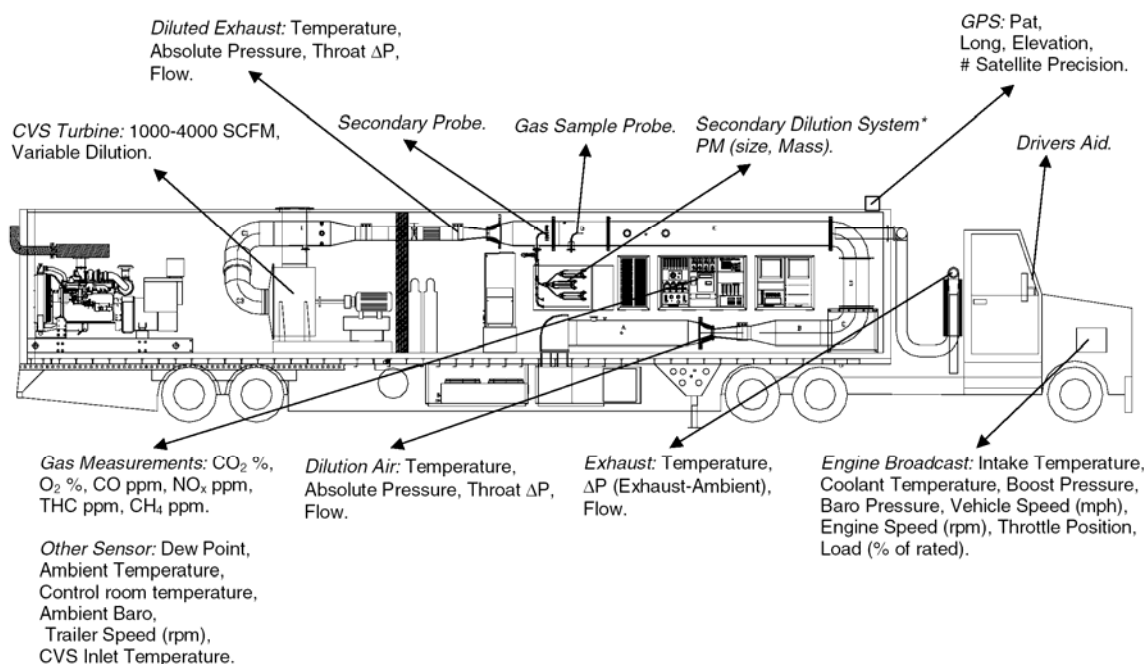


Figure 3.2
Schematic of the UCR Heavy-Duty Diesel Mobile Emissions Laboratory.

To complete the bus testing using the specified driving cycles, the NREL laboratory heavy-duty chassis dynamometer was employed. The NREL dynamometer is connected with two 40-inch diameter rolls that are capable of testing all highway ready single or twin-axle vehicles. The distance between the rolls can be varied between 42 and 56 inches. The dynamometer will accommodate vehicles with a wheelbase between 89 and 293 inches.

In the NREL lab, simulations of vehicle loads including, rolling resistance, air resistance, desired road grade, and acceleration of vehicle inertia are performed with the dynamometer and controller software. Vehicle weights between 8,000 to 80,000 lbs can be simulated via electrical inertial simulation. For each vehicle test, standard or customized driving test cycles are used that

match the duty-cycle of the test vehicle, ranging in speeds from idle up to 60 miles per hour. The dynamometer is equipped to run automated warm-up and coast-down routines to verify that dynamometer parasitic loads are stabilized and that road load simulations are accurate.

The NREL chassis dynamometer is supported by continuous exhaust emissions equipment similar to that previously described for the UCR Heavy-Duty Diesel Mobile Emissions Laboratory. An environmental chamber and microbalance specially designed to measure PM mass at EPA 2007 regulated levels is utilized. The lab does not, however, have the capability to chemically characterize HC and PM emissions to the extent of the UCR lab.

The NREL facility also has on-site fuel storage and blending capability. Test fuels can be received in drum quantities and blended on a mass or volume basis prior to testing. The test vehicle could be fueled directly from the fuel supply and blend shed located outside the laboratory through a high-accuracy inline fuel flow and density meter to directly measure fuel consumption during a drive cycle test.

3.8 Selection of Analytical/Testing Laboratory

As previously described, emissions testing was performed at the NREL laboratory. All required analytical testing of the fuels was performed at commercial laboratories under contract to UCR. The Cummins Fleetguard Nelson subsidiary in Stoughton, Wisconsin performed post removal analysis of the test filters.

4.0 PERFORMANCE ASSESSMENT

4.1 Performance Criteria

The performance criteria used for evaluation of the ESW and RPF are shown in Table 4.1.

Table 4.1
ESTCP Performance Criteria

Performance Criteria	Description	Primary or Secondary
Backpressure	Minimize Increase in Engine Backpressure	Primary
Regulated Air Pollutant Emissions	Reduce CO, HC & PM Air Pollutant Emissions	Primary
Fuel Economy	Minimize Fuel Use Penalty	Primary
HAP Emissions	Reduce HAP Air Pollution Emissions	Primary
Drivability	Maintain Engine Performance	Primary
Installation	Easy Retrofit on Existing DoD Diesel Engines	Primary
Reliability	No Maintenance Increase	Primary

4.2 Performance Confirmation Methods

Since the purpose of this demonstration was to verify the effectiveness of two diesel engine PM air pollution control devices installed on existing DoD operated engines, the overall success of this project will be measured in terms of the actual air pollution reductions achieved by the technologies and technologies effects on the performance of the tested engines. As an additional measure, this project must provide sufficient information to convince DoD diesel fleet purchasers and operators to implement the tested emission control technologies. In order for the project's test results to be accepted, standard recognized test methods were employed and the results reported in units consistent with other investigations.

For this project, standard EPA approved test methods were used, where applicable, for the air pollution emissions testing. To ensure the engines were consistently loaded, a chassis dynamometer was employed with the test vehicle operating on recognized driving cycles. All driving cycles were repeated with the reported results being the average of the tests. Gaseous air emissions data were continuously measured over the test cycle, with the results reported as an integrated value. Particulate emissions were collected on a filter paper throughout a cycle and weighed after the testing is complete. Both NREL and UCR testing organizations have extensive experience performing emissions testing. Their results from previous test efforts have been widely published in the literature.

The mechanism through which pollution control technologies can negatively affect engine performance is, primarily, through an increase in engine backpressure. Increased backpressure can lower effective engine power and increase fuel consumption, and this potential problem is of

special concern for soot filters. To ensure the successful operation of the demonstration technologies, backpressure along with inlet and outlet temperatures were monitored and recorded frequently while the engine was running. Trends in the backpressure can be detected over periods as short as a few days. Significant pressure increases would indicate that the device may have become plugged with soot. Temperature readings indicated how the vehicle was operating from minute to minute. High exhaust temperatures, for example, was evidence of high load operation.

Expected and actual engine performance from the demonstration and applicable performance confirmation methods are shown in Tables 4.2A and 4.2B for the ESW and RPF devices, respectively.

Table 4.2A
Expected Performance and Performance Confirmation Methods for ESW Filter

Performance Criteria	Expected Performance (pre demo)	Performance Confirmation Method	Actual Performance (post demo)
Primary Criteria (Performance Objectives) (Quantitative)			
Backpressure	34 kPa max.	Pressure transducer	33.9 kPa Max Average for 9 data sets was 2.0 kPa
CO Emissions	Reduce emissions by 60% minimum	40 CFR 86	68% Reduction
Fuel Economy	Achieve fuel penalty of less than 2%	40 CFR 86	No fuel penalty
HC Emissions	Reduce emissions by 60% minimum	40 CFR 86	82% Reduction
PM Emissions	Reduce emissions by 50% minimum	40 CFR 86	50% Reduction
HAP Emissions	Reduce emissions by 50% minimum	Various EPA methods	53% Reduction
Primary Performance Criteria (Qualitative)			
Driveability	No change	Driver response	One driver complaint, - Resolved
Installation	Easy Retrofit on existing DoD diesel engines	Mechanic response	All installations easily completed within one day
Reliability	No change	Mechanic response	No breakdowns

Table 4.2B
Expected Performance and Performance Confirmation Methods for RPF

Performance Criteria	Expected Performance (pre demo)	Performance Confirmation Method	Actual Performance (post demo)
Primary Criteria (Performance Objectives) (Quantitative)			
Backpressure	34 kPa max.	Pressure transducer	Average ΔP was 5kPa
CO Emissions	Reduce emissions by 60% minimum	40 CFR 86	Not measured
Fuel Economy	Achieve fuel penalty of less than 2%	40 CFR 86	Not measured
HC Emissions	Reduce emissions by 60% minimum	40 CFR 86	Not measured
PM Emissions	Reduce emissions by 50% minimum	40 CFR 86	Not measured
HAP Emissions	Reduce emissions by 50% minimum	Various EPA methods	Not measured
Primary Performance Criteria (Qualitative)			
Drivability	No change	Driver response	No complaints reported
Installation	Easy Retrofit on existing DoD diesel engines	Mechanic response	Difficult two day installations. for Ford F900 truck, specialized exhaust system fabrication equipment was required
Reliability	No change	Mechanic response	Several breakdowns of Ford F900 truck caused by high soot loading faults

4.3 Data Analysis, Interpretation, and Evaluation

A summary of the mileage accumulated on each test vehicle during the demonstration period is provided in Table 4.3.

Table 4.3
Summary of Demonstration Test Vehicle Mileage

Technology	Location	Vehicle Description	Vehicle Number	Installation Completion Date	Vehicle Mileage At Time of Installation	Vehicle Mileage At End of Test	Sytem Removal Date	Total Miles Accumulated
ESW Particulate Reactor	Cheyenne Mountain	Thomas Bus	USAF 001587	22-Mar-05	64,682	82,871	6-Feb-06	18,189
	Cheyenne Mountain	Thomas Bus	USAF 001589	10-Mar-05	37,657	60,057	6-Feb-06	22,400
	Camp Pendleton	ITEC 7600 Truck	291915	17-May-05	67,760	111,725	9-Feb-06	43,965
	Aberdeen Test Center	Ford 350 Pickup	AC 6384	2-Jun-05	82,000	95,861	29-Sep-06	13,861
Total								98,415
CES - Robust Particulate Filter	Camp Pendleton	Ford L9000 Truck	MC 288060	18-Aug-05	384,978	400,000	9-Feb-06	15,022
	Camp Pendleton	Ford FT900 Truck	C 291496	26-Aug-05	90,688	92,460	9-Feb-06	1,772
	Camp Pendleton	Thomas Bus	G 3200583	1-Sep-05	158,090	185,555	9-Feb-06	27,465
	Aberdeen Test Center	IH 4700 Truck	G71-01456	18-Apr-06	17,978	18,336	28-Aug-06	358
Total								44,617

4.3.1 ESW Filters

4.3.1.1 Operational Data

Cheyenne Mountain Buses. Operational data recorded for the ESW filters installed on one of the Thomas buses operated at the Cheyenne Mountain Air Force Station are shown on Figures 4.1 and 4.2 for successive time intervals. Plotted in blue are the measured exhaust gas inlet temperatures to the filter and in red the measured inlet pressures. Also shown on the figures are minimum, average, and maximum values for each.

This data shows that although the average temperature was around 140°C, spikes anywhere from 370°C to 388°C did occur occasionally, possibly providing some periodic regeneration of the ESW filter. This may account for the fact that the back pressure readings for the filter remained quite low (relative to the 34 kPa / 9.0 in Hg maximum). The exceptions were several high-pressure spikes, still less than the maximum permitted, that were observed half-way through the demonstration test. These did not affect vehicle operation, and their cause was later traced to partial plugging of the pressure measurement lines. The lines were blown out, correcting the high pressure faults previously observed. Additional evidence of adequate filter regeneration was that there was no continually increasing filter inlet pressure observed during the test. No other maintenance was required for the filters. Therefore it is clear that although the load duty of the Thomas buses at Cheyenne Mountain Air Force Station did not meet the filter manufacturer's recommendation that the EGT be greater than 300°C for at least 7 percent of the time (see Table 3.3), the filters were still able to adequately perform.

Ford F350 Pickup. The operational results for the F350 pick-up at ATC (Figure 4.3) showed even lower filter inlet temperatures (an average temperature of 60°C). Somewhat higher pressure readings were also recorded, but these also were significantly less than the permitted maximum. The total test mileage was low, but there was no significant increase in pressure during the test. There were no operator complaints.

ITEC 7600 Truck. The comparable results for the ESW filter test on the ITEC 7600 truck at Camp Pendleton (Figure 4.4) were quite different from those for the Cheyenne Mountain and the ATC tests. For the ITEC 7600 vehicle, the maximum inlet EGT's exceeded 500°C and the average inlet temperatures ranged from 284°C to 297°C, clearly indicating a much higher engine load thus easily meeting the target inlet temperature of 300°C for more than 7 percent of the time. The measured inlet pressures, although higher due to the increased loading of the engine (greater exhaust gas flow rate), remained well below the maximum permitted.

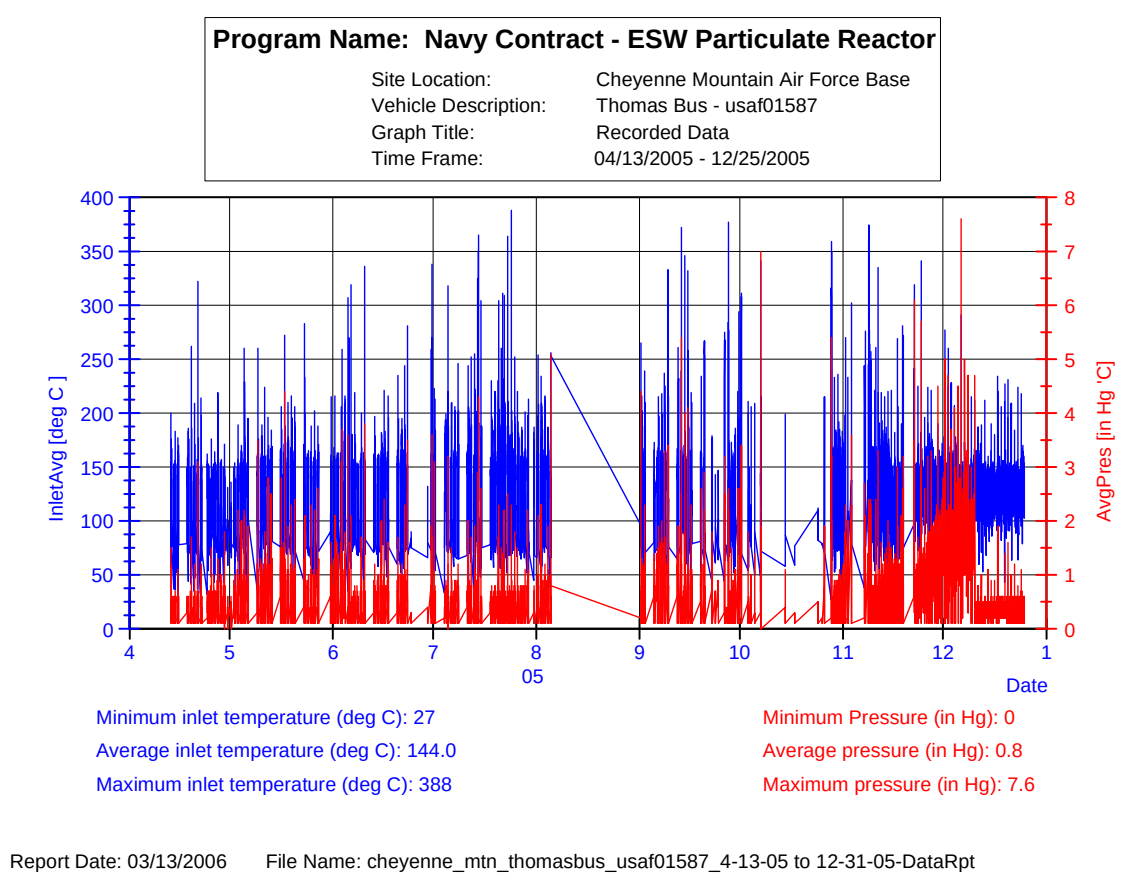
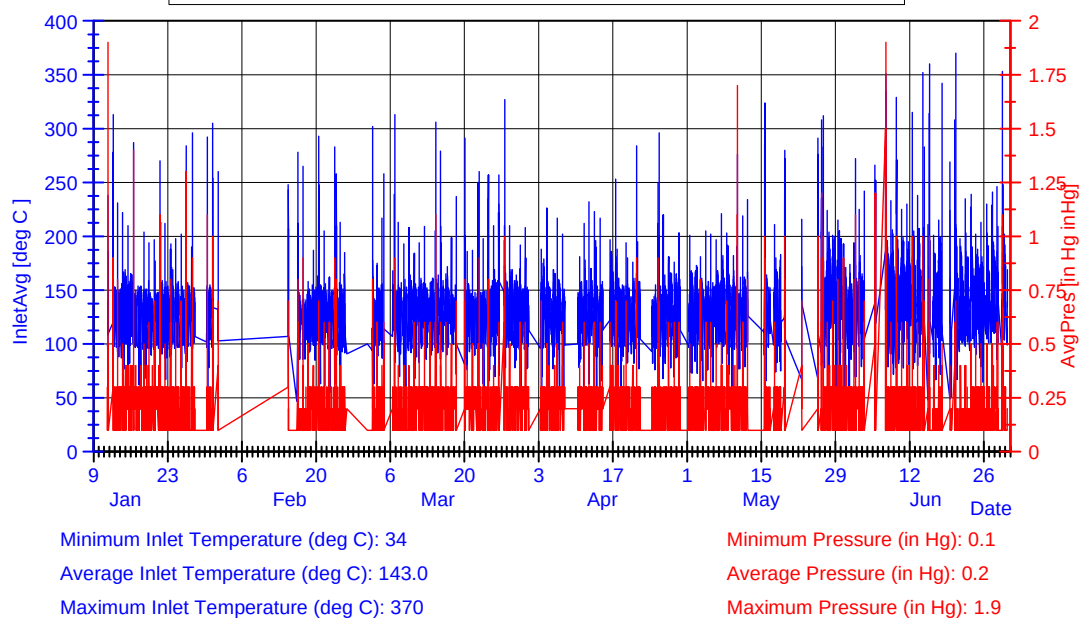


Figure 4.1
Inlet ESW Filter Average Temperatures and Pressures vs.
Time for Thomas Bus USAF 01587 (4/13/05 – 12/25/05)

Program Name: Navy Contract - ESW Particulate Reactor	
Site Location:	Cheyenne Mountain AFB
Vehicle Description:	Thomas Bus USAF01587
Graph Title:	Recorded Data
Time Frame:	01/11/2006 - 06/30/2006



Report Date: 08/14/2006 File Name: cheyenne_mtn_thomasbus_usaf01587_6_30_06-DataRpt

Figure 4.2
Inlet ESW Filter Average Temperatures and Pressures vs.
Time for Thomas Bus USAF 01587 (1/11/06 – 6/30/06)

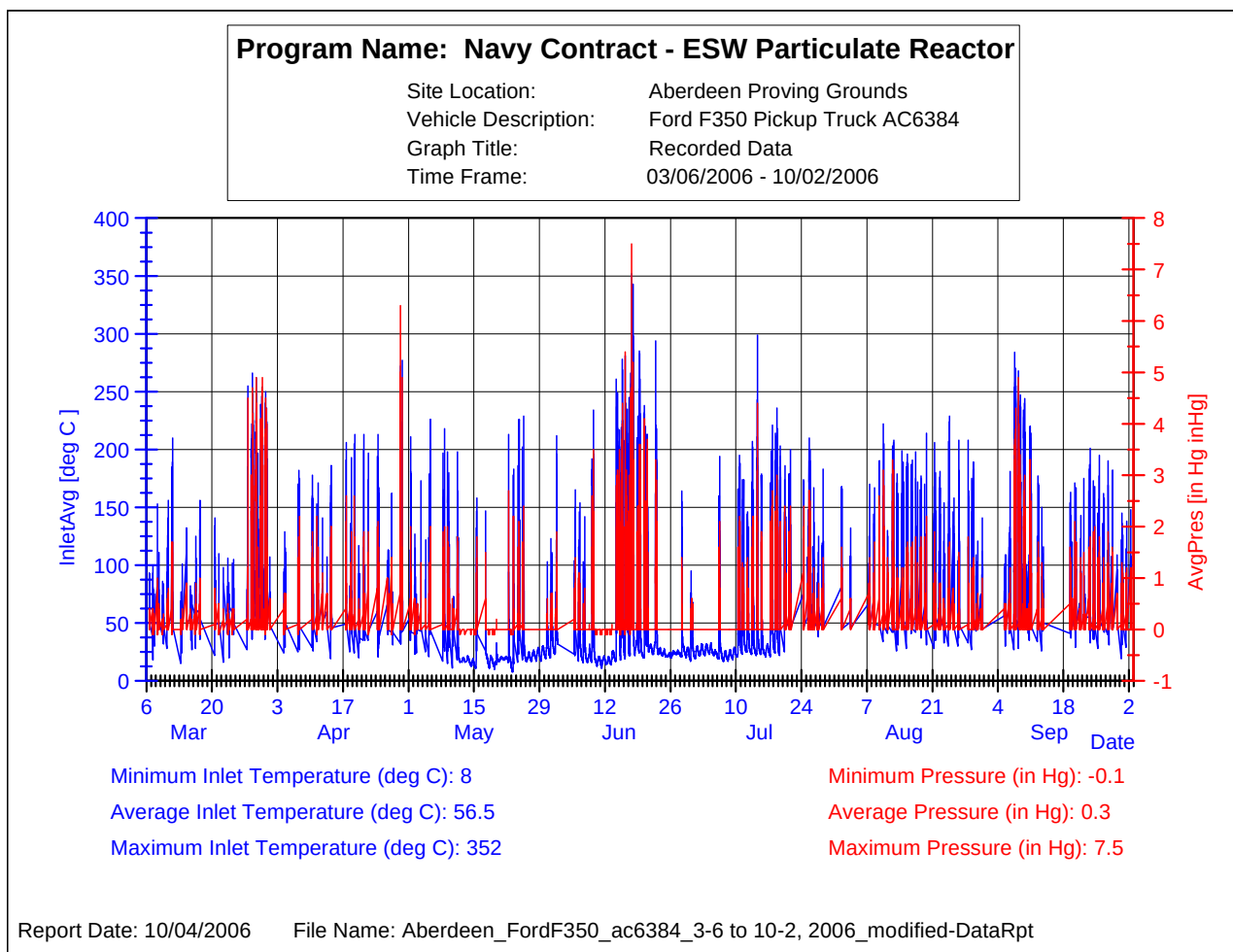


Figure 4.3
Inlet ESW Filter Average Temperatures and Pressures vs.
Time for Ford F350 Pickup Truck at ATC (3/6/05 to 9/21/06)

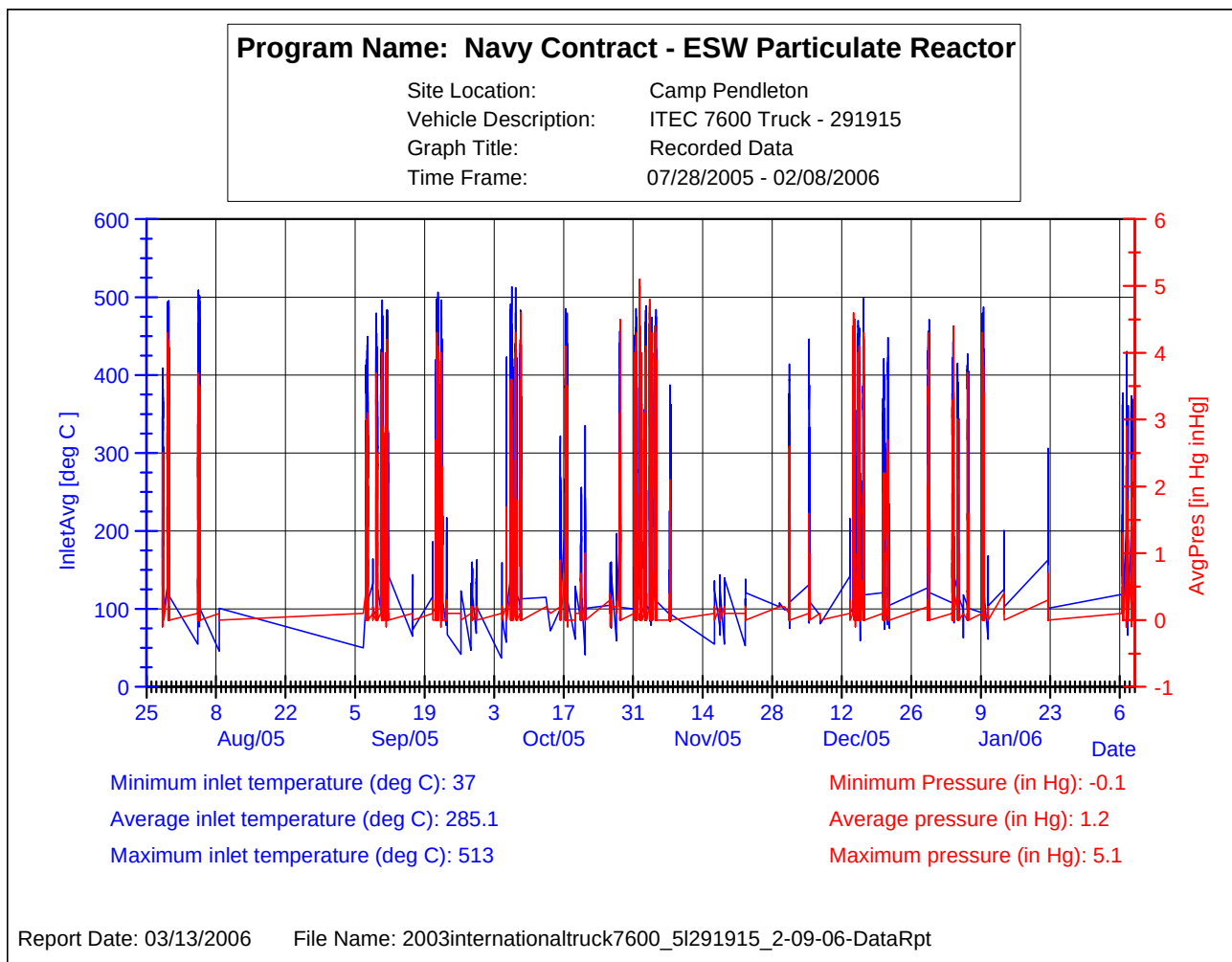


Figure 4.4
Inlet ESW Filter Average Temperatures and Pressures vs.
Time for ITEC 7600 Truck at Camp Pendleton (7/24/05 to 2/9//06)

Summary. The ITEC 7600 truck at Camp Pendleton ran with relatively high exhaust temperatures, as expected, while the two Thomas buses at Cheyenne Mountain Air Force Station and the Ford F350 pickup at ATC exhibited exhaust temperatures less than those indicated in Table 3.3. Even with the below specification temperatures, the ESW technology performed well under all conditions tested and demonstrated a wide tolerance for use with vehicles with low load factors (low exhaust temperatures). Maintenance required for them was at a minimum. There was one negative operator comment.

4.3.1.2 ESW Emissions Measurements

4.3.1.2.1 Regulated Emissions. Vehicle emissions measurements were made at the NREL laboratory on one of the two Cheyenne Mountain Air Force Station buses. Measurements were made employing the NREL chassis dynamometer both before and after the aftertreatment device was installed. Testing was performed by test teams from both NREL and UCR. The approach to the measurements included measuring the emissions from a driving cycle that was developed to closely match the actual cycle and using the standard CBD cycle. Emissions measurements were made with two fuels: a soy-based B20 biodiesel made with a California ULSD and a Fed EPA No. 2 low sulfur diesel fuel (i.e. conventional diesel fuel).

The Cheyenne Mountain and CBD driving cycles used for these tests are compared in Figure 4.5. The differences in the speed versus time of the two cycles are apparent. The CBD cycle has many more accelerations/decelerations per unit time than does the Cheyenne Mountain cycle that could lead to different experimental emission results. The CBD cycle is only 400 seconds in length compared to the 1,200 second round trip, but this in itself does not reflect a different engine duty.

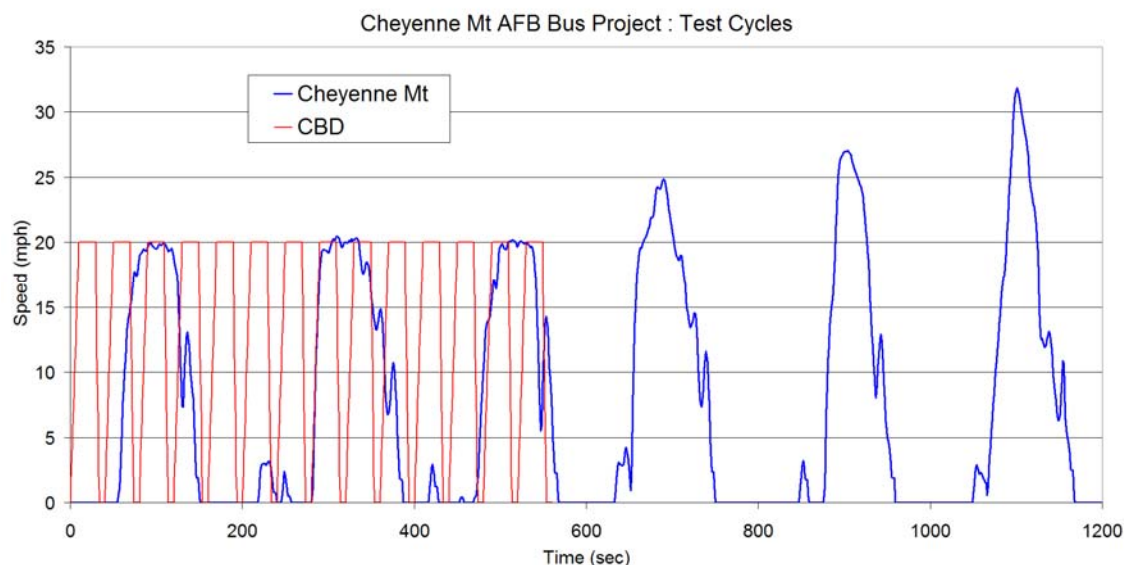


Figure 4.5
Plots of Cheyenne Mountain and CBD Test Cycles

A key purpose of the measurements were to verify the emissions reduction efficiencies of the ESW filter by measuring emissions from the bus both before and after the installation of the filter while it was being operated over the same driving cycles with the same fuels. Emissions were measured for the regulated pollutants NO_x, PM, CO, and THC. Fuel economy was also evaluated for both cycles and both laboratory groups. The results shown in Figures 4.6 through 4.9 are reported in grams per mile for criteria air pollutant emission factors and in gallons per mile for fuel economy. Multiple emissions measurements were performed at each test condition. Error bars on the figures reflect uncertainties in the measurements. The results in grams/mile were derived by dividing the species emissions for the cycle (grams) by the cycle distance. To incorporate data for different pollutants on the same plot, the results for NMHC, THC, and PM are plotted with a factor of 10 multiplier.

The results reported for PM reductions by the ESW filter are mixed. For the three results reported by NREL (see Figures 4.6 and 4.7 for Cheyenne Mountain cycle with both conventional diesel and B20 and the CBD cycle with B20) the reduction of PM emissions were 49.8 percent, 40.2 percent, and 55.0 percent respectively. Each reported result was the average of three experimental determinations. But there is considerable doubt regarding the 55.0 percent number, as one of the three experimental numbers (0.68, 0.51, and 0.53) is obviously incorrect. Eliminating that high number changes the 55.0 percent to 50.0 percent which still meets the PM reduction goal. The difference in the results for the B20 fuel (40.2 percent versus 55.0 percent) for the two cycles is interesting and seems to reflect the considerable differences in the two driving cycles. However, the low number for the Cheyenne Mountain cycle (40.2 percent) may not be important as a general result because the Cheyenne Mountain cycle is only locally accepted. For Fed EPA No. 2 low sulfur fuel, the PM emissions reduction (49.8 percent) was better than those for the B20 on the Cheyenne Mountain cycle.

The results reported by UCR were somewhat different (see Figures 4.8 and 4.9). These measurements indicated that PM reductions for conventional diesel fuel were > 50.0 percent for the Cheyenne Mountain cycle (Figure 4.8) but did not meet that standard for the B20 for either the Cheyenne Mountain cycle (Figure 4.8) or the CBD cycle (Figure 4.9).

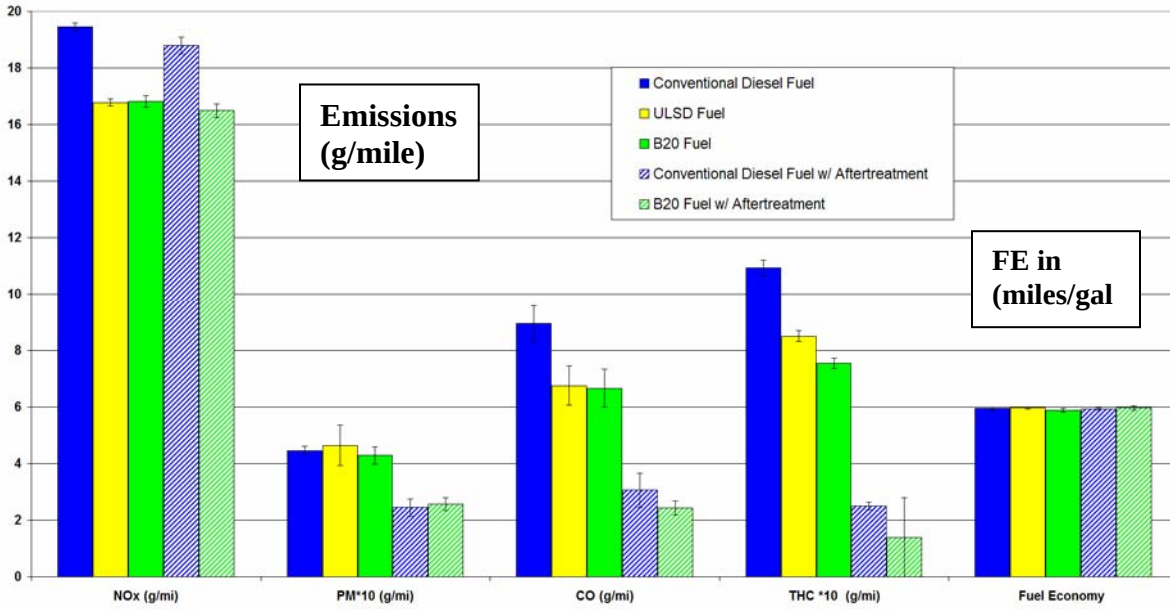


Figure 4.6
NREL's Emission Results for Cheyenne Mountain Test Cycle

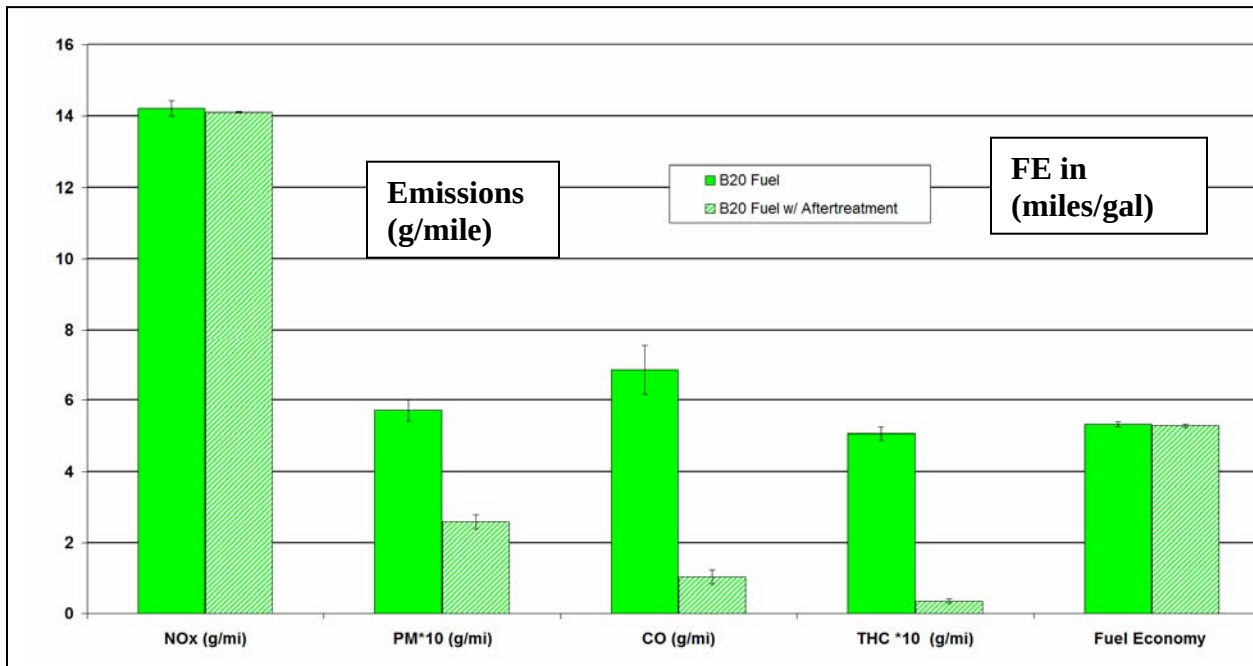


Figure 4.7
NREL's Emission Results for CBD Test Cycle

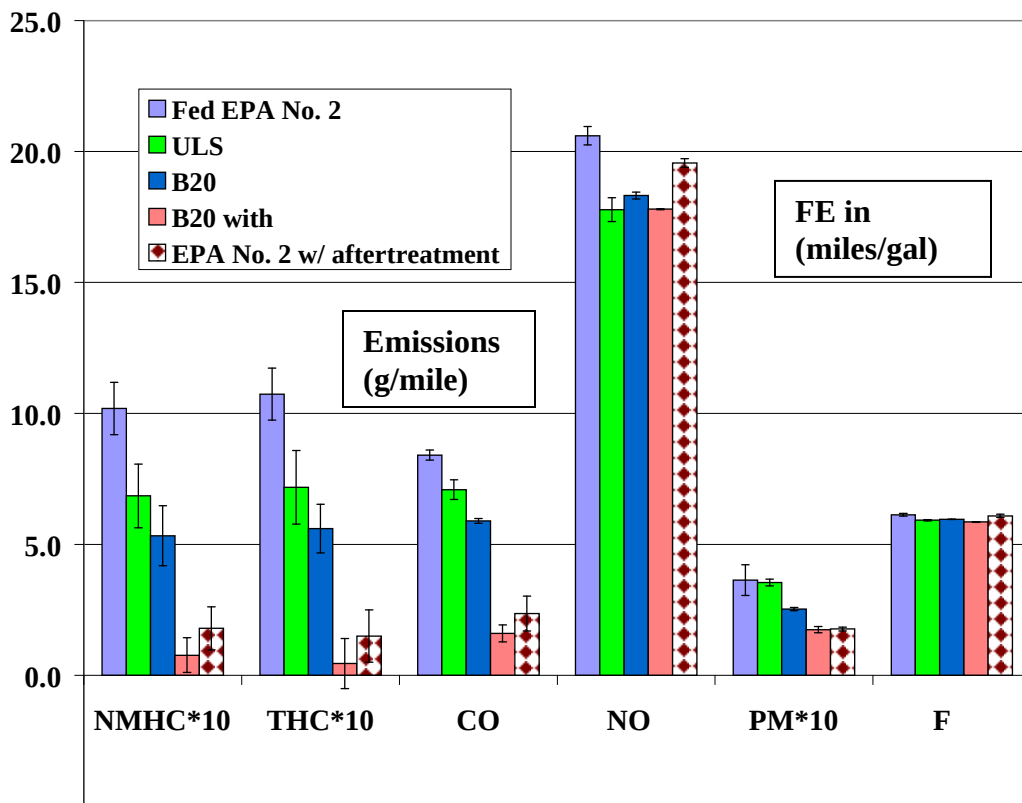


Figure 4.8
UCR Emission Results for Cheyenne Mountain Test Cycle

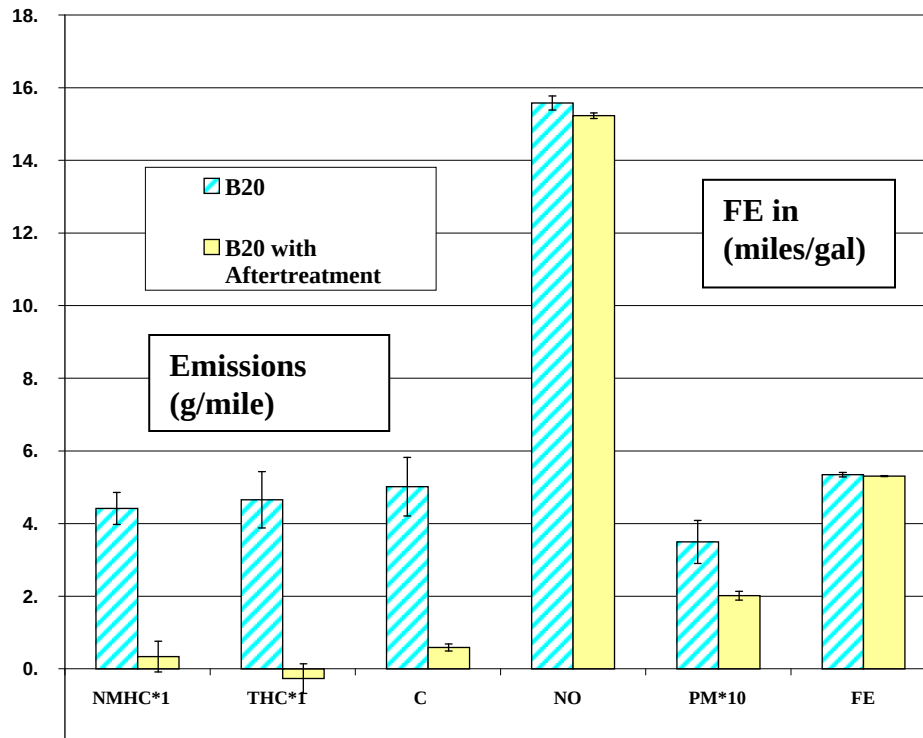


Figure 4.9
UCR Emission Results for CBD Test Cycle

The fact that the ESW filter was more effective in reducing PM emissions generated by Fed EPA No. 2 low sulfur fuel than for the B20 fuel may be explained (at least partially) by the organic/elemental carbon fractions of the PM particles from those fuels (see discussion in Section 4.3.1.2.2 and Figure 4.10). The carbon in PM from conventional diesel fuel contains almost 50 percent more organic material than it does for the B20 fuel. It is known that DOC filters are more effective in reducing the organic carbon fraction than the elemental carbon fraction. This result is supported by the data in Figure 4.10 where after passing through the ESW filter the organic carbon fraction of the PM (for the conventional fuel) is slightly less than the elemental carbon fraction (of the B20 fuel) although it started out at a level 50 percent greater.

The ESW filter has been verified by CARB as a Level II technology (50 percent reduction in PM) when used with EPA No. 2 diesel fuel on 1991 through 1993 model engines. The engine tested at Cheyenne Mountain was a 2002 model engine. Therefore these results seem to confirm the performance of the ESW filter for reduction of PM emissions by 50 percent for conventional diesel fuel (in this case for both the Cheyenne Mountain and CBD cycles) and leads to the expectation that the ESW filter would be a good candidate for verification by CARB as a Level II device for newer engines also.

In addition to its PM emissions reduction performance, the both NREL and UCR reported that the ESW filter also reduced hydrocarbon emissions by about 82 percent and CO emissions by about 68 percent while maintaining fuel economy essentially unchanged. Therefore, the

performance objectives for the reduction of all of these pollutants, as well as fuel economy, were met by the ESW filter (see Table 4.2A). NO_x emissions were also measured during these tests, but their reduction was not a goal of this demonstration. NO_x emissions were affected, mostly, by the composition of the base fuel and were about 15 percent lower for ULSD than for Fed EPA No. 2.

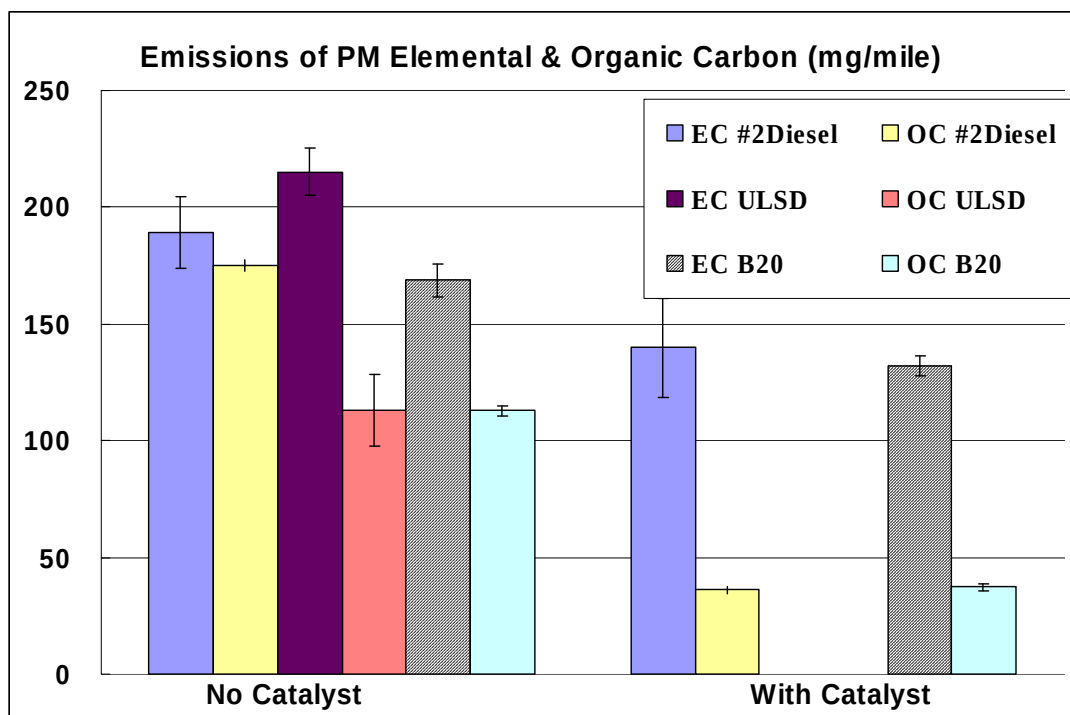


Figure 4.10
Emissions of Elemental and Organic Carbon for Cheyenne Mountain Cycle

4.3.1.2.2 Toxic and Speciated Emissions. In addition to the regulated emissions, UCR also determined the emissions of elemental and organic carbon and emissions for a number of toxic air contaminants. The results for elemental and organic emissions with/without the ESW (catalytic) filter as measured on the Cheyenne Mountain cycle are shown in Figure 4.10.

Here the elemental and organic carbon represented about equal fractions of the PM for the Fed EPA No. 2 diesel fuel (blue and yellow) without the filter installed, whereas for the B20 fuel, the organic carbon was considerably less than for the elemental carbon. It is also apparent that the emissions reduction with the catalyst is far greater for the organic carbon fraction than for the elemental carbon for both fuels. The data shows that the ESW filter removes about 75 percent of the organic fraction compared to about 25 percent of the elemental carbon for both fuels.

Another phase of the emissions measurements involved characterization of the emissions of non-regulated, toxic air contaminants including aromatic compounds (e.g., benzene) and carbonyls (e.g., formaldehyde) both before and after the catalyst was installed. These species are generally of very low concentration and are not currently regulated, but are of great interest because of their known carcinogenic effects on human health. Test results for the measurements on benzene

are shown on Figure 4.11 and show that benzene emissions were reduced by similar amounts (about 75 percent) for both fuels when the bus was operated on the Cheyenne Mountain cycle. As benzene is an organic species, this should not be surprising. Similarly, for total carbonyl and formaldehyde emissions (again, both are organic species), the reductions of both (shown in Figure 4.12) are about 75 percent.

4.3.1.3 ESW Filter Test Summary

The ESW particulate reactor, verified by CARB as a passive Level II PM Reduction device on older engines, performed very well during this demonstration test. Inclusion of the filter supplier on the project team was helpful in making certain that the warranty for the bus engines remained in force after installation of the exhaust treatment system. The device was easy to install and easy to maintain over the year that the device was operated. It provided the required results of reducing diesel engine PM emissions by 50 percent and proved itself sufficiently robust for long-term, trouble-free use.

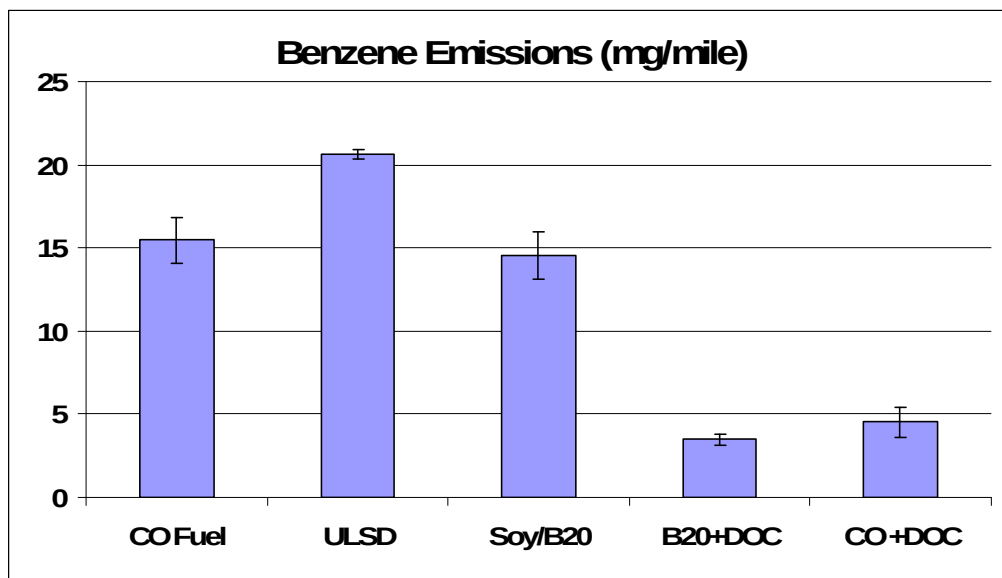


Figure 4.11
Benzene Emissions in mg/mile for Buses Operated on the Cheyenne Mountain Cycle using Fed EPA No.2 Fuel, ULSD, and B20

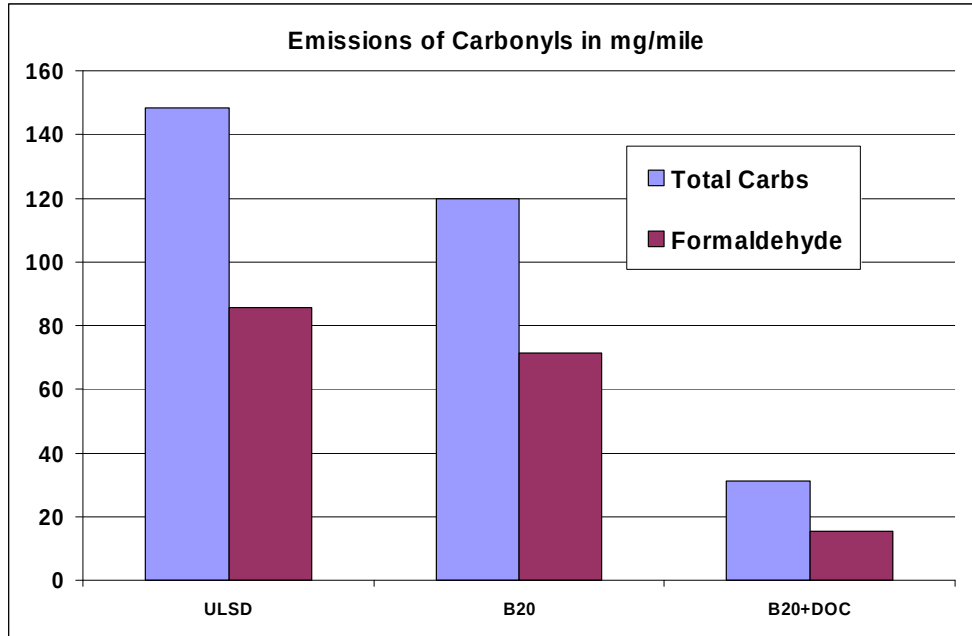


Figure 4.12
Emissions of Formaldehyde and Total Carbonyls in mg/mile for ULSD and B20

4.3.2 RPF Devices

4.3.2.1 Operational Data

Navistar 4700 Panel Truck. Operational and reduced data recorded for the RPF during field testing are shown on Figures 4.13 through 4.17. The data are shown for a time scale of 50,000 seconds (about 14 hours) of operation. These data are taken from that collected during operation of the Navistar 400 Panel Truck at the ATC.

Exhaust gas temperatures and the target programmed regeneration temperature of the RPF are shown as a function of time on the upper plot of Figure 4.13 (refer to Figure 2.2 for the physical location of the measurement points). The calculated soot load of the filter (grams) and the actual fuel dosing rate during that period are shown on the middle plot, and the engine intake manifold pressure and the exhaust throttle positions are indicated on the third plot. In the lower left-hand corner of the figure are shown (a) the number of DOC outlet temperature data points (purple line) recorded as a function of temperature, and (b) the percentage of time that that temperature exceeded a given temperature indicated by the abscissa (blue line). For example, the blue line shows that the DOC outlet gas temperature is below 300°C about 90% of the time. That temperature is indicated by the green trace of the top plot in the figure.

The soot loading of the filter decreases with time, indicating some regeneration of the filter was taking place (Note: as no fuel was being injected during this time, the conclusion must be that the regeneration was taking place by “passive” regeneration.). Although decreasing, the calculated soot loading remained at near 100 grams throughout the test period. However, as the soot load is a value calculated based upon measured exhaust gas flow rate and pressure drop across the filter, it is difficult to know with certainty the accuracy of the calculation.

Active filter regeneration (by fuel injection) was manually set to occur approximately every two hours for this vehicle. These regeneration intervals are indicated by the step-change signals (purple line in upper plot) showing that the system attempted six active regenerations during the approximately 14-hour time period. However, according to the plot, we also see that no fuel was injected at any time during this time period (i.e., the dosing rate was zero). The explanation for this is that the filter inlet temperature (green line) was not recognized to meet the 280°C exhaust temperature threshold needed for proper ignition and combustion of any fuel injected (see Figure 4.14 for an expanded view of these temperatures). That is, even if dosing were called for, if this threshold temperature were not met the inlet fuel control valve for dosing would not open. This, of course, is a required safety feature to prevent the accumulation of unburned fuel inside the filter which could combust at a rapid rate, overheating and probably damaging the filter.

That fuel was not injected is shown in better detail on Figure 4.15 which also shows an expanded view of six electronic signals being given to the fuel pump and the soot loading in better detail. Figure 4.16 shows the fuel pump actuating (black vertical lines) and adequate injection pressures being developed, but even so, a zero fuel dosing rate.

The times and quantity of fuel injected would normally be determined from calculations performed by the filter ECM based upon the filter target regeneration temperature, measured delta pressure across the filter, measured volumetric flow rate of gas through the exhaust system, and calculated soot loading of the filter. However, because the ECM for the RPF tested with these vehicles was not fully developed and qualified for application as a retrofit device (see Note in Section 3.6.1), it was not possible to operate them in an automatic mode for these tests. Therefore the needed calculations to determine when/if/how much regeneration and fuel injection was needed could not be performed on-line. Rather, for the modified versions of the RPFs used for this retrofit demonstration, the timing and quantity of the fuel to be injected for regeneration needed to be set manually ahead of time (and later manually adjusted, if necessary) according to the expected duty of each vehicle. For this particular vehicle that regeneration period was set for 2 hours.

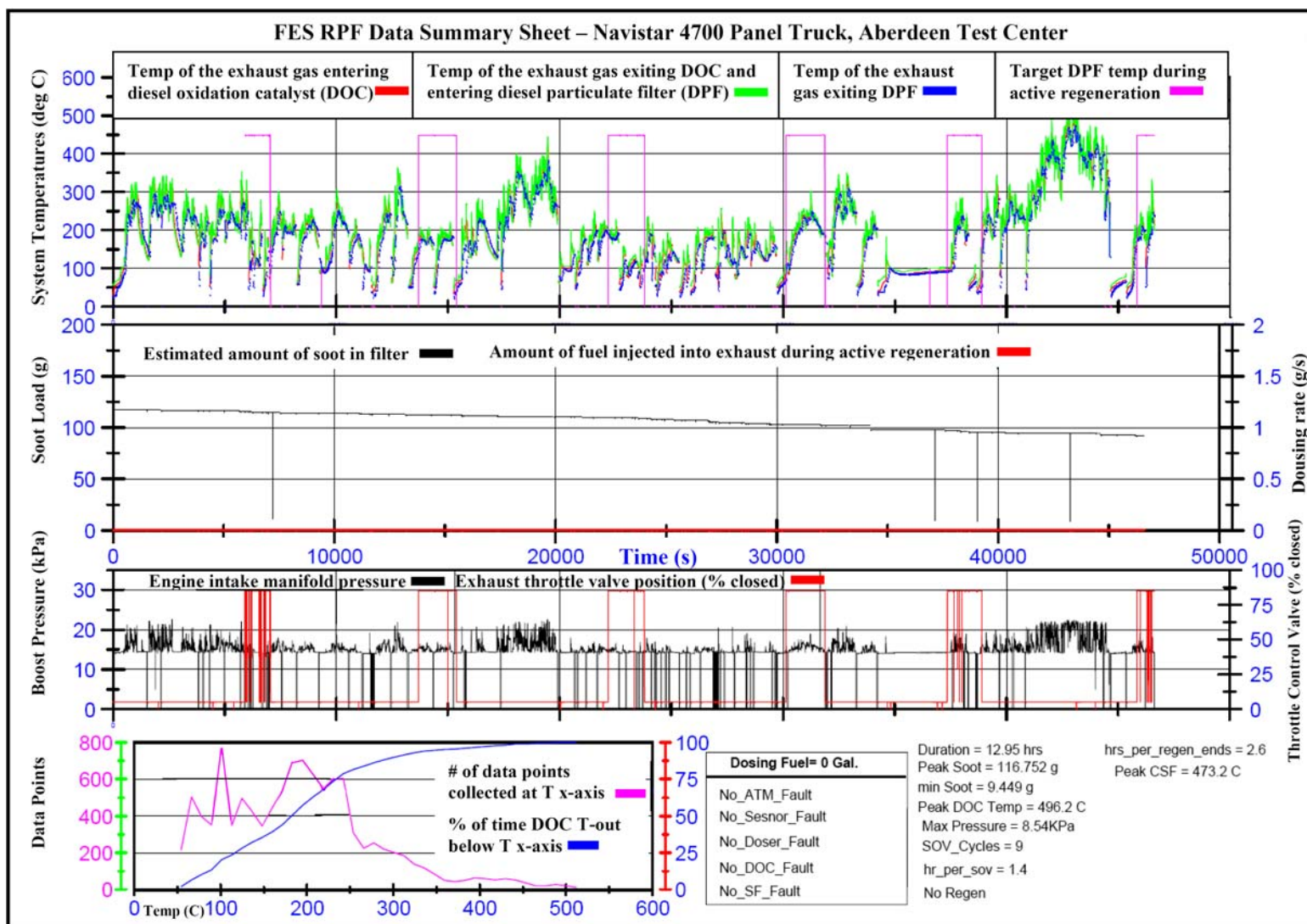


Figure 4.13
Instrumentation Results from Navistar 4700 Panel Truck at Aberdeen Test Center

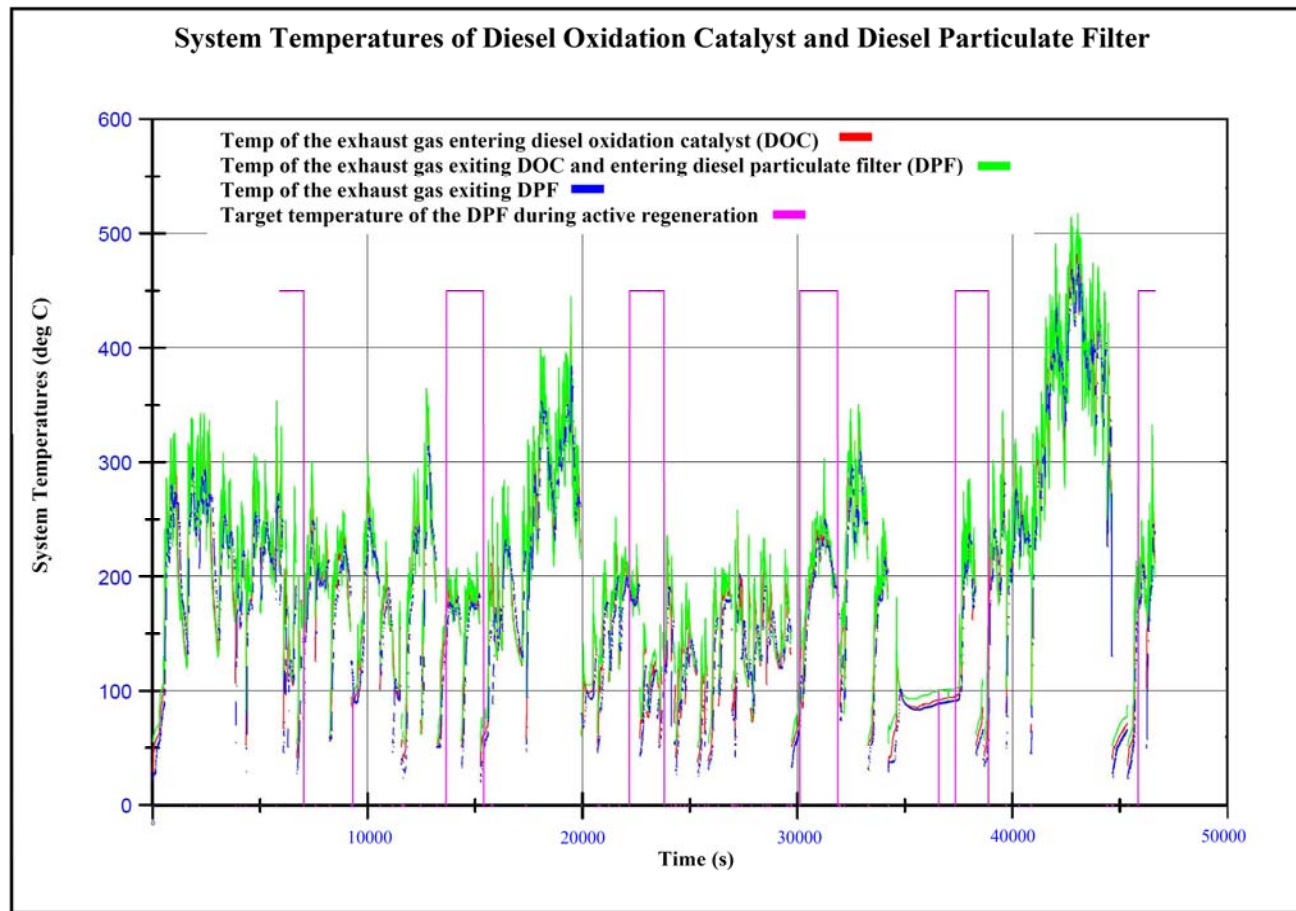


Figure 4.14
System Temperatures in Celsius vs. Time for Navistar 4700 Truck

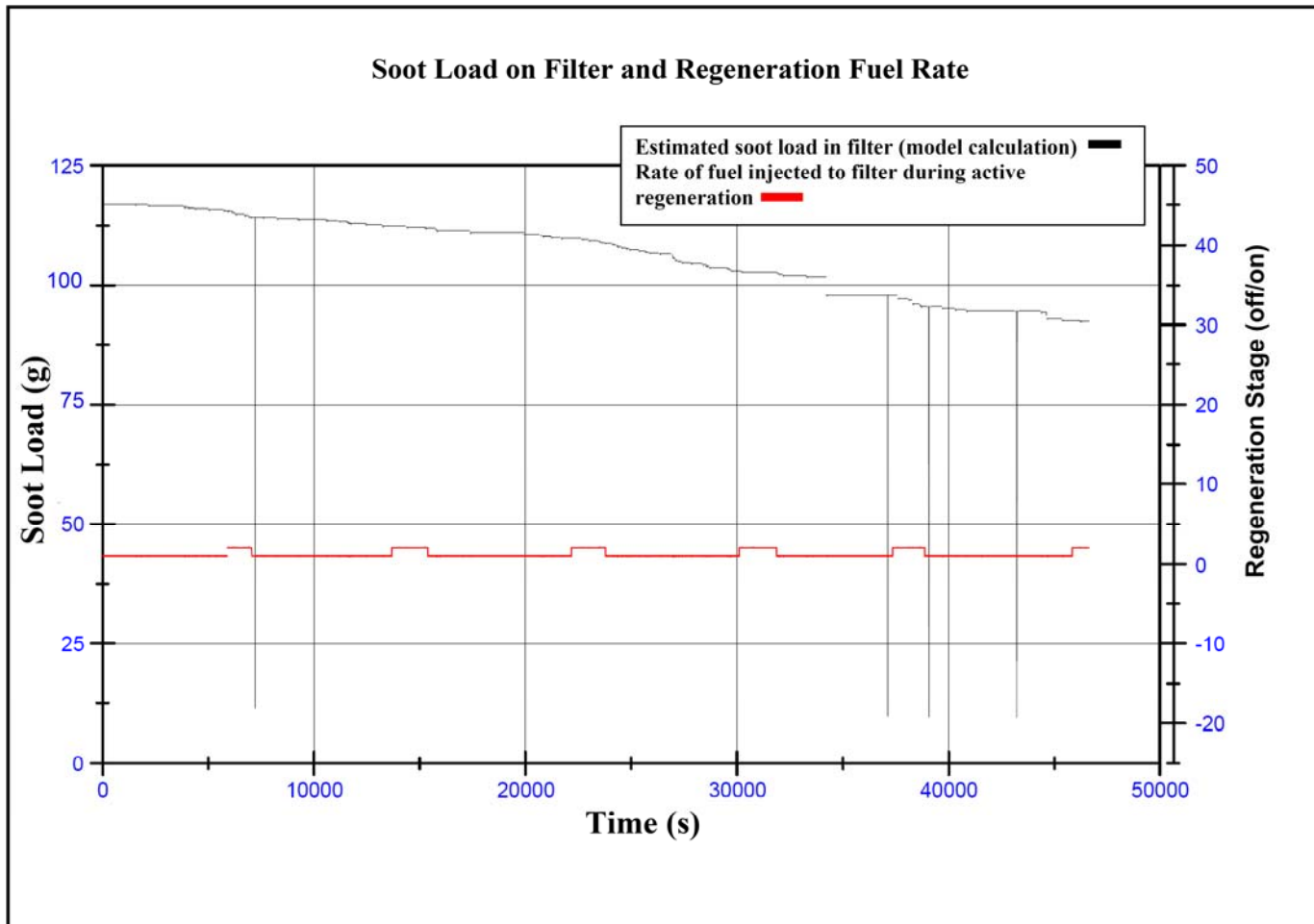


Figure 4.15
Calculated Soot Load and Fuel Dosing Stage (Signal) vs. Time for Navistar 4700

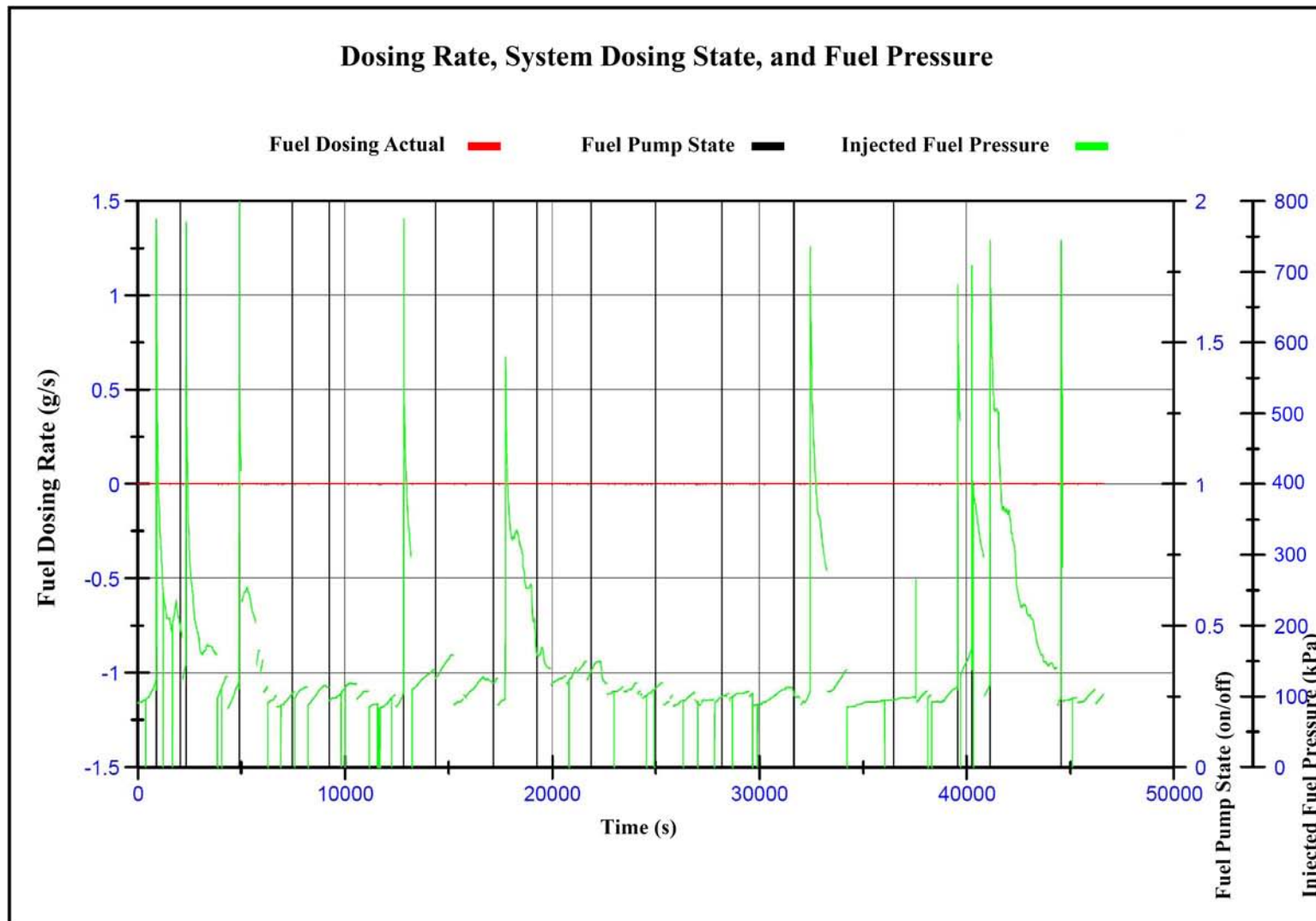


Figure 4.16
Fuel Dosing Rate, Fuel Pump State, and Injected Fuel Pressure vs. Time for Navistar 4700 Truck

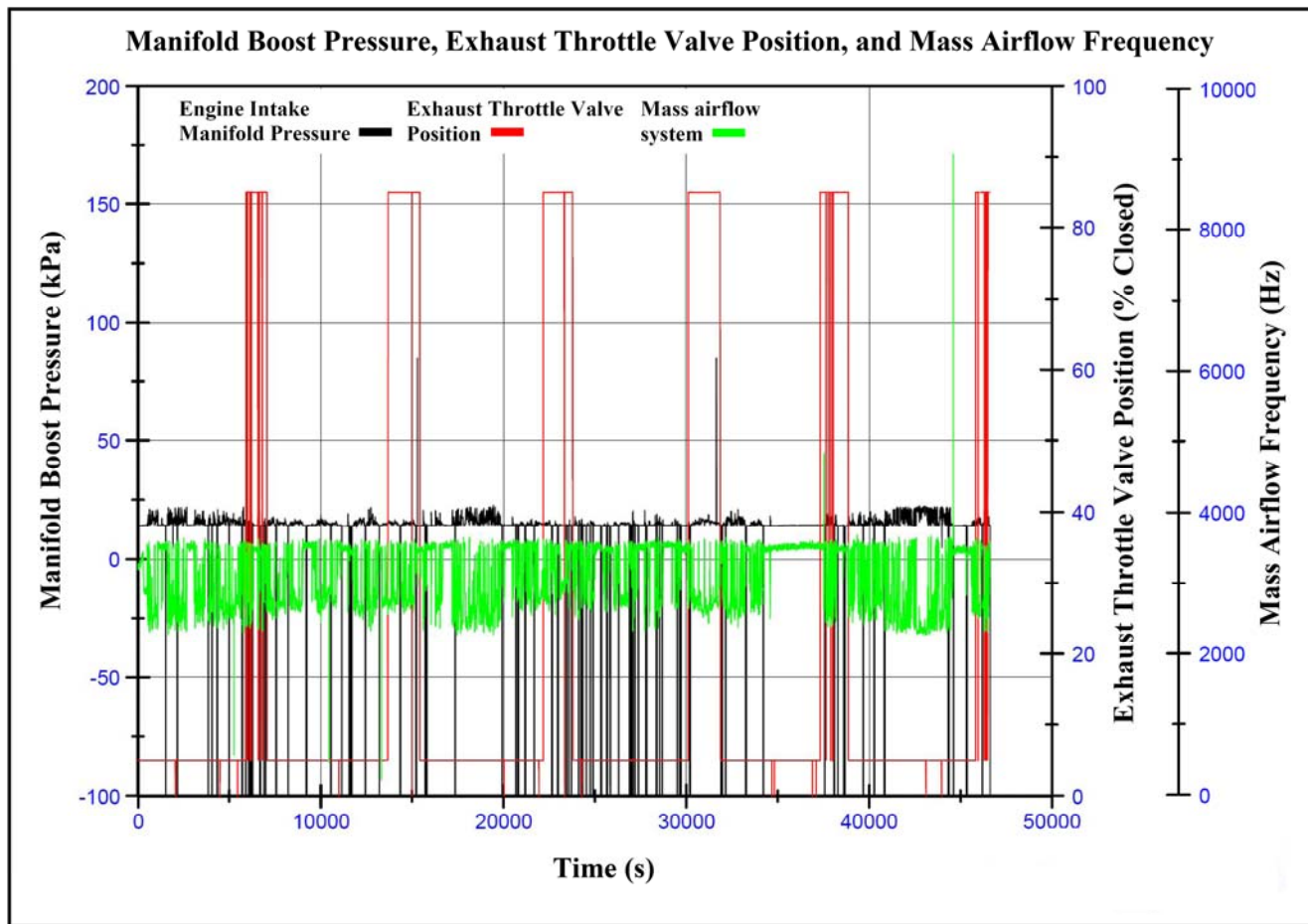


Figure 4.17
Manifold Boost Pressure, Exhaust Throttle Valve Position,
and Mass Airflow Frequency vs. Time for Navistar 4700 Truck

The temperature requirement for the RPF (see Table 3.3) is that the EGT be above 250°C 7 percent of the time. The pre-test estimate of the EGT for this vehicle was estimated to be greater than 250°C for 22 percent of the time, and the field-measured EGT, according to Figure 4.14, was above 250°C for 15 percent of the time. Therefore the measured temperatures appeared to meet the threshold of 250°C for the percent of the time called for in Table 3.3. However, it was the belief of the RPFs installation personnel that this temperature did not meet the second minimum ignition threshold of 280°C required at the time of fuel injection, when ordered by the ECM at the manually set 2-hour intervals. Although the temperature profile shows that 280°C was met at different times during the cycle, it apparently was not met during those specific periods when regeneration was being ordered by the ECM. This brings into better focus the question as to whether it was advisable to try and operate the RPF's in the manual mode attempted on this retrofit project. Manually setting the times for regeneration, satisfying the one (or two) fuel injection temperature criteria simultaneously with the pre-set manual order to regenerate may have been too difficult to achieve – i.e., individually the criteria may have been met, but to meet them simultaneously while in a manual mode control would be statistically much more difficult. In this example, on-line “active” regeneration of the filter did not occur. The conclusion seems to be that for effective control of “active” regeneration of the RPF device a fully operable filter (filter ECM operating on-line in automatic mode) is necessary. This would be particularly true for vehicles with low or borderline filter EGTs. The latter, of course, are the very vehicles for which “active” filter regeneration would be the most important.

When the ECM detects conditions verifying that criteria have been met, that active regeneration is needed, and that the temperature is too low, the filter ECM can try to correct that condition by closing the exhaust throttle valve. This is a valve in the exhaust line that can be partially closed by the filter ECM to increase back-pressure on the engine and increase exhaust temperatures. Figure 4.13 (and 4.17) show this exhaust valve opening and closing in concert with the signals for dosing (red lines), but it is difficult to confirm whether the closing of the exhaust throttle valve had any effect on the EGT. However, the load factor for this particular vehicle may have been so low that even closing the exhaust throttle valve was not helpful in bringing the exhaust temperatures up to the threshold temperatures so that dosing could begin.

Data and analysis plots as shown above were completed for data logged on all of the vehicles on which the RPF device was installed (Navistar 4700, Ford FT900, Ford L9000 and Thomas bus). These along with the raw data are stored on CDs. Additional notes are provided below on the results of testing the other vehicles on which the RPF were installed.

Ford L9000 Truck. The Ford L9000 truck logged a total of 555 hours of operation during the time the RPF system was installed on the vehicle. During this time the estimated soot load of the filter averaged about 40 grams, and the exhaust temperatures at the inlet of the catalyst were above 250°C 40 percent of the time. With this higher exhaust temperature, the regeneration time interval for this vehicle was manually set to 8 hours. Dosing did occur on this vehicle (the temperature dosing criteria were met) and a total of five gallons of fuel were dosed during the test period. During the latter part of the test period, the vehicle load factor was high enough so that regeneration of the RPF occurred “passively” (without fuel dosing) a high percentage of the time. There were no driver complaints when the exhaust throttle valve closed during

regeneration events. These results appear to confirm that the “active” regeneration of the RPF did occur when called upon in the “manual” mode of control, but at the same time confirm that in “manual” mode operation it works best for those conditions where “active” regeneration is least needed – at higher EGTs.

Thomas Bus. The Thomas bus logged 727 hours of operation during the demonstration period. Over the one-year test period the exhaust temperatures at the inlet of the DOC were high (above 250°C about 55 percent of the time) and the soot load estimated for the filter averaged about 25 grams. This is a significantly lower calculated soot loading than for the above two vehicles, and is attributed to the higher EGTs for this bus. Of course, this is what was expected, and serves to confirm that the ECM is performing the soot loading calculation properly. For this vehicle, the regeneration time was set for 40 hours. Fuel injection was dosed when needed, but the EGTs were so high that a total of only 1.17 gallons of fuel were dosed over the entire test period. This again showed that regeneration occurred almost totally “passively” so that an “active” filter, such as the RPF, would not be required for trouble-free operation of this vehicle. Because high EGTs were anticipated, an exhaust throttle valve was not installed.

Ford FT900 Truck. The Ford FT900 truck logged only 107.3 hours of operation during the time the RPF system was installed on the vehicle, largely because it was difficult to keep the vehicle running. The estimated soot load in the filter averaged a high 120 grams and the exhaust temperature at the inlet of the DOC was above 250°C less than 10 percent of the time, but still meeting the manufacturer’s criteria for minimum EGT (Table 3.3). Because of the expected low exhaust gas temperatures, the regeneration time on this vehicle was set for two hours, but only 0.21 gallons of fuel were dosed during the test period. This again is attributed to the fact that although the load factor on the engine met the manufacturer’s requirements and the exhaust-throttle-valve was set to 85 percent closed to attempt to obtain EGTs above the 280°C dosing threshold, the times that the dosing threshold could actually be met during vehicle operation were negligible. As a result, this vehicle was continually troubled with the accumulation of high levels of soot and soot level faults causing the engine to shut-down during the demonstration period. These shut-downs required the truck to be returned to the equipment yard numerous times during road operation. Because of the difficulties in keeping this vehicle operational and complaints from operators and maintenance personnel, it was decided to remove this RPF before the end of the demonstration period.

4.3.2.2 RPF Emissions Measurements

Plans were made for measuring the emissions reduction of an installed RPF device on the Camp Pendleton Thomas bus. Emissions measurements had been previously made on the bus prior to installation of the RPF device. But before emissions tests could be completed with the filter installed, difficulties were encountered in maintaining the RPF operational in the field. This led to a preliminary determination that the RPF devices were not ready for implementation within DoD vehicle fleets and the decision was made, in conjunction with the ESTCP program office, to discontinue this emission testing effort.

4.3.2.3 Summary of RPF Measurements

The RPF experienced problems and did not perform up to expectations during the demonstrations. While the duty cycles of the vehicles on which the RPF were tested appeared to produce EGTs sufficient to initiate “active” filter regeneration, “active” regeneration often did not occur when needed. Despite the various controls accompanying this technology (i.e., fuel dosing, exhaust throttle valve, and pressure measurement/control), the filter ECM in “manual” mode was not able to coordinate the required dosing criteria to initiate fuel dosing when “active” regeneration was needed. While there was evidence of filter regeneration during high duty cycles (through “passive” regeneration along with some fuel dosing), there were also recurring high soot errors on other vehicles (i.e., on those vehicles with lower duty cycles where “active” regeneration was needed but did not occur) requiring them to be returned to the shop on numerous occasions.

The RPF device seemed to meet the demonstration requirements on two of the vehicles, but these were vehicles with sufficiently high duty cycles where “passive” regeneration was effective. The inability of the RPF to meet the regeneration requirements for the other two installations (despite many extended efforts in the field to overcome these operational difficulties) made it impossible for the NAVFAC ESC to recommend this technology for DoD applications. Following completion of this testing, Cummins, Inc. also decided not to market the RPF as a retrofit device pending further development of it for that application.

5.0 COST ASSESSMENT

5.1 Cost Reporting

In this section only the costs associated with the ESW technology will be discussed since the Cummins RPF technology is not recommended for implementation within DoD. It is expected that the ESW technology demonstrated during this project will be suitable for a number of types and sizes of DoD diesel engines and that costs for its implementation will vary with the size of the engine, expected engine duty cycle, difficulty of hardware installation, and the number of similar units installed. Assessment and analysis of costs associated with implementation of the ESW filter are given in Table 5.1. These costs were developed assuming an on-road diesel powered heavy-duty vehicle such as a truck driven 16,000 miles annually with an engine size of 6 to 7 liters displacement.

The capital costs for the ESW filter are dependent on the size and use of the engine. If a number of similar units are installed/ordered simultaneously, a reduced unit cost can usually be negotiated. The needed physical size and exhaust handling capacity of the filter increases with the size and loading of the engine. Larger filter units are more costly, and a system must often be custom-designed and manufactured for an application for the filter to both fit into the available installation space on the vehicle as well as satisfactorily handle the exhaust gas flows.

The uniqueness of a design can affect the cost of a unit significantly, leading to cost discounts when several filters of a type are purchased. Pricing for the filters themselves and installation costs were provided by International Truck and Engine Corporation, the current distributor for the ESW filter. It is expected that filters will be installed by the distributor's mechanics.

Table 5.1
Types of Costs by Category for ESW Filter

Direct Environmental Activity Process Costs				Indirect Environmental Activity Costs		Other Costs	
Start-Up		Operation & Maintenance					
Activity	\$	Activity	\$	Activity	\$	Activity	\$
ESW Particulate Filter							
Equipment Purchase	4,200 – 5,400	Annual cleaning	None	Fuel Mileage Penalty	0	None	
Installation	400-600						

In general, the service life of exhaust gas filter technologies is only marginally dependent on vehicle age. Of greater importance is the vehicle mileage/engine operating hours. From preliminary research, Cummins, Inc. estimated that the service life of the ESW filter will be equal to or greater than the diesel engine service life for most DoD applications.

While annual filter cleaning is not normally required, ESW recommends that the filter should be periodically visually inspected. During engine operation, the only action required of an operator is to periodically monitor an indicator light on the vehicle control panel that warns of excessive filter back-pressures. In the event that this light becomes lit, the operator should report this to the maintenance department so that the filter could be cleaned.

5.2 Cost Analysis

Since the purpose of this ESTCP compliance project is to meet proposed future diesel engine PM emissions reduction retro-fit requirements, all costs associated with the development and implementation of the demonstrated technologies represents new costs. Only in the past year has EPA regulations begun to require the use of exhaust after-treatment technology for new vehicles. The required retrofit of existing engines with exhaust filters is now just starting in California.

Other than the ESW technology demonstrated in this project, other technologies have also been approved by CARB and EPA to reduce diesel engine PM emissions. However, all of these technologies are relatively new and cost and performance information for them is limited. An additional consideration is that most of these technologies require the use of ULSD fuel (<15 ppm).

The ESW technology has no expected operational or maintenance costs. For most potential DoD applications, the hardware is expected to last the life of the diesel engine. The total implementation costs will therefore include only the hardware purchase and installation. The purchase cost depends on the engine size, engine duty, and the number of equivalent systems to be manufactured. The installation costs will vary depending on the difficulty of the installation.

Based on the above, the life-cycle cost for implementing the ESW technology is expected to be \$4,200 to \$5,200 for the equipment plus \$400 to \$600 for installation, resulting in a total cost of \$4,600 to \$5,800 for a typical installation. This cost may increase/decrease based upon the size and use of a particular application and the number of similar units purchased.

To compare the ESW unit to competing technologies, data on all diesel aftertreatment CARB Level II certified particulate filters applicable to on or off-road diesel engines is shown in Table 5.2. The data compares unit cost, installation cost, fuel requirements, and percent PM emissions reduction.

Table 5.2 Comparison of ESW Filter with Other Technologies

Technology	Unit Cost	Installation	Fuel requirement	Emissions reduction
ESW Particulate Reactor	\$4,200-\$5,400	\$400-\$600, 8 hrs	Low Sulfur Diesel (<500 ppm)	~50%
Engine Control Systems AZ Purimuffler/Purifier	~\$1,000	Unknown	PuriNOx	~40%
Donaldson DMF Muffler	\$6,000 - \$8,000	Included, 1-3 hrs	Ultra Low Sulfur Diesel (<15 ppm)	71-75%

The cost of the ESW filter is somewhat less than that of the Donaldson filter; however, the ESW device can be used with fuel sulfur levels as high as 500 ppm (low-sulfur fuel). This can be an important advantage for some off-road applications where ULSD fuel is not required. The Donaldson Muffler is, however, reported to reduce the PM emissions by 70 percent compared to 50 percent for the ESW product. The Engine Control Systems filter is considerably less expensive; however, it only reduces PM emissions by only 40 percent unless the proprietary PuriNOx fuel is also used.

6.0 IMPLEMENTATION ISSUES

6.1 Environmental Permits

No environmental permits were required for this project since no existing air pollution control equipment was removed from the test vehicles. Neither is it anticipated that any permits will be required for implementation of the ESW filter technology on existing DoD vehicles where the implementation is voluntary. However, where implementation occurs in response to air pollution regulations, approval and/or a permit from the local air pollution control authority may be required.

6.2 Other Regulatory Issues

A current regulation that applies to full-scale technology implementation is the CARB In-Use Heavy-Duty Diesel Vehicle Regulation. While tactical military vehicles and equipment are exempt, non-tactical vehicles and a wide variety of DoD equipment (e.g., aircraft support equipment) will require the retro-fit of exhaust gas treatment devices or the replacement of the vehicle/equipment. Current CARB regulations will require the retrofit of the DoD off-road equipment prior to the on-road vehicles. Retrofit of all of these on- and off-road engines may pose practical problems not yet fully resolved, and the performance of the ESW filter on this project has shown the kind of behavior that could be valuable for these purposes: it provides PM reductions of 50 percent and has demonstrated itself useable for different engines over a wide range of operating conditions.

6.3 End-User Issues

The end-users of the results of this project will be DoD diesel-powered fleet and equipment operators. The primary concerns of these end-users will be obtaining and operating exhaust gas treatment technologies approved by environmental regulators to meet current and newly enacted air pollution compliance requirements for the lowest life-cycle costs. To ensure that the ESW filter technology demonstrated by this project is approved for use by potential DoD customers, it will need to be EPA or CARB certified. Currently, the ESW filter has been CARB qualified as a Level II (PM reductions of 50 percent) exhaust gas treatment device for older (1991 to 1997) engines, and CARB considers it to be the “Best Available Control Technology” for them. To be certified as a Level II device for newer engines it will need further qualification testing.

To ensure that project results are quickly transitioned to potential DoD customers, the transition plan for this project will focus on directly assisting the DoD fleet managers within California in complying with the recently approved CARB regulation to retrofit off-road diesel vehicles. This regulation requires that by the end of the year 2010, all DoD diesel off-road vehicles be retrofitted with the “Best Available Technology” (BAT). In many of these DoD applications, the ESW technology will be the BAT. The NAVFAC Engineering Service Center has been working

with the California DoD Air Team to ensure that a consistent implementation strategy is followed.

To further publicize the test results in various forms readily available to DoD, the NAVFAC Engineering Service Center will ensure that project results are published in a NAVFAC Fact Sheets and a technical report as well as a *Currents* Magazine article. Project results will also be posted on the DENIX WEB site.

In addition to the potential need in support of environmental compliance, the NAVFAC Engineering Service Center will also work with ESW to promote the use of its technology for tactical application where high sulfur fuel is used. Although tactical vehicles are not required to meet air pollution control standards, there is a significant tactical advantage of reducing black exhaust smoke. So far, the technology has already been implemented on a new Marine Corps Light Armored Vehicle Program. In addition, information on the ESW technology has been passed on to other tactical vehicle program offices.

7.0 REFERENCES

1. Naval Facilities Engineering Service Center Technical Report TR-2223-ENV, *Reduction of Diesel Engine Particulate Emissions Using A Self-Regenerating Soot Filter*, June 2003.
2. Siegl, W.O.; Richert, J.F.O.; Jensen, T.E.; Schuetzle, D.; Swarin, S.J.; Loo, J.F.; Probst, A.; Nagy, D.; and Schlenker, A.M. (1993) Improved Emissions Speciation Methodology for Phase II of the Auto/Oil Air Quality Improvement Research Program – Hydrocarbons and Oxygenates. SAE Technical Paper 930142. Society of Automotive Engineers, Warrendale, PA

8.0 POINTS OF CONTACT

Table 8.1
Points of Contact

POINT OF CONTACT Name	ORGANIZATION Name Address	Phone/Fax/Email	Role in Project
Dr. Norman Helgeson	NAVFAC ESC 1100 23 RD Avenue Port Hueneme, CA 93043	(805) 982-1335 (voice) (805) 982-4832 (fax) norman.helgeson@navy.mil	Principal Investigator
Bruce Holden	NAVFAC ESC 1100 23 RD Avenue Port Hueneme, CA 93043	(805) 982-6050 (voice) (805) 982-4832 (fax) bruce.holden@navy.mil	Initiating Principal Investigator
Patrick Pierz	Cummins Inc., Fleetguard Emission Solutions Business 1900 McKinley Ave. MC: 50183 Columbus, IN 47201	(812) 377-7217 (voice) patrick.m.pierz@fleetguard.com	Project Manager for Cummins, Inc.
David Trueblood	Cole Technologies 3360 Commerce Dr. Columbus, IN 47201	(812)-378-0678 (voice) (812)-377-8214 (fax) dave.trueblood@Fleetguard.com	Consultant for Cummins, Inc., Fleetguard Emission Solutions Business
Dr. Wayne Miller	University of California, Riverside CE-CERT 1084 Columbia Ave. Riverside, CA 92507	(909) 781-5579 (voice) (909) 781-5590 (fax) wayne@cert.ucr.edu	Supervisor, Emissions Testing for UCR
Dr. Christopher Tennant	ReFUEL Lab - National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	(303) 275-3140 (voice) (303) 275-3147 (fax) chris_tenant@nrel.gov	Supervisor, Emissions Testing for NREL

Appendix A: Pictures of Demonstration Vehicles
Ford F350 Pickup at ATC for ESW filter Installation



Ford F350 at ATC



Original Exhaust System

Thomas Buses at Cheyenne Mountain for Installation of ESW



Thomas Bus



Original Exhaust

Thomas Buses at Cheyenne Mountain for Installation of ESW (Cont.)

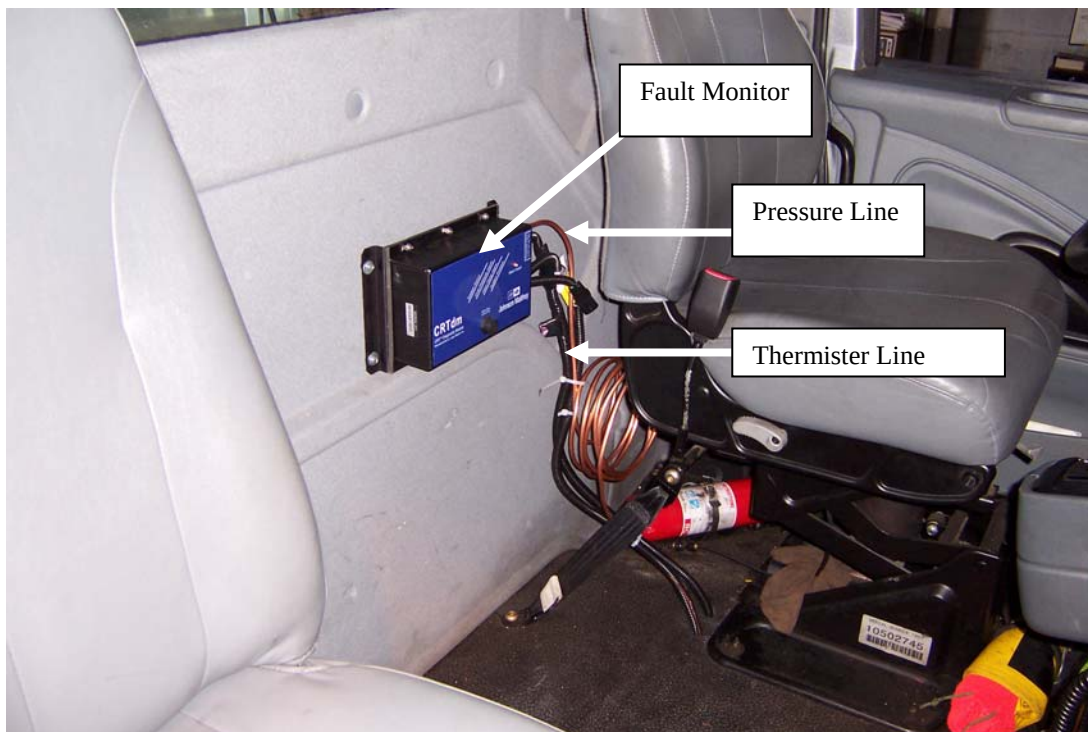


ESW Particulate Reactor Installed

ITEC 7600 Truck at Camp Pendleton for Installation of ESW



Truck Before Installation



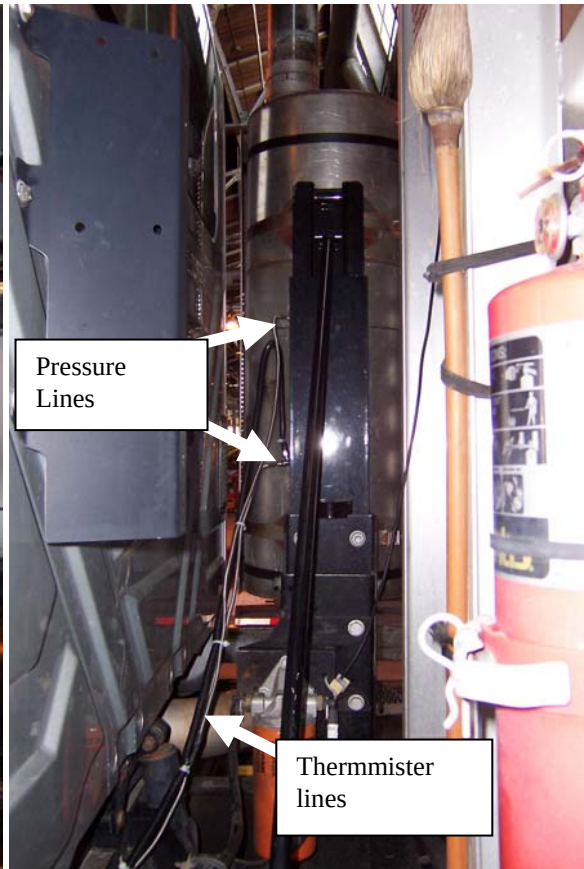
Monitor Inside Cab

ITEC 7600 Truck at Camp Pendleton for Installation of ESW (Cont.)

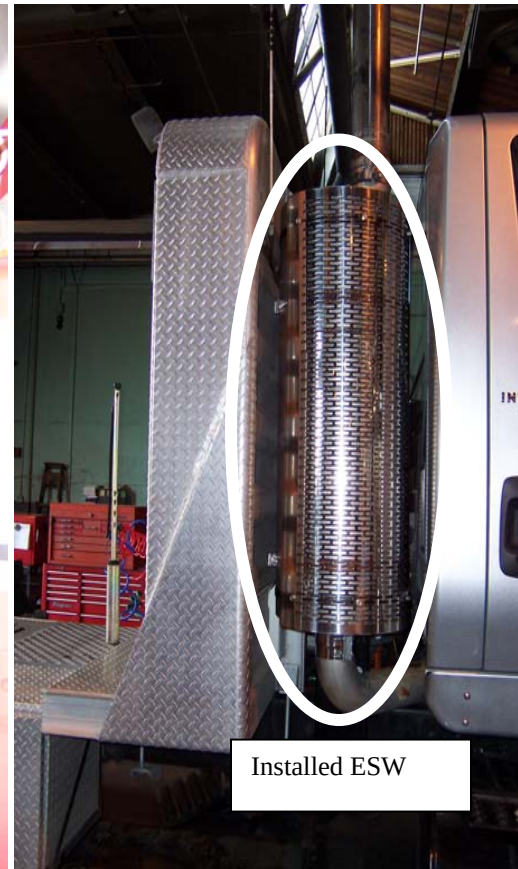


Muffler Housing

Muffler Removed



Thermister & Pressure Line



Installed ESW

Completed Installation

Ford FT900 Truck at Camp Pendleton for Installation of RPF

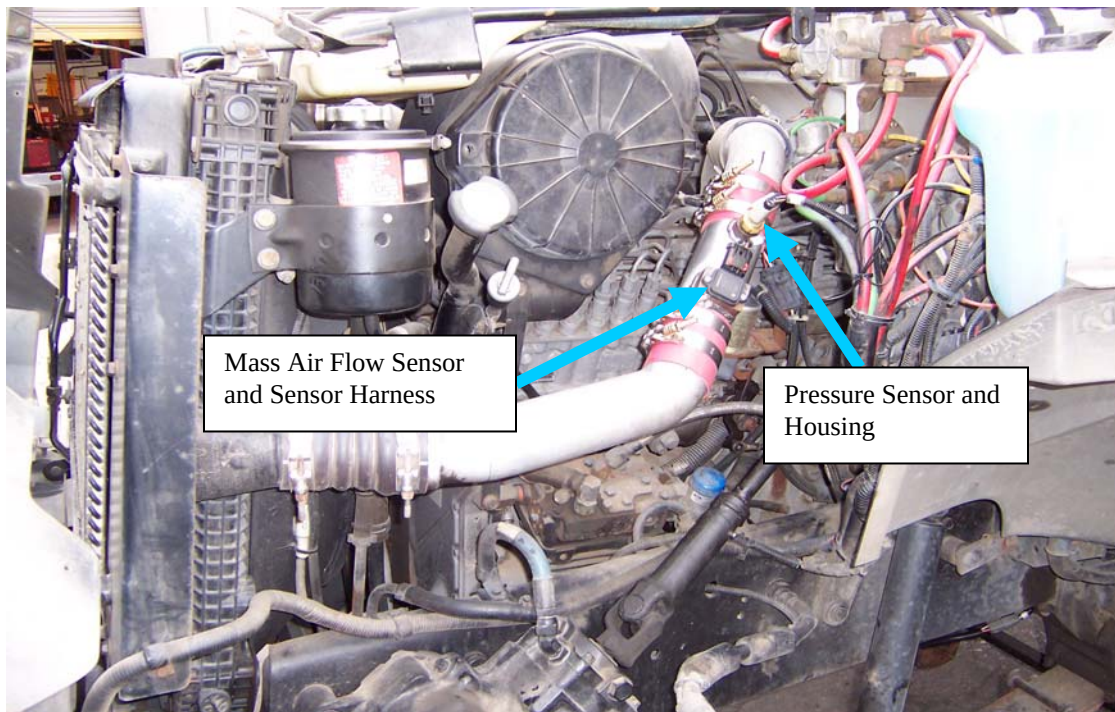


Vehicle Before Installation

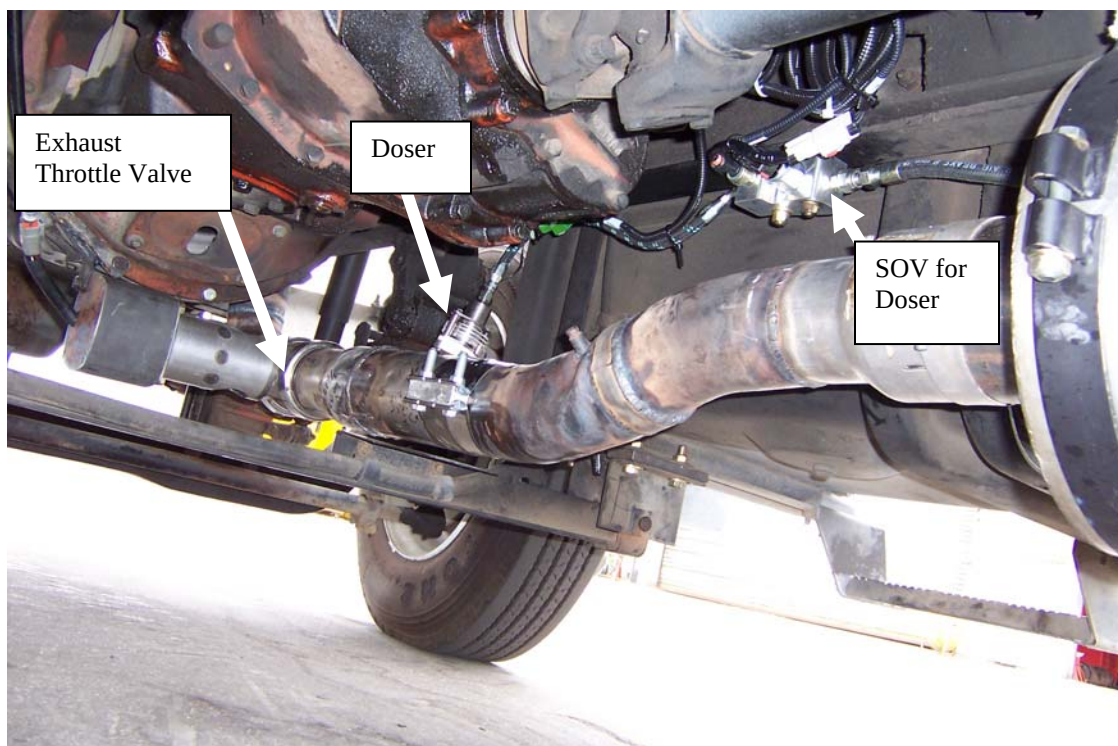


Original Muffler

Ford FT900 Truck at Camp Pendleton for Installation of RPF (Cont.)

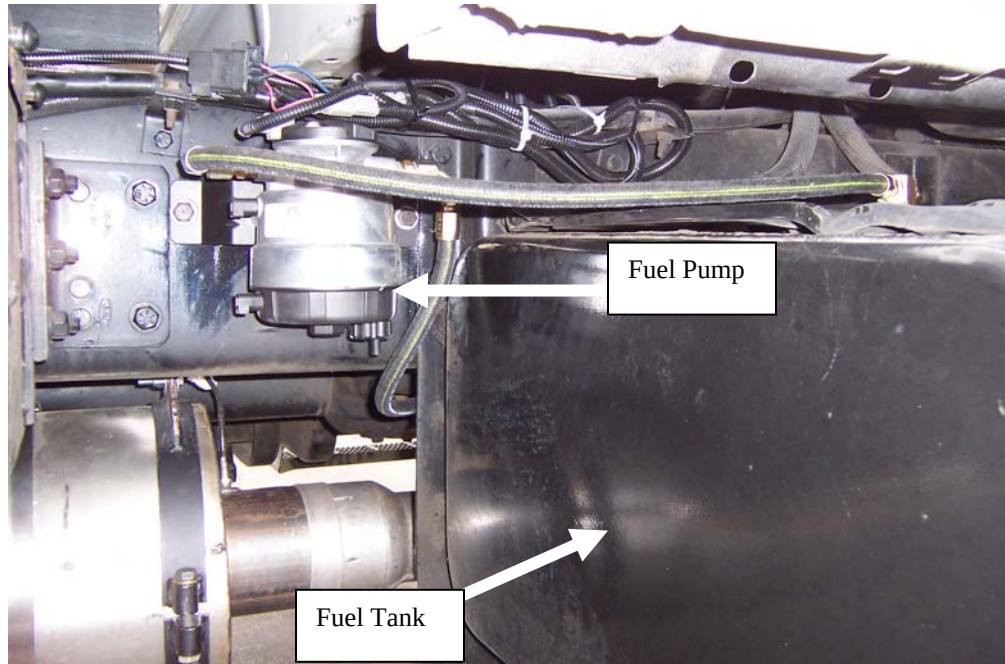


MAF and Boost Pressure Sensors



Exhaust Throttle/Doser/SOV

Ford FT900 Truck at Camp Pendleton for Installation of RPF (Cont.)



Racor Fuel Pump Drawing Fuel from Fuel Tank

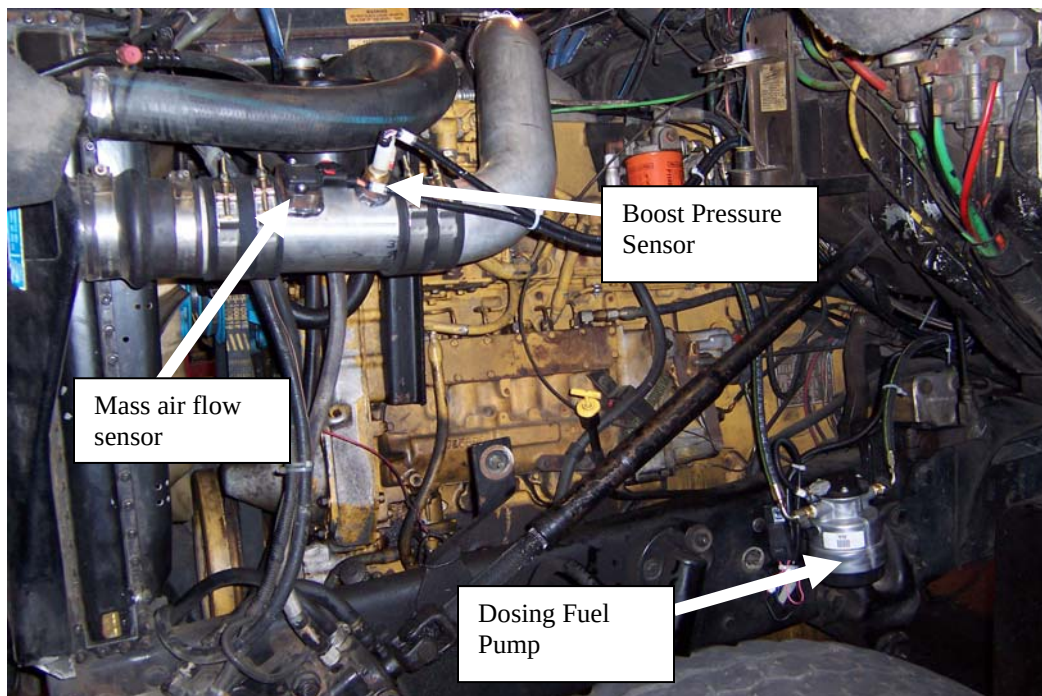


Vehicle After Installation

Ford L9000 Truck at Camp Pendleton for Installation or RPF (Cont.)

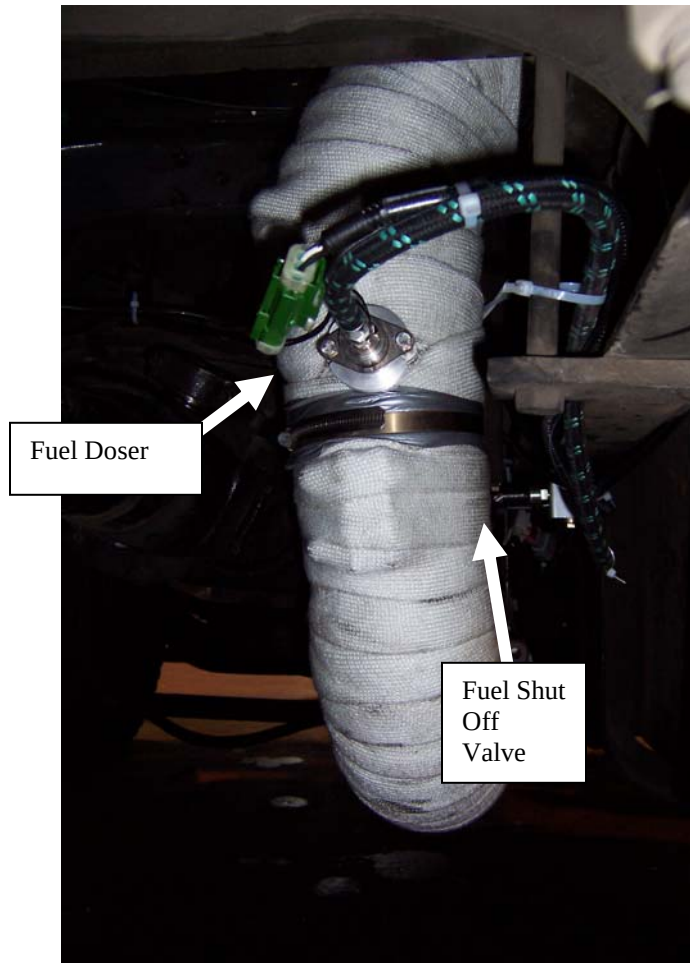


Vehicle Before Installation



Mass Air Flow/ Boost Pressure Sensors & Fuel Pump

Ford L9000 Truck at Camp Pendleton for Installation or RPF (Cont.)



Fuel Doser and Shut Off Valve



Exhaust Throttle

Ford L9000 Truck at Camp Pendleton for Installation or RPF (Cont.)



ECM Under Passenger Seat



Dash Lights

Ford L9000 Truck at Camp Pendleton for Installation of RPF (Cont.)



Data Logger



Completed Installation

Thomas Bus at Camp Pendleton for Installation of RPF



Vehicle Before Installation

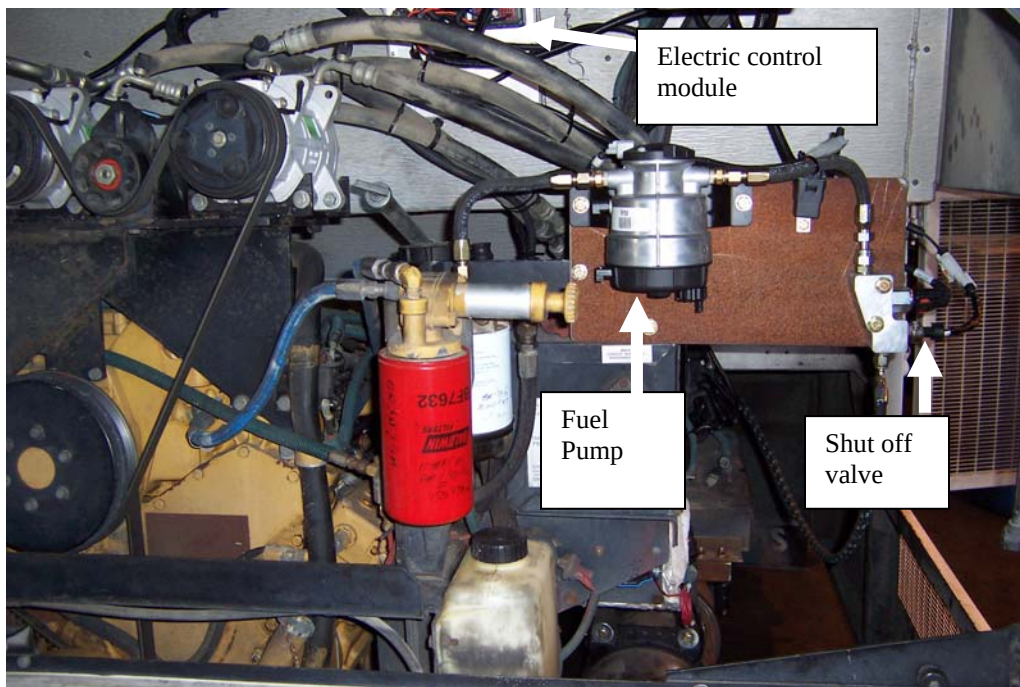


Original Muffler

Thomas Bus at Camp Pendleton for Installation of RPF (Cont.)

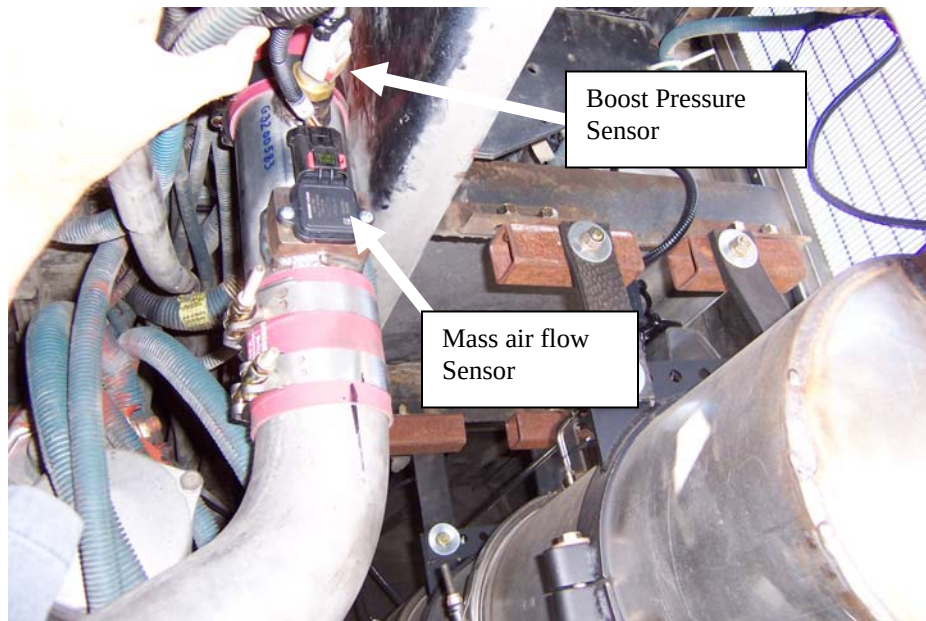


RPF Catalyst Installed

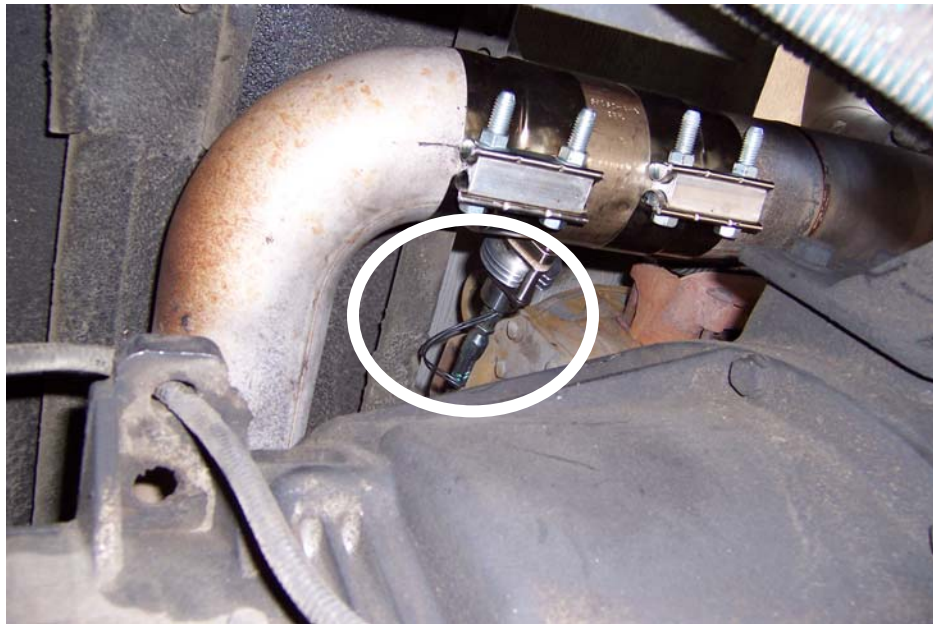


Fuel Pump, SOV and ECM

Thomas Bus at Camp Pendleton for Installation of RPF (Cont.)



MAF and Boost Pressure Sensors



Fuel Doser

An exhaust throttle was not used on this installation because the load factor/duty cycle of this vehicle was such that exhaust temperatures were high enough to provide a lot of passive regeneration and allow fuel dosing when active regeneration was scheduled (every 40 hours of operation).

Thomas Bus at Camp Pendleton for Installation of RPF (Cont.)



Dash Lights

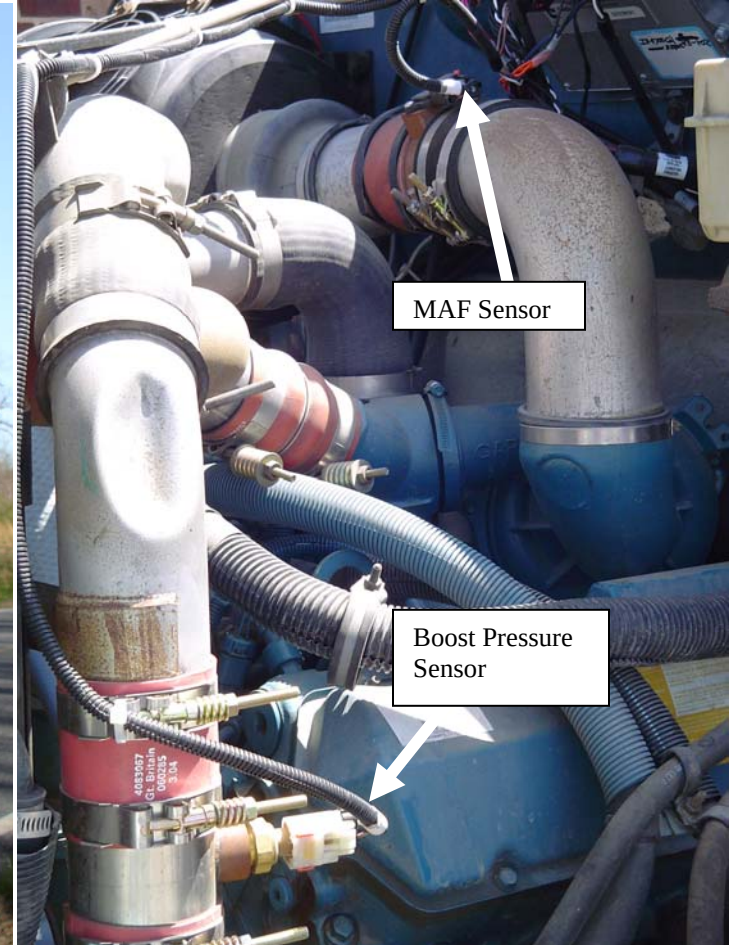


Data Logger

IH 4700 Truck at Aberdeen Proving Grounds for Installation of RPF

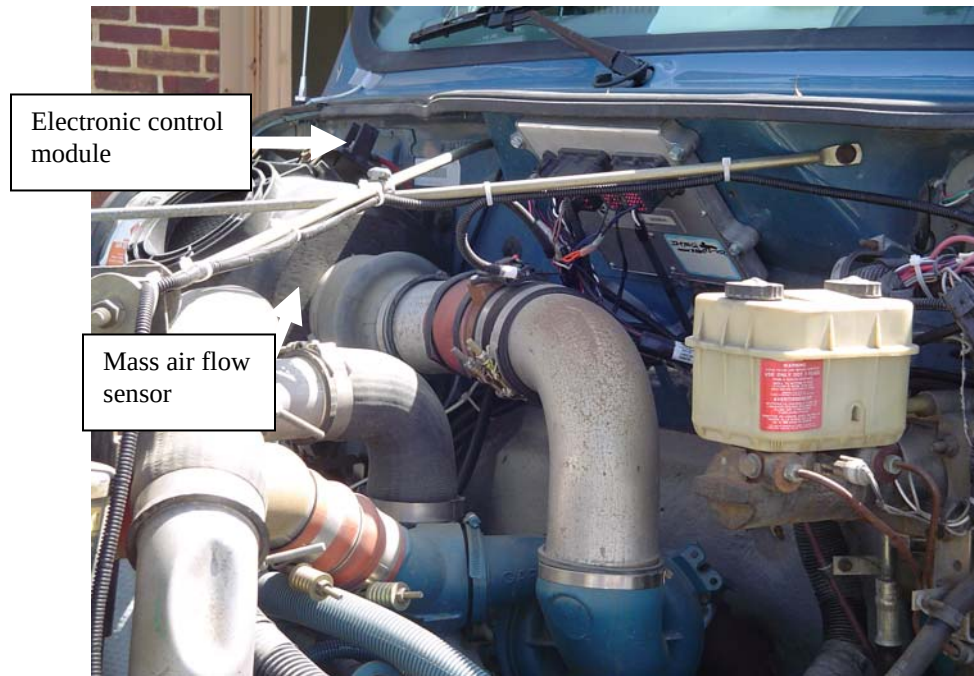


Vehicle



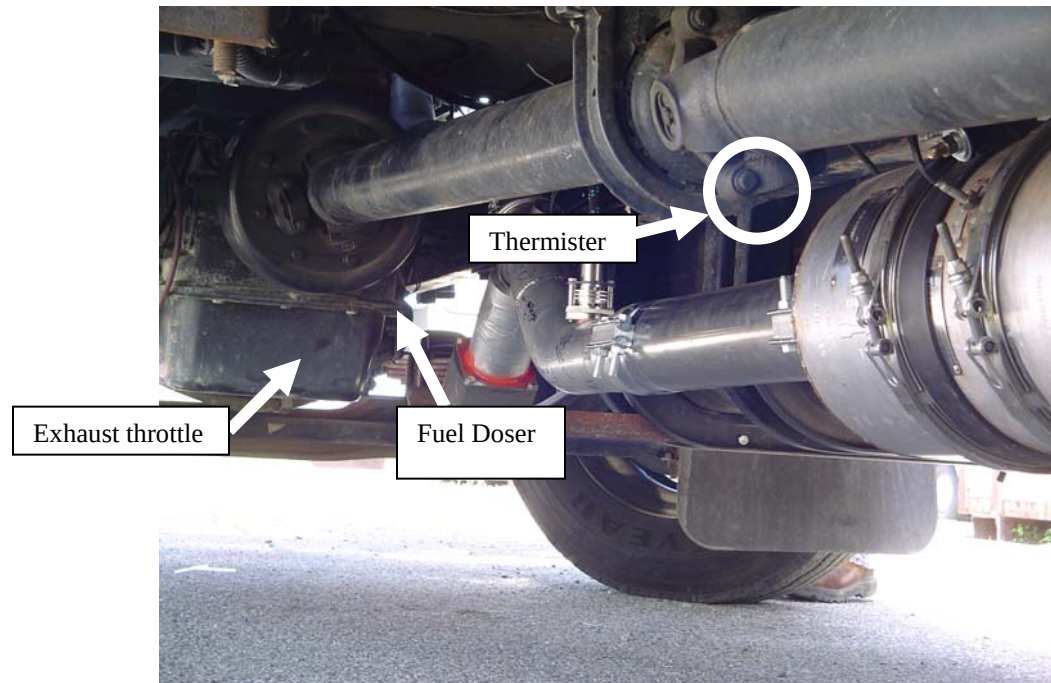
MAF and Boost Pressure Sensors

IH 4700 Truck at Aberdeen Proving Grounds for Installation of RPF (Cont.)



ECM and MAF Sensor

IH 4700 Truck at Aberdeen Proving Grounds for Installation of RPF (Cont.)



Exhaust Throttle and Fuel Doser

DOC Pictures



Camp Pendleton Ford L900 DOC in

DOC pictures (Cont.)



Camp Pendleton Ford L9000 DOC out

DOC pictures (Cont.)



Camp Pendleton Ford L9000 PF in

DOC pictures (Cont.)



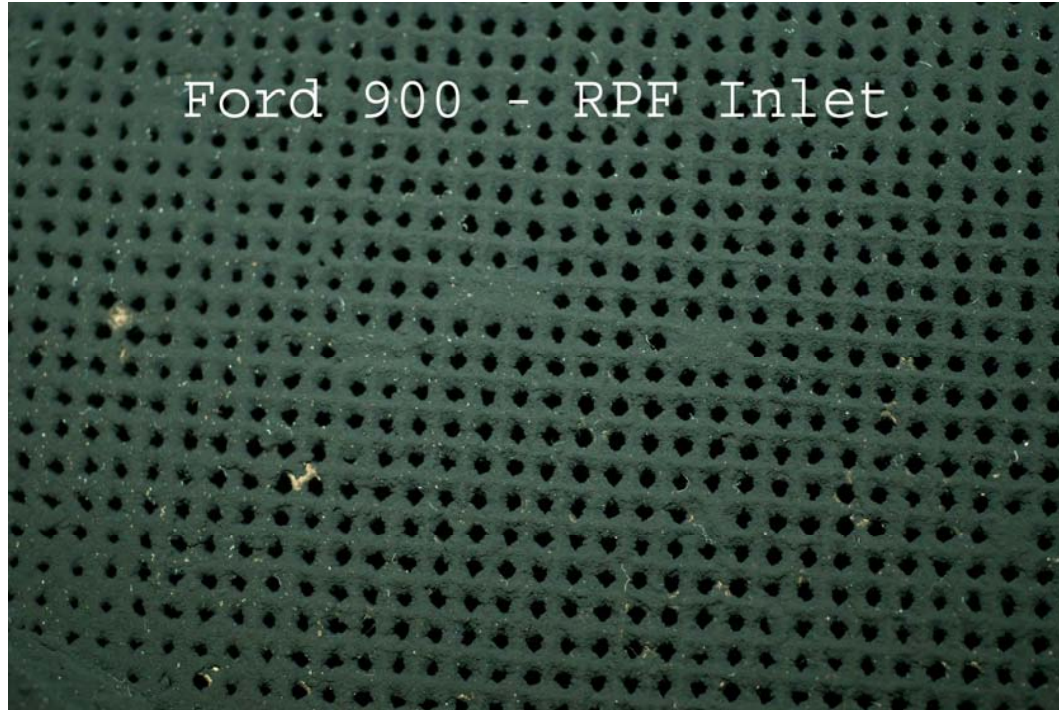
Camp Pendleton Ford L9000 OF out

DOC pictures (Cont.)



Ford 900 RPF Inlet

DOC pictures (Cont.)



Ford 900 RPF Inlet