Environmental Technology Verification

Test Report of Mobile Source Emission Control Devices

Paceco Corp.
Mitsui Engineering & Shipbuilding Diesel Particulate Filter

Prepared by

Southwest Research Institute

RTI International

Under a Cooperative Agreement with
U.S. Environmental Protection Agency

THE ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM

U.S. Environmental Protection Agency

ETV Joint Verification Statement

TECHNOLOGY TYPE:	**MOBILE DIESEL ENGINE AIR POLLUTION CONTROL**
APPLICATION:	**CONTROL OF EMISSIONS FROM MOBILE DIESEL ENGINES IN NONROAD USE BY DIESEL PARTICULATE FILTERS**
TECHNOLOGY NAME:	**MITSUI ENGINEERING & SHIPBUILDING – DIESEL PARTICULATE FILTER**
COMPANY:	**PACECO CORP.**
ADDRESS:	**3854 BAY CENTER PLACE HAYWARD, CA 94545 PHONE: (510) 264-9288 FAX: (510) 264-9280**

The U.S. Environmental Protection Agency (EPA) has created the Environmental Technology Verification (ETV) Program to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV Program is to further environmental protection by accelerating the acceptance and use of improved and cost-effective technologies. ETV seeks to achieve this goal by providing high-quality, peer-reviewed data on technology performance to those involved in the design, distribution, financing, permitting, purchase, and use of environmental technologies.

ETV works in partnership with recognized standards and testing organizations; stakeholder groups, which consist of buyers, vendor organizations, permitters, and other interested parties; and with the full participation of individual technology developers. The program evaluates the performance of innovative technologies by developing test plans that are responsive to the needs of stakeholders, conducting field or laboratory tests (as appropriate), collecting and analyzing data, and preparing peer-reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance (QA) protocols to ensure that data of known and adequate quality are generated and that the results are defensible.

The Air Pollution Control Technology Verification Center (APCT Center), one of six centers under the ETV Program, is operated by RTI International (RTI), in cooperation with EPA's National Risk Management Research Laboratory. The APCT Center has evaluated the performance of an emissions control system consisting of a diesel particulate filter for nonroad diesel engines.

ETV TEST DESCRIPTION

All tests were performed in accordance with the *Test/QA Plan for the Verification Testing of Diesel Exhaust Catalysts, PM Filters, and Engine Modification Technologies for Highway and Nonroad Use Diesel Engines* and the *Test-Specific Addendum to ETV Mobile Source Test/QA Plan for Paceco Corp. for the Mitsui Engineering & Shipbuilding-Diesel Particulate Filter*. These documents are written in accordance with the applicable generic verification protocol and include requirements for quality management, QA, procedures for product selection, auditing of the test laboratories, and test reporting format.

The mobile diesel engine air pollution control technology was tested at Southwest Research Institute. The performance verified was the percentage emission reduction achieved by the technology for particulate matter (PM), nitrogen oxides (NO_x), hydrocarbons (HC), and carbon monoxide (CO) relative to the performance of the same baseline engine without the technology in place. Operating conditions were documented and ancillary performance measurements were also made. A summary description of the ETV test is provided in Table 1.

Table 1. Summary Description of the ETV Test

Test type	Nonroad steady-state Federal Test Procedure (FTP)
Engine family	NA*
Engine make–model year	Cummins Engine Company – 1991 model NTA855-G2
Service class	Off-highway, heavy-duty diesel engine
Engine rated power	Nameplate ratings in generator set service: 420 hp in “prime” service; 465 hp in “standby” service
Engine displacement	14.0 L, six-cylinder inline
Technology	Mitsui Engineering & Shipbuilding Diesel Particulate Filter
Technology description	L-shaped cylindrical canister “muffler” design weighing nominally 200 lb, containing a catalyst bed and a metal mesh filter
Test cycle or mode description	5-mode test cycle for constant-speed engines (ISO 8781 D2 test)
Test fuel description	Ultra-low-sulfur diesel (ULSD) fuel with 15 ppm sulfur maximum
Critical measurements	PM, NO_x, HC, and CO
Ancillary measurements	CO_2, NO, NO_2 (by calculation), soluble organic fraction (SOF) of PM, exhaust back-pressure, exhaust temperature, and fuel consumption

* NA = not applicable. Nonroad engines manufactured prior to 1996 were not certified; no family name identification numbers were assigned.

VERIFIED TECHNOLOGY DESCRIPTION

This verification statement applies to the use of the Mitsui Engineering & Shipbuilding Diesel Particulate Filter (MES-DPF) on constant-speed nonroad engines such as those used on the gantry cranes manufactured by Paceco Corp. It is applicable to engines fueled only by ultra-low-sulfur (15 ppm or less) diesel fuel.

This verification statement describes the performance of the tested technology on the diesel engine and fuels identified in Table 1.

VERIFICATION OF PERFORMANCE

The MES-DPF achieved the reduction in tailpipe emissions shown in Table 2 compared to baseline operation without the MES-DPF.

Table 2. Verified Emissions Reductions

Device Type	Mean Emissions Reduction (%)				95% Confidence Limits on the Emissions Reduction (%)			
	PM	NO_x[a]	HC	CO	PM	NO_x	HC	CO
Aged	39.2	4.2	[b]	95.0	35-43	2.4-6.0	[b]	88-100
Degreened	38.8	3.0	[b]	94.5	35-42	0.1-5.9	[b]	88-100

[a] The mean NO_2/NO_X ratio in % NO_2 was 10 for the baseline test and 31 and 32 for the aged and degreened tests, respectively.

[b] Hydrocarbon emissions reductions could not be quantified or distinguished from 100% with 95% confidence.

The APCT Center QA Officer has reviewed the test results and quality control data and has concluded that the data quality objectives given in the generic verification protocol and test/QA plan have been attained. EPA and APCT Center QA staff have conducted technical assessments of the test laboratory and of the data handling. These assessments confirm that the ETV tests were conducted in accordance with the EPA-approved test/QA plan.

This verification statement verifies the emissions characteristics of the *Mitsui Engineering & Shipbuilding Diesel Particulate Filter* (*MES-DPF*) for the stated application. Extrapolation outside that range should be done with caution and an understanding of the scientific principles that control the performance of the technology. This verification focuses on emissions. Potential technology users may obtain other types of performance information from the manufacturer.

In accordance with the generic verification protocol, this verification statement is valid, commencing on the date below, indefinitely for application of the *MES-DPF* within the range of applicability of the statement.

Original signed by Sally Gutierrez *2/23/06*
Sally Gutierrez Date
Director
National Risk Management Research Laboratory
Office of Research and Development
United States Environmental Protection Agency

Original signed by A. R. Trenholm *2/13/06*
Andrew R. Trenholm Date
Director
Air Pollution Control Technology Verification Center

Environmental Technology Verification Report

Mobile Source Emission Control Devices

Mitsui Engineering & Shipbuilding
Diesel Particulate Filter

Prepared by

RTI International
Southwest Research Institute

EPA Cooperative Agreement No. CR831911-01-1

EPA Project Manager:
Michael Kosusko
Air Pollution and Control Division
National Risk Management Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

January 2006

Notice

This document was prepared by RTI International (RTI) and its subcontractor, Southwest Research Institute (SwRI), with partial funding from Cooperative Agreement No. CR829434-01-1 with the U.S. Environmental Protection Agency (EPA). The document has been submitted to RTI's and EPA's peer and administrative reviews and has been approved for publication. Mention of corporation names, trade names, or commercial products does not constitute endorsement or recommendation for use of specific products.

Foreword

The Environmental Technology Verification (ETV) Program, established by the U.S. Environmental Protection Agency (EPA), is designed to accelerate the development and commercialization of new or improved technologies through third-party verification and reporting of performance. The goal of the ETV Program is to verify the performance of commercially ready environmental technologies through the evaluation of objective and quality-assured data in order to provide potential purchasers and permitters an independent, credible assessment of the technology they are buying or permitting.

The Air Pollution Control Technology Verification Center (APCT Center) is part of the EPA's ETV Program, and is operated as a partnership between RTI International (RTI) and EPA. The APTC Center verifies the performance of commercially ready air pollution control technologies. Verification tests use approved protocols, and verified performance is reported in verification statements signed by EPA and RTI officials. RTI contracts with Southwest Research Institute (SwRI) to perform verification tests on engine emission control technologies.

Retrofit air pollution control devices used to control emissions from mobile diesel engines are among the technologies evaluated by the APCT Center. The Center developed (and EPA approved) the *Generic Verification Protocol for Diesel Exhaust Catalysts, Particulate Filters, and Engine Modification Control Technologies for Highway and Nonroad Use Diesel Engines* to provide guidance on the verification testing of specific products that are designed to control emissions from diesel engines.

The following report reviews the performance of the Mitsui Engineering & Shipbuilding Diesel Particulate Filter. ETV testing of this technology was conducted in July 2005 at SwRI. All testing was performed in accordance with an approved test/QA plan that implements the requirements of the generic verification protocol at the test laboratory.

Availability of Report

Copies of this verification report are available from:

- RTI International
  Engineering and Technology Unit
  P.O. Box 12194
  Research Triangle Park, NC 27709-2194

- U.S. Environmental Protection Agency
  Air Pollution Prevention and Control Division (E343-02)
  109 T. W. Alexander Drive
  Research Triangle Park, NC 27711

Web sites: http://www.epa.gov/etv/verifications/verification-index.html (.pdf format)
http://www.epa.gov/ncepihom/

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Acronyms/Abbreviations

ºF	degrees Fahrenheit
ºC	degrees Celsius
APCT	Air Pollution Control Technology
bhp	brake horsepower
bhp-hr	brake horsepower-hour
BSFC	brake-specific fuel consumption
C-B	carbon balance
CFR	Code of Federal Regulations
cm	centimeter(s)
CO	carbon monoxide
CO_2	carbon dioxide
CVS	constant volume sampler
EPA	U.S. Environmental Protection Agency
ETV	Environmental Technology Verification
FTP	Federal Test Procedure
ft	foot (feet)
g	gram(s)
HC	hydrocarbon(s)
HD	heavy duty
hp	horsepower
in.	inch(es)
in. Hg	inch(es) mercury
kW	kilowatt(s)
kWh	kilowatt hour(s)
L	liter(s)
lb	pound(s)
lb-ft	pound foot (feet)
LSD	low-sulfur diesel
m	meter(s)

MES-DPF	Mitsui Engineering & Shipbuilding Diesel Particulate Filter
mm	millimeter(s)
N	newton(s)
N-m	newton-meter
NO	nitrogen oxide
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
OTAQ	Office of Transportation and Air Quality
Pa	pascal(s)
PM	particulate matter
ppm	parts per million by volume
QA	quality assurance
QC	quality control
rpm	revolutions per minute
RTI	RTI International
SOF	soluble organic fraction of the particulate matter
SOP	standard operating procedure
SwRI	Southwest Research Institute
ULSD	ultra-low-sulfur diesel

Acknowledgments

The authors acknowledge the support of all of those who helped plan and conduct the verification activities. In particular, we would like to thank Michael Kosusko, Project Manager, and Paul Groff, Quality Assurance Manager, both of the U.S. Environmental Protection Agency's (EPA's) National Risk Management Research Laboratory in Research Triangle Park, NC. We would also like to acknowledge the assistance and participation of all Paceco Corp. personnel who supported the test effort.

For more information on the Mitsui Engineering & Shipbuilding Diesel Particulate Filter contact:

Mr. Philip Tam
Paceco Corp.
3854 Bay Center Place
Hayward, CA 94545
Telephone: (510) 264-9288
Fax: (510) 264-9280
Email: pt@pacecocorp.com
Web site: http://www.pacecocorp.com

For more information on verification testing of mobile sources air pollution control devices, contact:

Ms. Jenni Elion
RTI International
P.O. Box 12194
Research Triangle Park, NC 27709-2194
Telephone: (919) 541-6253
Email: jme@rti.org
Web site: http://etv.rti.org/apct/index.html

Section 1.0
Introduction

This report reviews the performance of the Mitsui Engineering & Shipbuilding Diesel Particulate Filter (MES-DPF) submitted for testing by Paceco Corp.* Environmental technology verification (ETV) testing of this technology was conducted during a series of tests in July 2005 by Southwest Research Institute (SwRI), under contract with the Air Pollution Control Technology Verification Center (APCT Center). The APCT Center is operated by RTI International (RTI)† in partnership with the U.S. Environmental Protection Agency's (EPA's) ETV Program. The objective of the APCT Center and the ETV Program is to verify, with high-quality data, the performance of air pollution control technologies, including those designed to control air emissions from diesel engines. With the assistance of a technical panel of experts assembled for the purpose, RTI has established an APCT program area specifically to evaluate the performance of diesel exhaust catalysts, particulate filters, and engine modification control technologies for mobile diesel engines. Based on the activities of this technical panel, the *Generic Verification Protocol for Diesel Exhaust Catalysts, Particulate Filters, and Engine Modification Control Technologies for Highway and Nonroad Use Diesel Engines*[1] was developed. This protocol was chosen as the best guide to verify the immediate performance effects of the MES-DPF technology. To determine these effects, emissions results from a heavy-duty turbocharged nonroad diesel engine were compared to emissions results obtained operating the same engine with the same fuel, but with the MES-DPF technology installed. The specific test/quality assurance (QA) plan addendum for the ETV test of the technology submitted by Paceco Corp. was developed and approved in April 2005.[2] The goal of the test was to measure the emissions control performance of the MES-DPF technology and its emissions reduction relative to an uncontrolled engine, in the context of applying the technology to diesel engines used on gantry cranes manufactured by Paceco. The uncontrolled engine selected by Paceco was representative of the type, size, and age of engines in use in gantry cranes.

A description of the Paceco Corp./Mitsui Engineering & Shipbuilding technology is presented in Section 2. Section 3 documents the procedures and methods used for the test and the conditions under which the test was conducted. The results of the test are summarized and discussed in Section 4, and references are presented in Section 5.

This report contains only summary data and the verification statement. Complete documentation of the test results is provided in a separate test report[3] and audit of data quality report.[4] These reports include the raw test data from product testing and supplemental testing, equipment calibration results, and QA and quality control (QC) activities and results. Complete documentation of QA/QC activities and results, raw test data, and equipment calibration results are retained in SwRI's files for 7 years.

The verification statement applies to the use of the MES-DPF on constant-speed nonroad engines, such as such as those used on the gantry cranes manufactured by Paceco Corp. It is applicable to engines fueled only by ultra-low-sulfur (ULSD) (15 ppm or less) diesel fuel.

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* Paceco Corp. is a subsidiary of Mitsui Engineering & Shipbuilding Co., Ltd.
† RTI International is a trade name of Research Triangle Institute.

Section 2.0
Product Description

The Mitsui Engineering & Shipbuilding Diesel Particulate Filter (MES-DPF) is a continuous regeneration type DPF consisting of an L-shaped cylindrical canister ("muffler" design) with a 6-inch-diameter flange at each end, and weighs nominally 200 pounds (Figure 1). Inside the canister are several beds of oxidation catalyst designed to control hydrocarbon (HC) and carbon monoxide (CO) and to oxidize nitrogen oxide (NO) to nitrogen dioxide (NO_2). These beds are followed by a particulate filter to capture carbon soot. At the soot filter, the carbon is changed to carbon dioxide (CO_2) by reacting it with NO_2 and reforming NO. These reactions are accomplished by means of the Johnson-Matthey CRT® (Continuously Regenerating Technology). Paceco Corp. provided an "aged" MES-DPF unit that had seen 1934 hours service installed on the diesel engine of a gantry crane in active use. This unit had a March 2004 date of manufacture and was designated serial number 2005001.

Figure 1. MES-DPF unit installed in exhaust system of test engine.

Paceco provided a "degreened" MES-DPF unit that had seen 83 hours of service on the same engine. It had a June 2004 date of manufacture and was designated serial number 2005002.

Section 3.0
Test Documentation

The ETV testing took place during July 2005 at SwRI under contract to the APCT Center. Testing was performed in accordance with:

- *Generic Verification Protocol for Diesel Exhaust Catalysts, Particulate Filters, and Engine Modification Control Technologies for Highway and Nonroad Use Diesel Engines*[1]
- *Test/QA Plan for the Verification Testing of Diesel Exhaust Catalysts, Particulate Filters, and Engine Modification Control Technologies for Highway and Nonroad Use Diesel Engines*[5]
- *Test-Specific Addendum to ETV Mobile Source Test/QA Plan for Paceco Corp. for the MES-Diesel Particulate Filter*.[2]

The applicant reviewed the generic verification protocol and had an opportunity to review the test/QA plan prior to testing.

3.1 Engine Description

The ETV testing was performed on an in-line, six-cylinder, 14-L, 1991 model year, Cummins Engine Company, heavy-duty (HD) turbocharged nonroad diesel engine 1991 (model NTA855-G2, SN: 23220015, CPL 1383). The nameplate rating of this model engine is 313 kW (420 bhp) in “prime” power service at 1800 rpm, and 347 kW (465 bhp) in “standby” service. Paceco Corp. supplied the engine to SwRI. A certified Cummins service facility verified that the engine’s fuel injection pump was original equipment, and that the engine’s overhead was set to manufacturer’s specifications. This is the same make and model of engine that was used for “aging” the test DPF units. Rather than pull a gantry crane out of service, however, Paceco obtained the test engine from a leased 300 kW generator set. The test engine had 5214 hours of operation accumulated on it (compared to 11,765 cumulative hours of operation on the engine that was used for the aging of the test units).

Table 1 provides the engine identification details. Figure 2 shows the engine as it was received at SwRI, installed on a leased portable generator set (genset). SwRI technicians removed the engine from the genset and installed it in a dynamometer test cell. Prior to starting the ETV testing, SwRI verified the condition of the engine by operating it with 2D emission grade, low-sulfur diesel fuel (nominally 350 ppm sulfur). For this setup phase, the instrument calibration and torque mapping adhered to 40 CFR, Part 86, Subpart N.[6]

3.2 Engine Fuel Description

Following engine setup verification, a thorough fuel flush and change to ULSD was completed. All emissions testing was conducted with ULSD fuel with a sulfur level of 9 ppm, meeting the specification for 2007 emissions certified fuel.[7]

Table1. Engine Identification Information

Engine serial number	23220015, CPL-1383
Date of manufacture	June 11, 1991
Make	Cummins Engine Company, Inc.
Model year	1991
Model	NTA855-G2
Engine displacement and configuration	14 L (855 CID), in-line six-cylinder
Service class	Nonroad, heavy-duty (HD) diesel engine
EPA engine family identification	NA*
Rated power (nameplate)	347 kW (465 bhp) at 1800 rpm
Rated torque (calculated from nameplate power)	1840 N-m (1357 lb-ft) at 1800 rpm
Certified emission control system	NA – Tier 0 engine
Aspiration	Turbocharger and aftercooler
Fuel system	Direct injection, mechanically controlled unit injectors

*NA = not applicable. Nonroad engines manufactured prior to 1996 were not certified; no family name identification numbers were assigned.

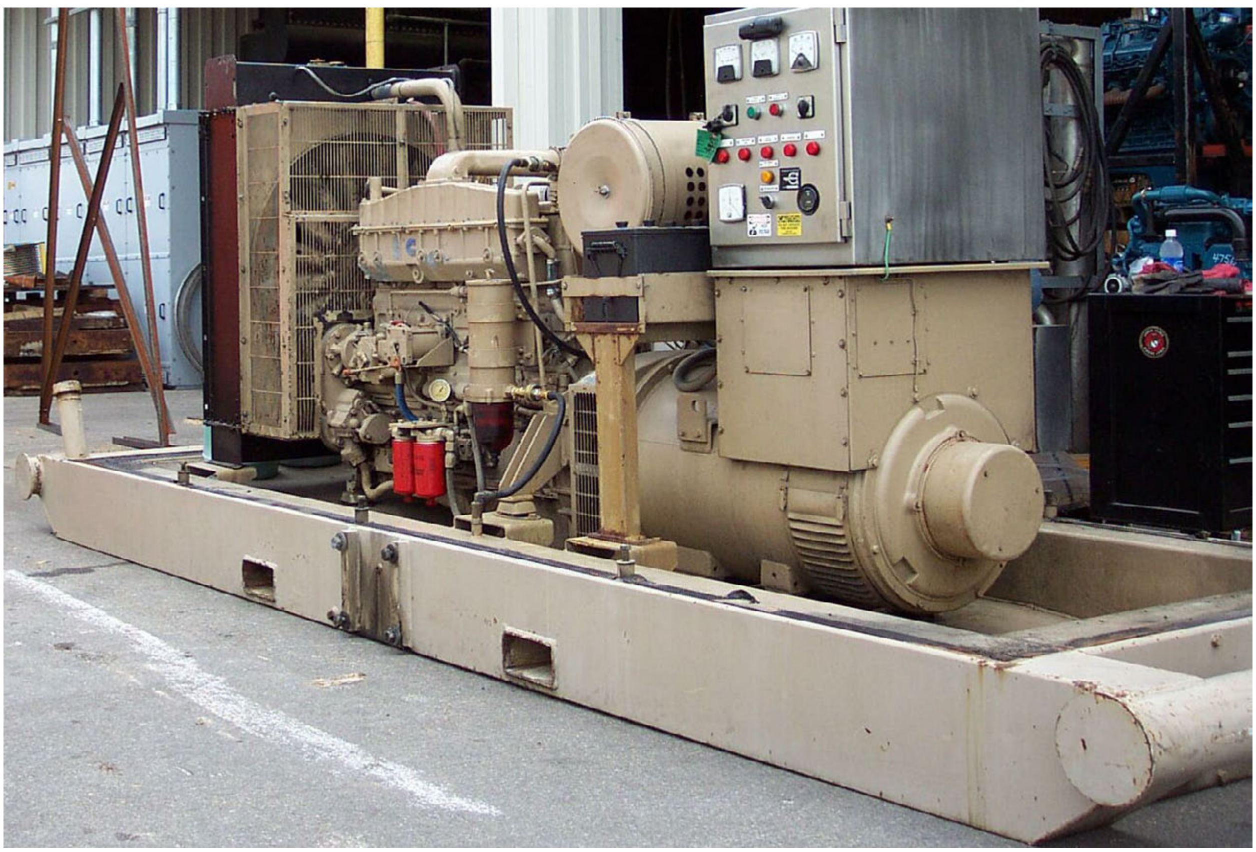

Figure 2. Cummins 14-L test engine, model year 1991, as received (installed in a generator set).

3.3 Summary of Emissions Measurement Procedures

The ETV tests consisted of baseline uncontrolled tests and tests with the control technology installed. Engine operation and emissions sampling adhered to techniques developed by EPA in the Code of Federal Regulations (CFR), Title 40, Part 89, Subparts D and E.[8] Emissions were measured over triplicate runs of the 5-mode test cycle[9] for the baseline, aged DPF, and degreened DPF exhaust configurations.

In general, the 5-mode test cycle (also referred to as the ISO D2 test) involves running the engine at its rated speed (1800 rpm) and quantifying emissions at five separate torque loadings (i.e., 100, 75, 50, 25, and 10%) relative to the maximum torque developed at the given engine's rated speed. The maximum torque is measured on each separate run and the "target" torque loadings are calculated. Emissions are quantified at the five steady-state operating conditions, and weighted using EPA-assigned factors for calculating composite emission levels.[9] Table 10 in Section 4.0 lists the operating conditions and weighting factors. The calculation procedure is explained more fully in that section.

Triplicate tests were performed with the engine without the MES-DPF control technology, with an aged MES-DPF unit, and with a degreened unit. The aged and degreened units were identical size, L-shaped cylindrical canister "muffler" designs, with a 6-inch-diameter flange at each end. Each weighed nominally 200 pounds and was marked with a serial number stamped into its steel housing. For evaluating emissions, each DPF in turn was mounted 72 inches downstream of the turbocharger in its "as received" condition and was fully insulated. Steps taken to degreen or age each DPF had been completed by Paceco prior to the units' delivery to SwRI (as explained in Section 2.0). Table 2 provides an overview of the scope of emissions testing.

Table 2. Overview of Emissions Testing of MES-DPF at SwRI

Run	Fuel	Cycle	Test Name	MES-DPF
1	ULSD	ISO-D2	BUL-D2A	None
2	ULSD	ISO-D2	BUL-D2B	None
3	ULSD	ISO-D2	BUL-D2C	None
4	ULSD	ISO-D2	AUL-D2A	Aged
5	ULSD	ISO-D2	AUL-D2B	Aged
6	ULSD	ISO-D2	AUL-D2C	Aged
7	ULSD	ISO-D2	AUL-D2D	Aged
8	ULSD	ISO-D2	DUL-D2A	Degreened
9	ULSD	ISO-D2	DUL-D2B	Degreened
10	ULSD	ISO-D2	DUL-D2C	Degreened

ULSD = Ultra-low-sulfur diesel fuel (EM-5443-F).
ISO-D2 = ISO 8178 constant-speed, 5-mode steady-state test.
MES-DPF = Diesel Particulate Filter from Mitsui Engineering & Shipbuilding.

The NTA855-G2 engine was operated in an engine dynamometer test cell, with exhaust sampled using full-flow dilution constant volume sampling (CVS) techniques to measure regulated emissions of HC, CO, nitrogen oxides (NO_X), and particulate matter (PM), plus nitric oxide. The NO_2 levels are expressed as the difference between measured NO_X and NO levels for each run.

In addition to results presented in this report, raw data were gathered at the rate of one series of measurements per second over each test to record the engine speed, torque value, concentration of selected emissions, exhaust temperature, and various pressures. Figure 3 depicts the sampling system and related components. The system is designed to comply with the requirements of CFR 40, Part 89.[8] Figure 4 shows the engine with DPF hardware in the exhaust system, as tested.

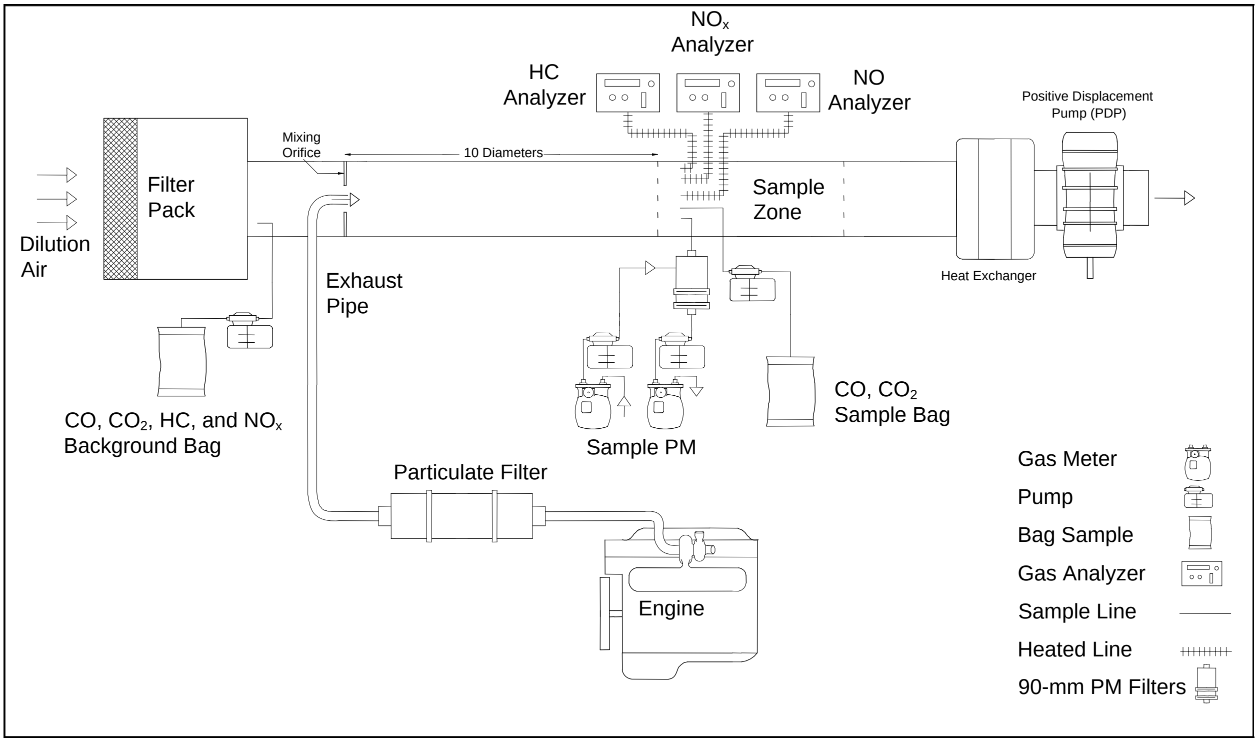

Figure 3. Schematic of emissions sampling system at SwRI.

Figure 5 shows torque map information measured on the NTA855-G2 engine using the ULSD fuel. The measured torque at 1800 rpm [1891 N-m (1395 lb-ft)] was 2.8% greater than the "nameplate" value for this engine. An increased output of this magnitude is not unusual for an older engine that has some wear resulting in enlargement of the injector orifices and a consequent increase in fuel flow rate.

Figure 4. 1991 Cummins NTA855-G2 engine mounted in emissions test cell with MES-DPF unit shown in exhaust system.

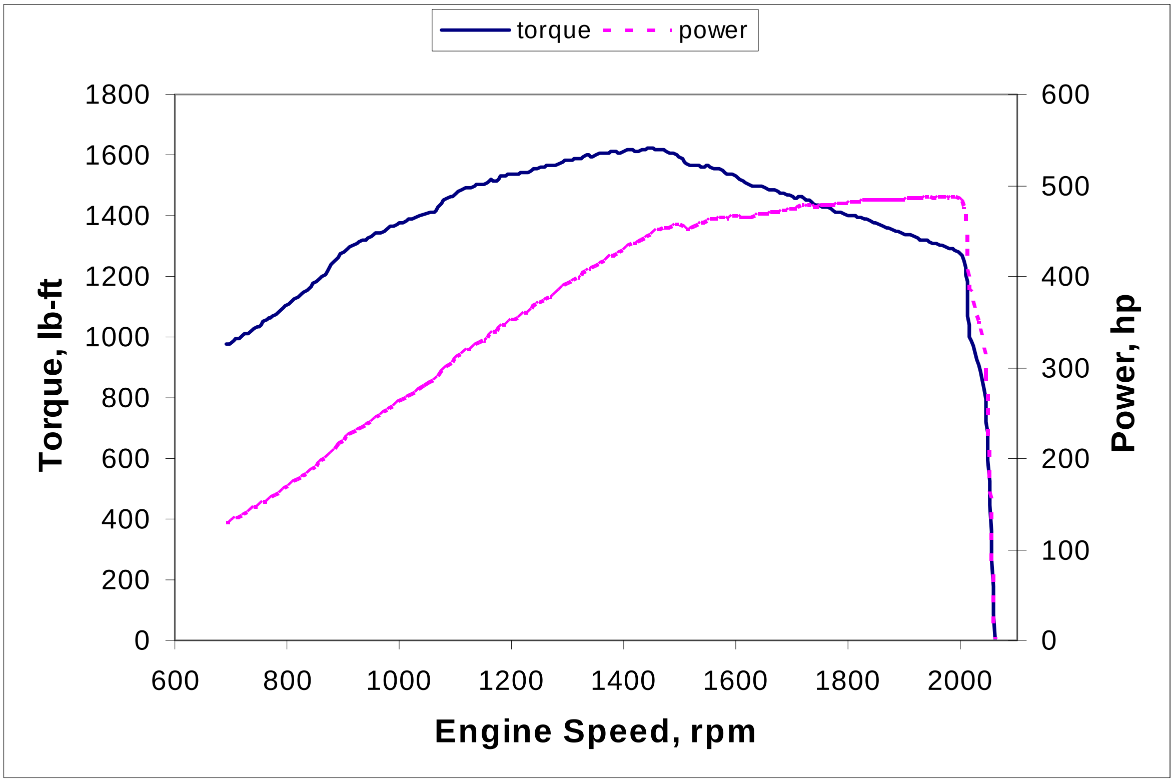

Figure 5. Torque map of 1991 Cummins NT855-G2 engine using ULSD fuel.

The criteria established to indicate that the test engine was acceptable and that the verification testing could proceed were that the baseline emissions from the engine using ULSD fuel could not exceed 1.425 times the certification levels for 1996 nonroad engines. The verification protocol requires that test engines manufactured before emission standards must not exceed 150% of the first standards for that engine category.[10] After discussion with the Office of Transportation and Air Quality (OTAQ) and the applicant, this margin was reduced by 5% for this verification test based on the assumption of 5% emissions reduction due to the use of ULSD fuel. Table 3 below presents the required baseline emission performance of the test engine. (Section 4.0 of this report contains the emissions data to show that the performance of the selected engine was acceptable.)

Table 3. Test Engine Baseline Emissions Requirement

	NO_x g/kWh (g/hp-hr)	HC g/kWh (g/hp-hr)	CO g/kWh (g/hp-hr)	PM g/kWh (g/hp-hr)
1996 Standard – Nonroad engines	9.2 (6.9)	1.2 (1.0)	11.4 (8.5)	0.54 (0.40)
1.425 x 1996 Standard	13.1 (9.8)	1.9 (1.4)	16.2 (12.1)	0.77 (0.57)

3.4 Deviations from the Test/QA Plan

The test-specific addendum calls for use of a Cummins engine, model year between 1992 and 1995, but a 1991 model was used. The impact of this deviation is negligible. The date range in the test plan was selected by Paceco as being representative of the fleet of engines installed in gantry cranes in service that would be candidates for a diesel retrofit device. The model year of the engine on the generator set that was available for lease was close enough to the range that the client decided to select it as being representative.

Four test runs were made with the “aged” MES-DPF installed, although the plan only called for making three runs. The reasoning for the extra test is explained in Section 3.5 below. The data from all the tests were included in the calculations.

After completion of the runs with the “aged” DPF, it was removed from the exhaust system and the “degreened” DPF was fitted in its place. Engine warm-up and related preparatory work then resumed. As technicians attempted to begin testing with the degreened DPF unit, they noticed smoke in the test cell coming from the engine. No visible smoke had been observed in the test cell during prior activities. An investigation found the source of smoke to be a failing exhaust manifold gasket at one of the engine’s six cylinders (i.e., pre-turbo). SwRI replaced two of the six separate exhaust manifold gaskets closest to the flywheel-end of the engine (i.e., cylinders 5 and 6). This unscheduled maintenance was a simple, noninvasive procedure that did not involve handling the turbocharger. The CO_2 levels measured after the unscheduled maintenance were consistent with those measured before. Thus, it was concluded that the engine performance was not affected by the resolution of the problem so that emissions data taken after the repair could be included in the data set with the data taken previously.

3.5 Documented Test Conditions

Engine Performance

Table 4 summarizes the engine performance over the multiple days of constant-speed testing. As a measure of stability of engine operation, the measured "bhp from Work" values for each of the test modes were within 1% to 2% of the mean values shown in the table.

Table 4. Summary of Engine Performance

Fuel	Test Date	Test Number	Test Type	Measured Peak Power kW (bhp)[a]	Measured Peak Torque N-m (lb-ft)[b]
ULSD	7/26/2005	BUL-D2	Baseline	352 (473)	1875 (1383)
ULSD	7/27-28/2005	AUL-D2	Aged device	356 (477)	1890 (1394)
ULSD	7/29/2005	DUL-D2	Degreened device	355 (476)	1885 (1391)

[a] Engine power at rated speed of 1800 rpm, average of all replicate runs.
[b] Engine peak torque at rated speed of 1800 rpm, average of all replicate runs.

For particulate emissions, test-to-test variations for Modes 2 through 5 were within 3% of the mean. Mode 1 testing showed a greater deviation. The Mode 1 testing with the "aged" DPF especially exhibited elevated PM levels in the initial runs made (Test AUL-D2A, Mode 1 in Table 10 in Section 4.0). For completeness, a fourth test was run with the aged DPF to help assemble a more complete picture of the aged unit performance. All subsequent calculations include the data from all four test runs.

For NO_x emissions, the test-to-test variation for all modes was within 2% of the mean.

Figure 6 and Figure 7 present the exhaust back-pressure and engine temperature information graphically, using the arithmetic mean values of the replicate tests in each mode. There was typically less than 1% run-to-run variation in exhaust temperature, and less than 3% variation in exhaust back pressure.

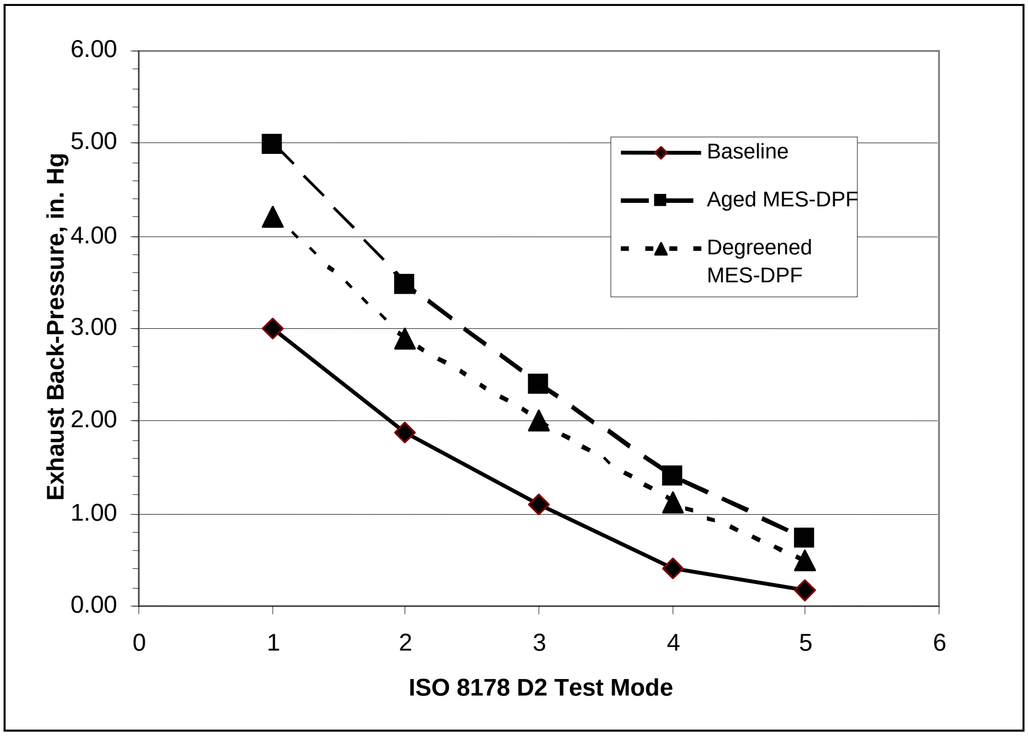

Figure 6. Exhaust back-pressure for each test mode, average of all replicates, for baseline and two exhaust configurations.

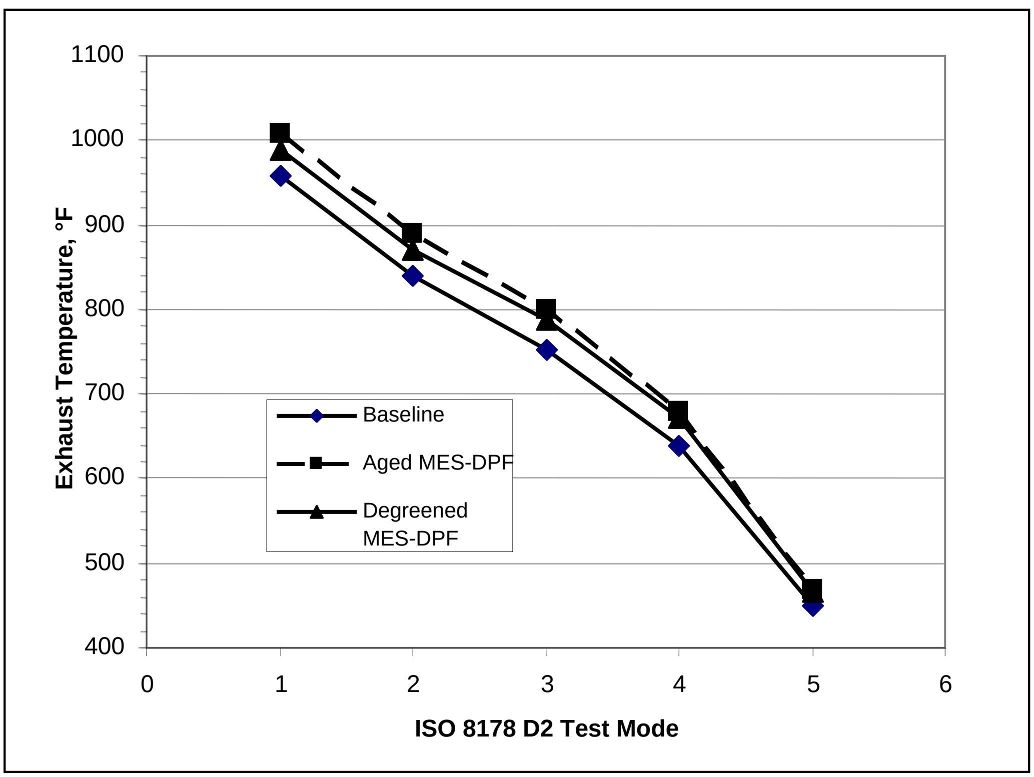

Figure 7. Exhaust temperature for each test mode, average of all replicates, for baseline and two exhaust configurations.

On the second test of each set of replicates of the three exhaust configurations, the particulate material was tested for soluble organic fraction (SOF). Table 5 reports the results. As mentioned above, during Mode 1 of the first run with the aged DPF in place, an unexpectedly high value for PM was noted. Related to this observation is the high SOF value that was obtained for Mode 1 of the second replicate. The SwRI test report notes that a possible reason for the elevated PM value could be sulfate release. Similarly, the high SOF value could be due to extraction of sulfate. On the fourth replicate test with the aged DPF unit, an additional SOF analysis was made during Mode 1 run. These results are shown in Table 5 for comparison.

Table 5. Particulate Characterization — SOF from Run 2 of Each Test

Test Description	Test Number	Mode	PM, g/h	SOF, % of PM
Baseline Without DPF (Run 2 of 3)	BUL-D2B	1	110.1	17
		2	69.7	16
		3	63.4	15
		4	56.7	33
		5	33.7	70
With Aged DPF Unit (Run 2 of 3)	AUL-D2B	1	89.8	49
		2	45.1	0
		3	40.1	2
		4	29.8	7
		5	12.2	44
(Run 4 of 4)	AUL-D2D	1	73.2	12
With Degreened DPF Unit (Run 2 of 3)	DUL-D2B	1	71.9	10
		2	45.5	2
		3	41.6	4
		4	33.2	9
		5	13.0	30

The fuel consumption was not measured explicitly during the engine testing. Rather, a calculated “carbon-balance” (C-B) fuel consumption rate was determined based on the measured exhaust flow rate and the carbon content (i.e., the CO and the CO_2) in the exhaust gas analysis. The individual per-mode, per-test values for fuel consumption were divided by the measured power (bhp from Work) during that mode, were weighted according to the weighting factors in Table 10 in Section 4.0 and were summed in order to calculate the weighted brake-specific fuel consumption (BSFC). The weighted BSFC calculations are similar to the weighted emissions calculations explained in Section 4.0. However, the composite emissions calculation includes the 5-mode test weighting factors applied to the power values in the denominator. The weighted BSFC calculations do not use the weighted denominator; the weighting factors only appear in the numerator. Table 6 summarizes the results of these calculations and compares the fuel consumption during the baseline runs with that measured during the tests with the MES-DPF units installed.

Table 6. Brake-Specific Fuel Consumption (by Carbon Balance)

Test Number	Test Date	Weighted BSFC		Change in BSFC Compared to Baseline	95% Confidence Limits on the BSFC % Change
		lb/bhp-hr	kg/kWh	%	%
BUL-D2A	7/26/2005	0.404	0.246		
BUL-D2B	7/26/2005	0.400	0.244		
BUL-D2C	7/26/2005	0.397	0.242		
Mean of 3 Baseline Runs		0.401	0.244		
AUL-D2A	7/27/2005	0.403	0.245		
AUL-D2B	7/27/2005	0.401	0.244		
AUL-D2C	7/27/2005	0.402	0.244		
AUL-D2D	7/28/2005	0.396	0.241		
Mean of 4 Aged Runs		0.401	0.244	0%	-1.7% - 1.7%
DUL-D2A	7/29/2005	0.405	0.246		
DUL-D2B	7/29/2005	0.405	0.247		
DUL-D2C	7/29/2005	0.404	0.246		
Mean of 3 Degreened Runs		0.405	0.246	-1.1%	-3.1% - 1.0%

Section 4.0
Summary and Discussion of Emission Results

Tables 7 through 9 report the emissions from all the tests that were conducted: baseline, with an aged MES-DPF installed, and with a degreened MES-DPF installed. The concentration measurements were converted to units of grams per hour for all species. The "bhp from Work" (the integrated measured power during each test period) values are also shown in these tables.

Table 7. Emissions Data from Baseline Tests

Test Number	Mode	PM	NO_x	NO	NO_2	NO_2/ NO_x	HC	CO	CO_2	bhp from Work
		g/h				%	g/h			
BUL-D2A	1	109.0	4074.0	3573.4	500.6	12.3	206.5	1069.4	239,949	472.2
	2	69.25	2318.2	2103.4	214.8	9.3	116.4	350.0	180,298	354.4
	3	63.15	1104.0	1009.9	94.1	8.5	68.0	183.4	126,262	235.8
	4	55.82	378.6	335.2	43.4	11.5	72.4	130.2	72,281	116.9
	5	34.11	667.0	602.9	64.1	9.6	37.2	115.5	38,167	47.1
BUL-D2B	1	110.1	4052.1	3520.4	531.7	13.1	192.5	1070.7	239,895	472.5
	2	69.66	2304.5	2102.8	201.7	8.8	104.0	332.8	180,211	354.5
	3	63.36	113.7	1022.5	91.2	8.2	71.5	172.0	125,715	236.4
	4	56.73	384.7	336.0	48.7	12.7	74.9	119.1	71,363	116.5
	5	33.66	657.6	591.2	66.4	10.1	39.3	109.5	37,494	47.3
BUL-D2C	1	115.8	4030.6	3535.1	495.5	12.3	208.3	1056.4	240,070	473.4
	2	72.01	2265.6	2048.6	217.0	9.6	112.6	334.4	178,654	353.5
	3	63.67	1104.5	998.5	106.0	9.6	76.0	178.1	124,893	237.0
	4	58.50	382.9	329.5	53.4	13.9	78.0	120.6	71,821	118.5
	5	32.07	661.3	585.8	75.5	11.4	39.2	110.0	37,039	47.0

Table 8. Emissions Data from "Aged" MES-DPF Unit Tests

Test Number	Mode	PM	NO_x	NO	NO_2	NO_2/ NO_x	HC	CO	CO_2	bhp from Work
		g/h				%	g/h			
AUL-D2A	1	139.1	3789.5	3442.8	346.7	9.1	*	65.0	243,883	476.1
	2	50.26	2206.5	1779.3	427.2	19.4	*	25.6	182,876	356.2
	3	40.86	1067.6	689.8	377.8	35.4	*	12.1	127,608	236.6
	4	30.55	374.5	145.5	229.0	61.1	*	3.9	73,896	118.9
	5	12.82	644.5	135.0	509.5	79.1	*	2.0	38,556	48.1
AUL-D2B	1	89.80	3861.5	3397.1	464.4	12.0	*	56.1	246,547	477.6
	2	45.07	2211.0	1698.9	512.1	23.2	*	18.3	184,455	357.5
	3	40.10	1073.4	671.8	401.6	37.4	*	12.1	127,744	238.6
	4	29.82	371.3	140.3	231.0	62.2	*	4.8	72,835	119.2
	5	12.24	648.4	146.1	502.3	77.5	*	2.1	38,837	48.1
AUL-D2C	1	74.61	3834.3	3288.8	545.5	14.2	*	58.6	245,749	479.0
	2	42.39	2267.2	1700.9	566.3	25.0	*	19.6	184,384	359.2
	3	39.92	1106.4	672.2	434.2	39.2	*	10.5	128,985	240.2
	4	30.36	393.3	145.3	248.0	63.1	*	5.1	74,183	120.7
	5	11.56	658.5	141.2	517.3	78.6	*	0.1	38,295	47.4
AUL-D2D	1	73.21	3849.9	3450.1	399.8	10.4	*	52.2	244,574	475.2
	2	42.26	2191.6	1679.6	512.0	23.4	*	17.1	183,577	356.3
	3	41.00	1069.2	666.4	402.8	37.7	*	6.3	125,862	237.6
	4	30.76	369.0	139.1	229.9	62.3	*	0.0	71,173	119.6
	5	11.18	637.6	134.6	503.0	78.9	*	0.0	37,662	47.5

*Not possible (within 95% confidence limits) to distinguish the exhaust gas hydrocarbon content from the background hydrocarbon content in the downstream dilution air.

Table 9. Emissions Data from "Degreened" MES-DPF Unit Tests

Test Number	Mode	PM	NO_x	NO	NO_2	NO_2/ NO_x	HC	CO	CO_2	bhp from Work
		g/h				%	g/h			
DUL-D2A	1	81.10	3,927.6	3,509.3	418.3	10.7	0.86	69.60	245,430	475.5
	2	46.74	2,197.2	1,664.7	532.5	24.2	*	22.60	183,642	356.4
	3	40.48	1,064.1	657.8	406.3	38.2	*	7.60	128,293	237.2
	4	32.54	365.1	147.7	217.4	59.5	*	2.60	73,901	118.6
	5	12.59	638.5	210.4	428.1	67.0	*	6.00	38,848	48.2
DUL-D2B	1	71.86	3,980.9	3,449.5	531.4	13.3	*	72.80	245,152	477.4
	2	45.50	2,263.2	1,673.2	590.0	26.1	*	22.00	183,089	356.5
	3	41.64	1,101.7	664.2	437.5	39.7	*	10.10	128,488	238.1
	4	33.19	376.5	149.2	227.3	60.4	*	4.40	74,432	118.6
	5	13.02	664.3	181.3	483.0	72.7	*	7.10	38,842	48.0
DUL-D2C	1	67.96	3,974.4	3,436.1	538.3	13.5	*	69.90	244,781	476.1
	2	44.75	2,244.9	1,660.8	584.1	26.0	*	20.10	184,093	357.5
	3	42.11	1,096.8	664.1	432.7	39.5	*	9.00	128,424	238.0
	4	32.80	383.5	152.5	231.0	60.2	*	4.30	74,189	119.4
	5	12.71	660.6	172.4	488.2	73.9	*	5.00	38,886	48.0

*Not possible (within 95% confidence limits) to distinguish the exhaust gas hydrocarbon content from the background hydrocarbon content in the downstream dilution air.

Results of this verification test were obtained by calculating a composite value of the emissions during each of the operating modes and normalizing these values across tests on a weighted power basis. The composite value E_{COMP} for nonroad tests is obtained from the multimode nonroad test following the weightings in Appendix B to Subpart E of 40 CFR Part 89[9] as appropriate for the intended nonroad use as shown in the equation below:

$$(E_{COMP})_i = \sum_{j=1}^{k} f_j \bullet E_{MODE_j}$$

where:

$(E_{COMP})_i$ = combined emissions rate for test i^{th} of n tests required at test point
f_j = mode weighting factor from 40 CFR 89, Subpart E, Appendix B for j^{th} mode
$E_{MODE\,j}$ = pollutant emissions rate during mode j
k = total number of modes for intended application (per 40 CFR 89).

Table 10 shows the weighting factors for the five modes that are used to calculate the composite emissions figures. To normalize the composite emissions values to a unit power basis, the composite emissions values are divided by a weighted power value (using the measured "bhp from Work" data) according to the following formula:[11]

$$E_{COMP} = \frac{\sum_{i=1}^{i=n} (WF_i \times E_i)}{\sum_{i=1}^{i=n} (WF_i \times P_i)}$$

where:

E_{COMP} = weighted composite emissions, g/bhp–hr
WF_i = weighting factor for mode i
E_i = emissions for mode i, g/hr
P_i = power for mode i, bph
n = number of nodes.

(Note that the weighted power factor in the denominator is not used when calculating the composite fuel consumption values.)

Table 10. Emissions and Power Weighting Factors for FTP 5-Mode Test Cycle (ISO 8178 D2) Composite Calculations

Test Mode	Torque (%)	Speed (rpm)	Emissions Weighting Factor (%)
1	100	1800	5
2	75	1800	25
3	50	1800	30
4	25	1800	30
5	10	1800	10

Applying the emissions weighting factors to the measured emissions in each mode of each test run, and then normalizing to a weighted power basis, produces the composite emissions values shown in Tables 11 and 12 below. The tables also show the arithmetic mean of the replicate runs.

Table 11. Composite Weighted Emission Values (U.S. Common Units)

Test Number	Test Date	PM	NO_x	NO	NO_2	NO_2/NO_x	HC	CO	CO_2
		g/bhp-hr				%	g/bhp-hr		
Baseline									
BUL-D2A	7/26/05	0.278	5.81	5.25	0.567	9.8	0.383	1.11	541
BUL-D2B	7/26/05	0.280	5.81	5.24	0.564	9.7	0.374	1.05	538
BUL-D2C	7/26/05	0.285	5.73	5.13	0.602	10.5	0.397	1.06	534
Mean of 3 Baseline Runs		0.281	5.78	5.21	0.578	10.0	0.385	1.07	538
Aged MES-DPF									
AUL-D2A	7/27/05	0.188	5.52	3.93	1.592	28.8	*	0.065	545
AUL-D2B	7/27/05	0.168	5.52	3.78	1.736	31.4	*	0.056	543
AUL-D2C	7/27/05	0.162	5.62	3.74	1.875	33.4	*	0.055	543
AUL-D2D	7/28/05	0.164	5.50	3.77	1.727	31.4	*	0.039	538
Mean of 4 Aged Runs		0.171	5.54	3.81	1.732	31.3	*	0.054	542
Degreened MES-DPF									
DUL-D2A	7/29/05	0.173	5.52	3.81	1.711	31.0	*	0.057	547
DUL-D2B	7/29/05	0.172	5.67	3.79	1.876	33.1	*	0.063	546
DUL-D2C	7/29/05	0.170	5.64	3.77	1.869	33.1	*	0.058	546
Mean of 3 Degreened Runs		0.172	5.61	3.79	1.819	32.4	*	0.059	546

*Not possible (within 95% confidence limits) to distinguish the exhaust gas hydrocarbon content from the background hydrocarbon content in the downstream dilution air.

Table 12. Composite Weighted Emission Values (Metric Units)

Test Number	Test Date	PM	NO_x	NO	NO_2	NO_2/NO_x	HC	CO	CO_2
		g/kWh				%	g/kWh		
Baseline									
BUL-D2A	7/26/05	0.372	7.79	7.03	0.761	9.8	0.513	1.48	725
BUL-D2B	7/26/05	0.375	7.78	7.03	0.756	9.7	0.502	1.41	721
BUL-D2C	7/26/05	0.382	7.68	6.88	0.806	10.5	0.532	1.42	716
Mean of 3 Baseline Runs		0.376	7.75	6.98	0.774	10.0	0.516	1.44	721
Aged MES-DPF									
AUL-D2A	7/27/05	0.253	7.40	5.27	2.13	28.8	*	0.088	730
AUL-D2B	7/27/05	0.226	7.40	5.07	2.33	31.4	*	0.075	728
AUL-D2C	7/27/05	0.218	7.53	5.02	2.51	33.4	*	0.074	728
AUL-D2D	7/28/05	0.220	7.37	5.05	2.31	31.4	*	0.052	722
Mean of 4 Aged Runs		0.229	7.43	5.10	2.32	31.3	*	0.072	727
Degreened MES-DPF									
DUL-D2A	7/29/05	0.232	7.40	5.10	2.29	31.0	*	0.076	733
DUL-D2B	7/29/05	0.231	7.60	5.09	2.52	33.1	*	0.085	732
DUL-D2C	7/29/05	0.228	7.56	5.06	2.51	33.1	*	0.077	732
Mean of 3 Degreened Runs		0.230	7.52	5.08	2.44	32.4	*	0.080	732

*Not possible (within 95% confidence limits) to distinguish the exhaust gas hydrocarbon content from the background hydrocarbon content in the downstream dilution air.

The mean composite weighted emission values from Tables 11 and 12 are the key values for the verification test. Table 13 summarizes that information. The first line shows the baseline engine results; the emissions in all categories are below the Table 3 threshold.

Table 13. Summary of Verification Test Data

Device type	Mean Composite Weighted Emission Value, g/kWh (g/bhp-hr)				
	PM	NO_x	HC	CO	CO_2
Baseline	0.376 (0.281)	7.75 (5.78)	0.516 (0.385)	1.44 (1.07)	721 (538)
Aged	0.229 (0.171)	7.43 (5.54)	*	0.072 (0.054)	727 (542)
Degreened	0.230 (0.172)	7.52 (5.61)	*	0.080 (0.059)	732 (546)

*Not possible (within 95% confidence limits) to distinguish the exhaust gas hydrocarbon content from the background hydrocarbon content in the downstream dilution air.

Table 14 summarizes the emissions reductions that were achieved by the use of the MES-DPF. These are the "verified emissions reductions" reported in Table 2 of the ETV Joint Verification Statement.

Table 14. Summary of Verification Test Emission Reductions

Device type	Mean Emissions Reduction (%)				95% Confidence Limits on the Emissions Reduction (%)			
	PM	NO_x	HC	CO	PM	NO_x	HC	CO
Aged	39.2	4.2	*	95.0	35-43	2.4-6.0	*	88-100
Degreened	38.8	3.0	*	94.5	35-42	0.1-5.9	*	88-100

*Hydrocarbon emission reductions were near 100% but the value could not be quantified with 95% confidence.

4.1 Quality Assurance

The environmental technology verification of the MES DPF with ULSD fuel for heavy-duty constant-speed nonroad diesel engines was performed in accordance with the approved test/QA plan and the test-specific addendum.[2] An audit of data quality included the review of equipment, personnel qualifications, procedures, record keeping, data validation, analysis, and reporting. Preliminary, in-process, and final inspections, and a review of 10% of the data showed that the requirements stipulated in the test/QA plan[5] were achieved. The SwRI, APCT Center, and EPA Quality Managers reviewed the test results and the QC data and concluded that the data quality objectives given in the generic verification protocol were attained. EPA and RTI QA staff conducted audits of SwRI's technical and quality systems in April 2002 and found no deficiencies that would adversely impact the quality of results. The equipment was appropriate for the verification testing, and it was operating satisfactorily. SwRI's technical staff was well qualified to perform the testing and conducted themselves in a professional manner.

Section 5.0
References

1. RTI International. 2002. *Generic Verification Protocol for Diesel Exhaust Catalysts, Particulate Filters, and Engine Modification Control Technologies for Highway and Nonroad Use Diesel Engines*. Research Triangle Park, NC, January. Available: http://www.epa.gov/etv/pdfs/vp/05_vp_devrev.pdf

2. RTI International. 2005. *Test-Specific Addendum to ETV Mobile Source Test/QA Plan for Paceco Corp. for the MES-Diesel Particulate Filter*. Research Triangle Park, NC, April 20.

3. Southwest Research Institute. 2005. *Environmental Technology Verification of Mitsui Engineering & Shipbuilding Diesel Particulate Filter (MES-DPF).* Final Report. San Antonio, TX, August.

4. Southwest Research Institute. 2005. *Audit of Data Quality for Environmental Technology Verification of Mitsui Engineering & Shipbuilding Diesel Particulate Filter (MES-DPF).* San Antonio, TX, August.

5. RTI International. 2002. *Test/QA Plan for the Verification Testing of Diesel Exhaust Catalysts, Particulate Filters, and Engine Modification Control Technologies for Highway and Nonroad Use Diesel Engines*. Research Triangle Park, NC, April. Available: http://www.epa.gov/etv/pdfs/vp/05_tp_diesel.pdf.

6. 40 CFR, Part 86 (Protection of Environment: Control of Emissions from New and In-Use Highway Vehicles and Engines), Subpart N.

7. 40 CFR §86.1313-2007 (Protection of Environment: Control of Emissions from New and In-Use Highway Vehicles and Engines, Fuel Specifications), Table N07-2. Available: http://www.epa.gov/epahome/cfr40.htm (updated July 27, 2005).

8. 40 CFR Part 89 (Protection of Environment: Control of Emissions from New and In-Use Nonroad Compression-Ignition Engines), Subparts D and E. Available: http://www.epa.gov/epahome/cfr40.htm (updated July 21, 2005).

9. 40 CFR Part 89, (Protection of Environment: Control of Emissions from New and In-Use Nonroad Compression-Ignition Engines), Subpart E, Appendix B, Table 2 – 5-Mode Test Cycle for Constant-Speed Engines.

10. RTI International. 2003. *Generic Verification Protocol for Determination of Emissions Reductions from Selective Catalytic Reduction Control Technologies for Highway, Nonroad, and Stationary Use Diesel Engines*. Research Triangle Park, NC, September. Available: http://www.epa.gov/etv/pdfs/vp/05_vp_emissions.pdf.

11. 40 CFR §89.424 (a) (Protection of Environment: Control of Emissions from New and In-Use Nonroad Compression-Ignition Engines), Dilute Emissions Sampling Calculations.