

# Environmental Technology Verification

## Test Report of Mobile Source Emission Control Devices

Johnson Matthey

PCRT2<sup>®</sup> 1000, Version 2, Filter + Diesel Oxidation Catalyst

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

<b>TECHNOLOGY TYPE:</b>	<b>MOBILE DIESEL ENGINE AIR POLLUTION CONTROL</b>
<b>APPLICATION:</b>	<b>CONTROL OF EMISSIONS FROM MOBILE DIESEL ENGINES IN HIGHWAY USE BY DIESEL OXIDATION CATALYSTS AND DIESEL PARTICULATE FILTERS</b>
<b>TECHNOLOGY NAME:</b>	<b>PCRT2<sup>®</sup> 1000, VERSION 2, FILTER + DIESEL OXIDATION CATALYST</b>
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The U.S. Environmental Protection Agency (EPA) 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. The ETV Program 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.

The ETV Program works in partnership with recognized standards and testing organizations; stakeholder groups, which consist of buyers, vendor organizations, permittees, 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<sup>1</sup> in cooperation with EPA's National Risk Management Research

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<sup>1</sup> RTI International is a trade name of Research Triangle Institute.

Laboratory. The APCT Center has evaluated the performance of an emission control system consisting of a flow-through partial filter combined with a diesel oxidation catalyst (DOC).

## 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 Johnson Matthey for the PCRT2<sup>®</sup> 1000, V.2 System*. These documents are written in accordance with the applicable generic verification protocol and include requirements for quality management and QA, procedures for product selection and auditing of the test laboratories, and the test reporting format.

The mobile diesel engine air pollution control technology was tested August 2008 at Southwest Research Institute. The performance verified was the percentage of emissions reduction achieved by the technology for particulate matter (PM), nitrogen oxides (NO<sub>x</sub>), 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	Highway Transient Federal Test Procedure (FTP)
Engine family	YCEXH0661MAH
Engine make–model year	Cummins – 2000 ISM350 ESP
Service class	Highway, heavy-duty diesel engine
Engine rated power	350 hp at 1800 rpm
Engine displacement	10.8 L, inline six cylinder
Technology	Johnson Matthey PCRT2 <sup>®</sup> 1000, v.2
Technology description	Flow-through partial filter combined with a DOC
Test cycle or mode description	One cold-start and multiple hot-start tests according to FTP test for baseline engine, degreased, and aged systems
Test fuel description	Ultra–low-sulfur diesel fuel with 15 ppm sulfur maximum
Critical measurements	PM, NO <sub>x</sub> , HC, and CO
Ancillary measurements	CO <sub>2</sub> , NO, NO <sub>2</sub> (by calculation), soluble organic fraction of PM, exhaust backpressure, exhaust temperature, and fuel consumption

hp = horsepower, rpm = revolutions per minute, CO<sub>2</sub> = carbon dioxide, NO = nitric oxide, NO<sub>2</sub> = nitrogen dioxide

## VERIFIED TECHNOLOGY DESCRIPTION

The Johnson Matthey PCRT2<sup>®</sup> 1000, v.2 system is a partial continuously regenerating technology (PCRT) system that consists of a flow-through partial filter combined with a DOC. The system is designed for low temperature exhaust resulting from intermittent loads from medium and heavy heavy-duty diesel on-highway non-urban bus engines. This verification statement describes the performance of the tested technology on the diesel engine and fuels identified in Table 1, and applies only to the use of the Johnson Matthey PCRT2<sup>®</sup> 1000, v.2 system on highway engines fueled by ultra–low-sulfur diesel (ULSD) (15 ppm or less) fuel.

## VERIFICATION OF PERFORMANCE

The Johnson Matthey PCRT2<sup>®</sup> 1000, v.2 system achieved the reduction in tailpipe emissions shown in **Table 2**

compared to baseline operation without the system.

**Table 2. Verified Emissions Reductions**

Device Type	Fuel	Mean Emissions Reduction (%)				95% Confidence Limits on the Emissions Reduction (%)			
		PM	NO <sub>x</sub>	HC	CO	PM	NO <sub>x</sub>	HC	CO
Degreened	ULSD	55	0.99	96	74	37 to 73	- <sup>a</sup>	- <sup>b</sup>	73–75
Aged	ULSD	43	-0.24	92	68	26 to 61	- <sup>a</sup>	86–97	66–69

<sup>a</sup> The emissions reduction could not be distinguished from zero with 95% confidence.

<sup>b</sup> The emissions reduction could not be quantified or distinguished from 100% with 95% confidence.

The APCT Center quality manager 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. APCT Center QA staff have conducted technical assessments of the test laboratory procedures 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 *Johnson Matthey PCRT2<sup>®</sup> 1000, v.2 system* 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 *Johnson Matthey PCRT2<sup>®</sup> 1000, v.2 system* within the range of applicability of the statement.

signed by Sally Gutierrez      03/20/09  
 Sally Gutierrez      Date  
 Director  
 National Risk Management Research Laboratory  
 Office of Research and Development  
 United States Environmental Protection Agency

signed by Jenia Tufts      03/13/09  
 Jenia Tufts      Date  
 Director  
 APCT Center  
 RTI International

**NOTICE:** ETV verifications are based on an evaluation of technology performance under specific, predetermined criteria and the appropriate quality assurance procedures. EPA and RTI make no express or implied warranties as to the performance of the technology and do not certify that a technology will always operate as verified. The end user is solely responsible for complying with any and all applicable federal, state, and local requirements. Mention of commercial product names does not imply endorsement.

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# Environmental Technology Verification Report

## Mobile Source Emission Control Devices

Johnson Matthey Plc  
PCRT2<sup>®</sup> 1000, Version 2  
Flow-Through Partial Filter and  
Metal Diesel Oxidation Catalyst

Prepared by

RTI International  
Southwest Research Institute

EPA Cooperative Agreement No. CR831911-01-1

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May 2009

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### **Notice**

This document was prepared by RTI International (RTI) and its subcontractor, Southwest Research Institute, with partial funding from Cooperative Agreement No. CR831911-01-1 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 permittees an independent, credible assessment of the technology they are buying or permitting.

The Air Pollution Control Technology Verification Center (APCT Center) is part of EPA's ETV Program and is operated as a partnership between RTI International (RTI) and EPA. The APCT 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 APCT 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 Johnson Matthey PCRT2<sup>®</sup> 1000, v.2 system, comprising a flow-through partial filter and diesel oxidation catalyst. ETV testing of this technology was conducted in August 2008 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 the following:

- 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/nrmrl/std/etv/vt-apc.html#msd> (pdf format)  
  
                  <http://www.epa.gov/ncepihom/>



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### **Acronyms/Abbreviations**

°C	degrees Celsius
°F	degrees Fahrenheit
APCT Center	Air Pollution Control Technology Verification Center
ASTM	American Society for Testing and Materials
bhp	brake horsepower
bhp-hr	brake horsepower-hour
BSFC	brake-specific fuel consumption
CFR	Code of Federal Regulations
cm	centimeter(s)
CO	carbon monoxide
CO <sub>2</sub>	carbon dioxide
DOC	diesel oxidation catalyst
DPF	diesel particulate filter
EPA	U.S. Environmental Protection Agency
ETV	environmental technology verification
g	gram(s)
g/hp-hr	grams per horsepower-hour
HC	hydrocarbon(s)
hp	horsepower
in.	inch(es)
in. Hg	inch(es) mercury
kg/kWh	kilograms per kilowatt-hour
kPa	kilopascals
kW	kilowatt(s)

kWh	kilowatt hour(s)
L	liter(s)
lb	pound(s)
lb-ft	pound foot (feet)
NO	nitric oxide
NO <sub>2</sub>	nitrogen dioxide
NO <sub>x</sub>	nitrogen oxides
PM	particulate matter
ppm	parts per million
QA	quality assurance
QC	quality control
rpm	revolutions per minute
RTI	RTI International
SOF	soluble organic fraction
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 officer, and Paul Groff, quality manager, both of the U.S. Environmental Protection Agency's National Risk Management Research Laboratory in Research Triangle Park, NC. We would also like to acknowledge the assistance and participation of all Johnson Matthey personnel who supported the test effort.

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

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## 1.0 INTRODUCTION

This report reviews the performance of the Johnson Matthey PCRT2<sup>®</sup> 1000, v.2 system, comprising a flow-through partial filter and a diesel oxidation catalyst (DOC) submitted for testing by Johnson Matthey Plc. Environmental technology verification (ETV) testing of this technology was conducted during a series of tests in August 2008 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) 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 the APCT Center 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*<sup>1</sup> was developed. This protocol was chosen as the best guide to verify the immediate performance effects of the PCRT2<sup>®</sup> 1000, v.2 system. To determine these effects, emissions results from a heavy-duty highway diesel engine were compared to emissions results obtained operating the same engine with the same fuel, but with the PCRT2<sup>®</sup> 1000, v.2 technology installed. The specific test/quality assurance (QA) plan addendum for the ETV test of the technology submitted by Johnson Matthey was developed and approved in April 2008.<sup>2</sup> The goal of the test was to measure the emissions control performance of the PCRT2<sup>®</sup> 1000, v.2 system and its emissions reduction relative to an uncontrolled engine.

A description of the technology is presented in Section 2.0. Section 3.0 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 4.0, and references are presented in Section 5.0.

This report contains only summary data and the verification statement. Complete documentation of the test results is provided in a separate test report<sup>3</sup> and audit of data quality report.<sup>4</sup> 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 only to the use of the PCRT2<sup>®</sup> 1000, v.2 system on highway engines. It is applicable to engines fueled only by ultra-low-sulfur diesel (ULSD) (15 ppm or less) fuel.

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\* RTI International is a trade name of Research Triangle Institute.

## 2.0 PRODUCT DESCRIPTION

The Johnson Matthey PCRT2® 1000, v.2 system, shown installed in **Figure 1**, is a partial continuously regenerating technology (PCRT) system that consists of a flow-through partial filter combined with a DOC. Exhaust gases are routed through the oxidation catalyst and then processed through a particulate matter (PM) filter to achieve emissions reductions. The system is designed for low temperature exhaust resulting from intermittent loads from medium and heavy heavy-duty diesel on-highway non-urban bus engines. This verification statement describes the performance of the tested technology on the diesel engine and fuels identified in Table 1, and applies only to the use of the Johnson Matthey PCRT2® 1000, v.2 system on highway engines fueled by ultra-low-sulfur diesel (ULSD) (15 ppm or less) fuel.

Johnson Matthey provided a new PCRT2® 1000, v.2 unit that had never been used before. The DOC had serial number C269057, and the filter had serial number PFT0138. The unit had a February 2006 date of manufacture. The unit was preconditioned in accordance with the requirements in Title 13, California Code of Regulations, Section 2706(a)(4) for a total of 28 hours.

Johnson Matthey provided an “aged” PCRT2® 1000, v.2 unit that had seen 1,503 hours of service on a 1988 Caterpillar 3208T engine installed in a 1989 Expedito truck. This unit had a June 2006 date of manufacture, the DOC had serial number C6110188-8, and the filter had serial number PFT0079.

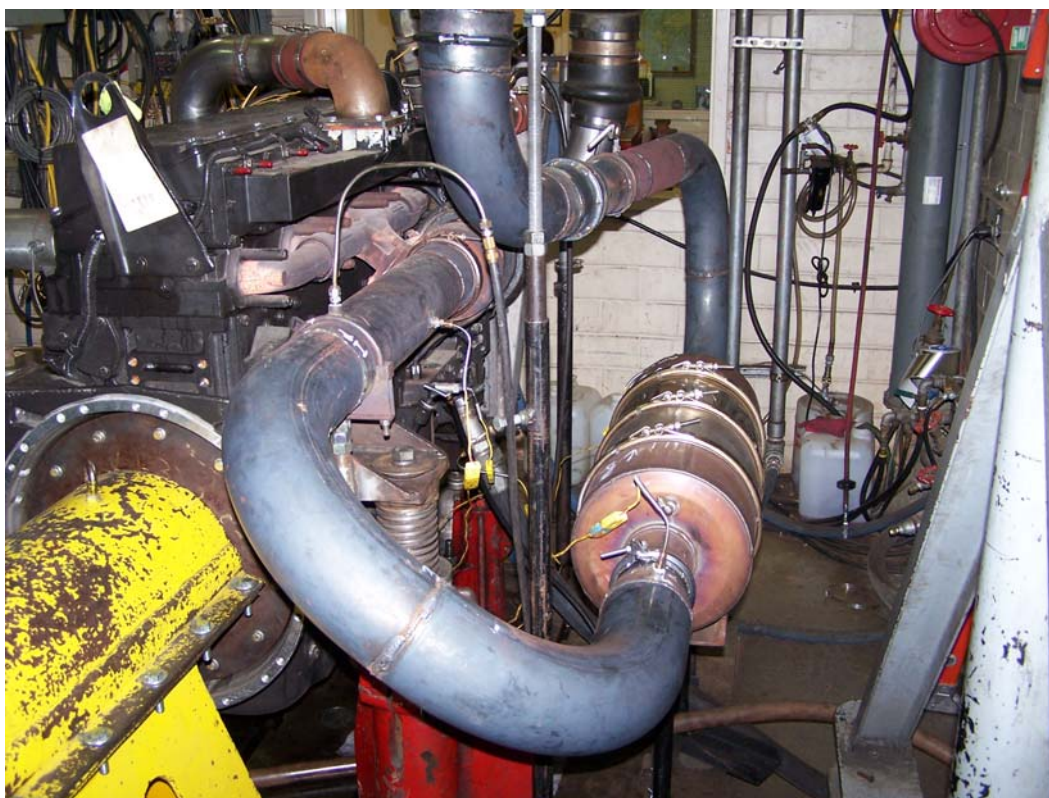


Figure 1. The PCRT2® 1000, v.2 system installed for emissions tests.

### 3.0 TEST DOCUMENTATION

The ETV testing took place during August 2008 at SwRI under contract to the APCT Center. Testing was performed in accordance with the following:

- *Generic Verification Protocol for Diesel Exhaust Catalysts, Particulate Filters, and Engine Modification Control Technologies for Highway and Nonroad Use Diesel Engines*<sup>1</sup>
- *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*<sup>5</sup>
- *Test-Specific Addendum to ETV Mobile Source Test/QA Plan for Johnson Matthey for the PCRT2<sup>®</sup> 1000, V.2 System.*<sup>2</sup>

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

The ETV testing was performed on a six-cylinder, 10.8 L, 2000 model year Cummins ISM350 highway heavy heavy-duty diesel engine (SN: 35010881) borrowed from EPA. The nameplate rating of this model engine is 260 kW [350 brake horsepower (bhp)] in “prime” power service at 1,800 revolutions per minute (rpm). The test engine had about 215 hours of operation accumulated on it before arriving at SwRI.

**Table 1** provides the engine identification details, and **Figure 2** shows the identification plates from the engine and its electronic control module.

**Table 1. Engine Identification Information**

Engine serial number	35010881
Date of manufacture	June 2000
Make	Cummins
Model year	2000
Model	ISM350 ESP
Engine displacement and configuration	10.8 L, inline six cylinder
Service class	Highway heavy heavy-duty diesel engine
EPA engine family identification	YCEXH0661MAH
Certification standards (g/hp-hr)	HC 1.30/CO 15.50/NO <sub>x</sub> 4.00/PM 0.100
Rated power (nameplate)	350 hp at 1800 rpm
Rated torque (nameplate)	1350 lb-ft at 1200 rpm
Certified emission control system	Typical exhaust
Aspiration	Turbo charged
Fuel system	Electronically controlled fuel injection

HC = hydrocarbons, hp = horsepower





Figure 2. Identification labels for 2000 Cummins ISM350 engine and its electronic control module.

### 3.1 Engine Fuel Description

All emissions testing was conducted with ULSD fuel meeting the 40 CFR 86.1313-2007 specification for emissions certified fuel.<sup>6</sup> Selected fuel properties from the supplier's analyses are summarized in **Table 2**. All testing was conducted using fuel from a single batch, identified as EM-6539-F.

**Table 2. Selected Fuel Properties and Specifications**

Item	Code of Federal Regulations (CFR) Specification <sup>a</sup>		Test Fuel
	ASTM	Type 2D	EM-6539-F
Cetane number	D613	40–50	43.9
Cetane index	D976	40–50	n/a <sup>b</sup>
Distillation range:			
Initial boiling point, °C (°F)	D86	171–204 (340–400)	176 (348)
10% Point, °C (°F)	D86	204–238 (400–460)	219 (427)
50% Point, °C (°F)	D86	243–282 (470–540)	267 (513)
90% Point, °C (°F)	D86	293–332 (560–630)	317 (603)
End point, °C (°F)	D86	321–366 (610–690)	347 (657)
Gravity (American Petroleum Institute)	D287	32–37	33.7 <sup>c</sup>
Specific gravity	D4052	0.865–0.840	0.857 <sup>c</sup>
Total sulfur, ppm	D2622	7–15	8 <sup>d</sup>
Hydrocarbon composition:			
Aromatics (minimum), %	D5186	27	30.3 <sup>e</sup>
Olefins, saturates %	D5186	NA <sup>f</sup>	69.7 <sup>e</sup>
Flash point (minimum), °C (°F)	D93	54 (130)	66 (151)
Viscosity, centistokes at 40°C	D445	2.0–3.2	2.9

<sup>a</sup> 40 CFR 86.1313-2007(b)(2) for the year 2007 and beyond for heavy-duty diesel engines<sup>6</sup>

<sup>b</sup> n/a=not applicable

<sup>c</sup> Measured per American Society for Testing and Materials (ASTM) D4052

<sup>d</sup> Measured per ASTM D5453; this method is an acceptable substitute for ASTM D2622

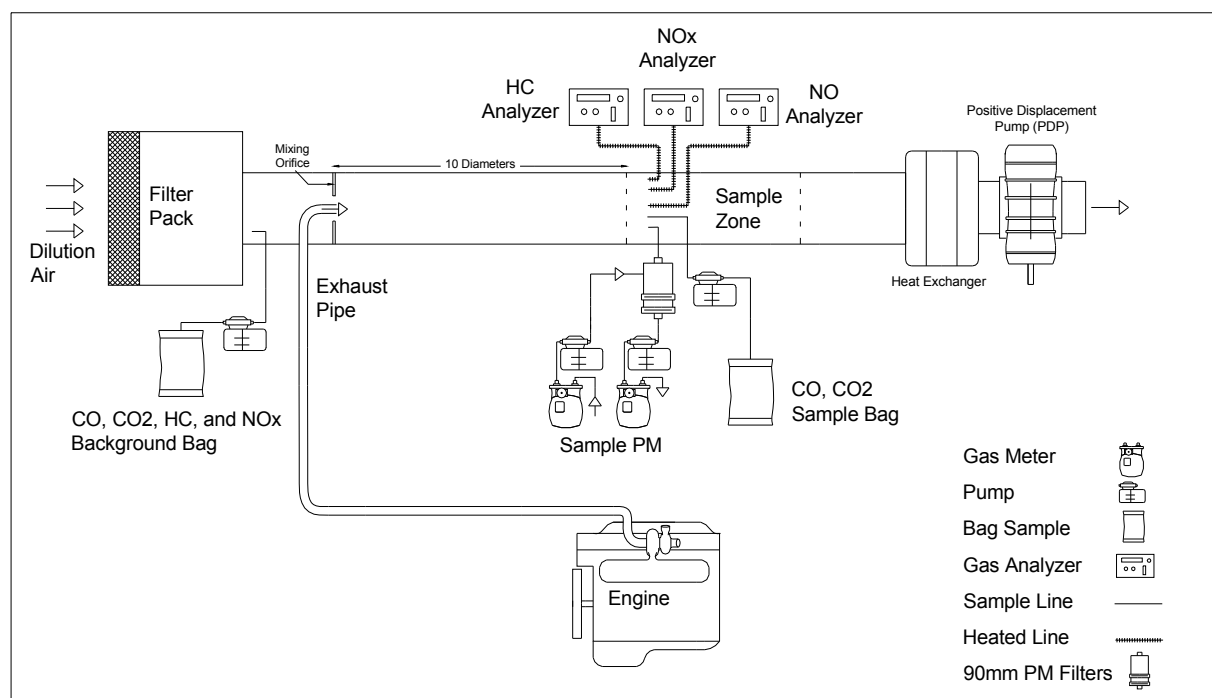
<sup>e</sup> Measured per ASTM D1319

<sup>f</sup> Remainder of the hydrocarbons

### 3.2 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 40 CFR, Part 86, Subpart N.<sup>7</sup> Emissions were measured over triplicate runs of the highway transient test cycle for the baseline, degreened diesel particulate filter (DPF), and aged DPF exhaust configurations.

The 2000 Cummins ISM350 engine was operated in an engine dynamometer test cell, with exhaust sampled using full-flow dilution constant volume sampling techniques to measure regulated emissions of hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO<sub>x</sub>), and PM, plus nitric oxide (NO). The nitrogen dioxide (NO<sub>2</sub>) levels are expressed as the difference between measured NO<sub>x</sub> 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 40 CFR, Part 86.<sup>7</sup>



**Figure 3. Schematic of emissions sampling system at SwRI.**

The verification protocol requires that the emissions from engines used for verification testing must not exceed 110% of the certification standards for that engine category.<sup>8</sup> For 1998–2003 nonurban bus engines, the certification standards are defined in EPA’s on-highway engine family box OH-10.<sup>8</sup> Furthermore, the Office of Transportation and Air Quality assumes 5% reduction in PM emissions due to the use of ULSD fuel.

Therefore, 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 110% of OH-10 ( $1.1 \times \text{OH-10}$ ) for HC, CO, and  $\text{NO}_x$ , and also could not exceed 110% of  $[(\text{OH-10})-5\%]$ , or  $(1.045 \times \text{OH-10})$  for PM. **Table 3** presents the required emissions performance of the test engine, as well as the certification standards and baseline results for comparison.

**Table 3. Test Engine Baseline Emissions Requirement for 2000 Cummins ISM350**

	HC		CO		$\text{NO}_x$		PM	
	g/kWh	g/hp-hr	g/kWh	g/hp-hr	g/kWh	g/hp-hr	g/kWh	g/hp-hr
OH-10	1.74	1.30 <sup>a</sup>	20.79	15.50 <sup>a</sup>	5.36	4.00 <sup>a</sup>	0.130	0.100 <sup>a</sup>
Acceptance criteria	1.92	1.43	22.86	17.05	5.90	4.40	0.140	0.105
Baseline results	0.39	0.29	1.414	1.055	5.41	4.03	0.116	0.087

<sup>a</sup> Certification standards for EPA highway engine family box OH-10 for 1998–2003 nonurban bus engines

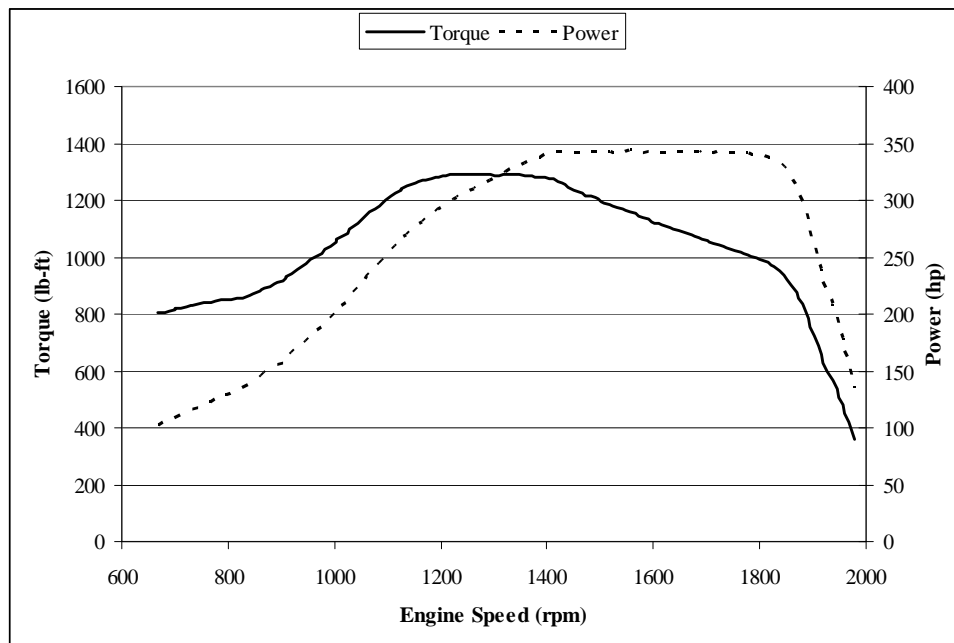
### 3.3 Deviations from the Test/QA Plan

There were no deviations from the test/QA plan.

### 3.4 Documented Test Conditions

#### Engine Performance

**Figure 4** shows torque map information measured on the 2000 Cummins ISM350 engine using the ULSD fuel.



**Figure 4. Torque map of 2000 Cummins ISM350 engine using ULSD fuel.**

#### Engine Exhaust Backpressure and Exhaust Temperature

The engine backpressure for the 2000 Cummins ISM350 engine was set in accordance with the engine manufacturer's specifications of 2.4" Hg for the baseline configuration. The backpressure was adjusted to the same specification after installation of the degreened and aged devices. Maximum exhaust backpressure levels for transient Federal Test Procedure tests on the PCRT2<sup>®</sup> 1000, v.2 systems are given in **Table 4**. The degreened and aged PCRT2<sup>®</sup> 1000, v.2 systems significantly increased exhaust backpressure over the transient test cycle, exceeding the manufacturer's maximum specification of 3" Hg. Higher exhaust backpressure levels were noted from the engine power validation data.

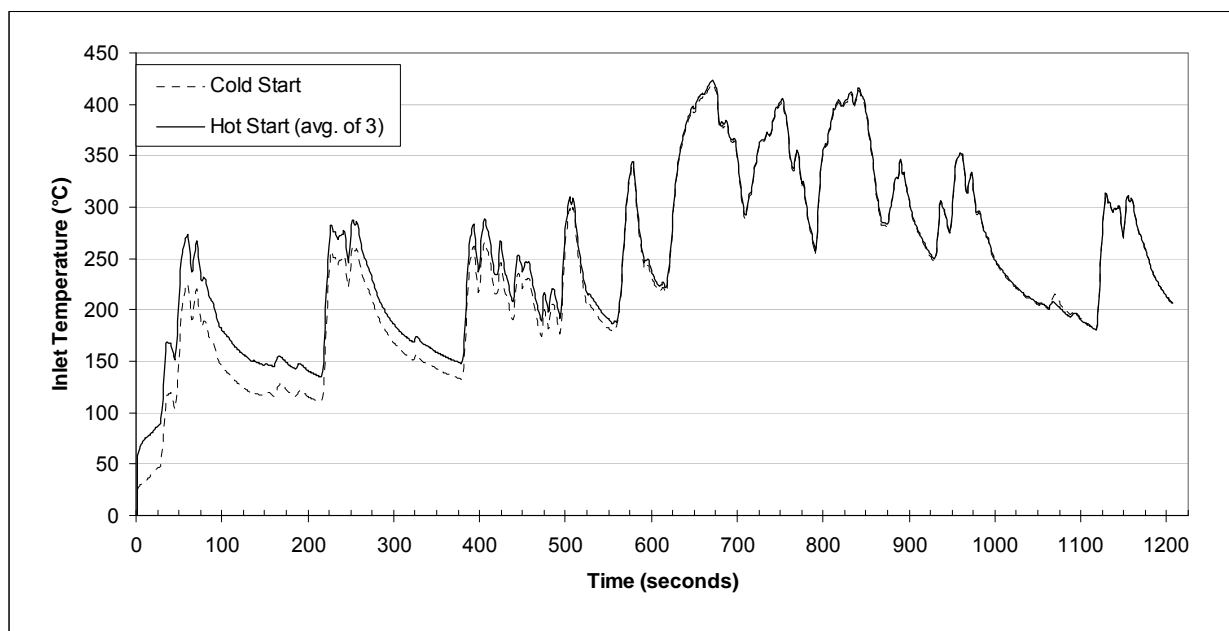
Temperature measurements were made in the exhaust system of the Cummins engine at the inlet and outlet of the DOC within 1 in. (2.54 cm) of the flange openings. Average inlet and outlet temperatures over the transient test cycle, shown in Table 4, were 483°F (251°C) and 552°F (289°C), respectively.

**Table 4. Engine Exhaust Backpressure and Average Device Inlet/Outlet Temperature**

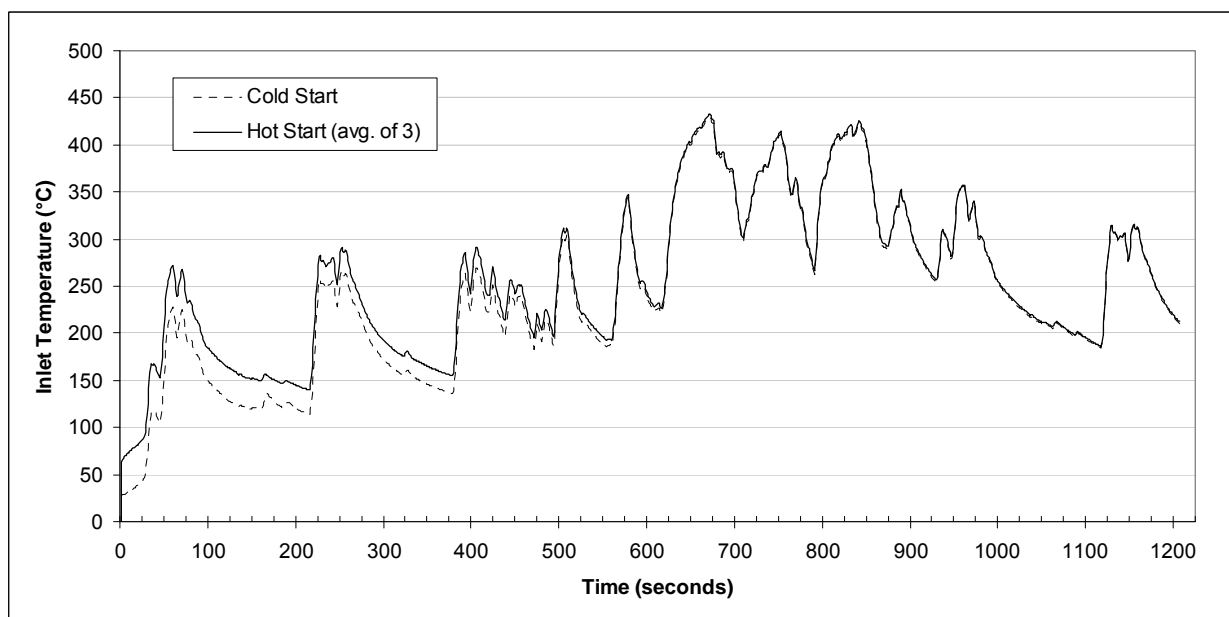
Test Number	Test Type	Test Date	Maximum Exhaust Backpressure <sup>a</sup>		Average DOC Inlet Temperature		Average DOC Exhaust Temperature	
			kPa	in. Hg	°C	°F	°C	°F
Baseline with ULSD Fuel on a 2000 Cummins ISM350 Engine								
BASE-C1	Cold Start	08/07/08	8.2	2.42	Not measured (no device in place)			
BASE-H1	Hot Start	08/07/08	8.4	2.49				
BASE-H2	Hot Start	08/07/08	8.5	2.50				
BASE-H3	Hot Start	08/07/08	8.5	2.50				
Average		8.4	2.48					
Degreened PCRT2 <sup>®</sup> 1000, V.2 System with ULSD Fuel on a 2000 Cummins ISM350 Engine								
0138-C1	Cold Start	08/08/08	14.4	4.24	238.6	461.5	265.8	510.5
0138-H1	Hot Start	08/08/08	14.7	4.34	250.4	482.6	292.4	558.3
0138-H2	Hot Start	08/08/08	14.9	4.41	250.7	483.3	293.4	560.2
0138-H3	Hot Start	08/08/08	15.0	4.43	251.7	485.1	294.9	562.8
Average		14.8	4.36	247.9	478.1	286.6	548.0	
Aged PCRT2 <sup>®</sup> 1000, V.2 System with ULSD Fuel on a 2000 Cummins ISM350 Engine								
0079-C2	Cold Start	08/14/08	17.0	5.01	243.8	470.9	271.9	521.4
0079-H4	Hot Start	08/14/08	17.4	5.13	255.7	492.3	296.9	566.5
0079-H5	Hot Start	08/14/08	17.6	5.20	256.4	493.4	298.2	568.7
0079-H6	Hot Start	08/14/08	17.7	5.24	256.8	494.2	298.8	569.8
Average		17.4	5.15	253.2	487.7	291.5	556.6	

<sup>a</sup> Exhaust backpressure set with exhaust stack damper for baseline tests

**Figure 5** shows the inlet temperature over time for the degreened device, and **Figure 6** shows the inlet temperature over time for the aged device. In both figures, the hot-start profile is the average of the three hot-start tests.



**Figure 5. Inlet temperature profile of degreened PCRT2® 1000, v.2 system.**



**Figure 6. Inlet temperature profile of aged PCRT2® 1000, v.2 system.**

### Soluble Organic Fraction

On each test, the particulate material was tested for soluble organic fraction (SOF). **Table 5** reports the results.

**Table 5. Particulate Characterization—Soluble Organic Fraction from Each Test**

Test Number	Test Type	PM	
		g	% SOF
Baseline with ULSD Fuel on a 2000 Cummins ISM350 Engine			
BASE-C1	Cold Start	1.83	34.0
BASE-H1	Hot Start	2.02	30.0
BASE-H2	Hot Start	2.03	28.0
BASE-H3	Hot Start	2.33	24.0
Degreened PCRT2® 1000, V.2 System with ULSD Fuel on a 2000 Cummins ISM350 Engine			
0138-C1	Cold Start	0.793	15.0
0138-H1	Hot Start	0.881	15.0
0138-H2	Hot Start	0.956	12.0
0138-H3	Hot Start	1.01	2.00
Aged PCRT2® 1000, V.2 System with ULSD Fuel on a 2000 Cummins ISM350 Engine			
0079-C2	Cold Start	1.05	9.00
0079-H4	Hot Start	1.15	4.00
0079-H5	Hot Start	1.22	0.00
0079-H6	Hot Start	1.21	3.00

### Brake-Specific Fuel Consumption

The fuel consumption was not measured directly during the engine testing. Rather, a calculated “carbon-balance” fuel consumption rate was determined based on the measured exhaust flow rate and the carbon content [i.e., the CO and the carbon dioxide (CO<sub>2</sub>)] in the exhaust gas analysis. The weighted brake-specific fuel consumption (BSFC) calculations are similar to the weighted emissions calculations explained in Section 4.0. **Table 6** shows the weighted BSFC calculations. **Table 7** summarizes the results of these calculations and compares the fuel consumption during the baseline runs with that measured during the tests with the PCRT2<sup>®</sup> 1000, v.2 units installed.

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

Test Number	Test Type	Test Date	BSFC		Weighted BSFC	
			lb/bhp-hr	kg/kWh	lb/bhp-hr	kg/kWh
Baseline with ULSD Fuel on a 2000 Cummins ISM350 Engine						
BASE-C1	Cold Start	8/7/2008	0.405	0.246		
BASE-H1	Hot Start	8/7/2008	0.392	0.238	0.394	0.239
BASE-H2	Hot Start	8/7/2008	0.390	0.237	0.392	0.238
BASE-H3	Hot Start	8/7/2008	0.389	0.237	0.392	0.238
Mean					0.392	0.239
Degreened PCRT2 <sup>®</sup> 1000, V.2 System with ULSD Fuel on a 2000 Cummins ISM350 Engine						
0138-C1	Cold Start	8/8/2008	0.409	0.249		
0138-H1	Hot Start	8/8/2008	0.394	0.240	0.396	0.241
0138-H2	Hot Start	8/8/2008	0.391	0.238	0.394	0.240
0138-H3	Hot Start	8/8/2008	0.392	0.238	0.394	0.240
Mean					0.395	0.240
Aged PCRT2 <sup>®</sup> 1000, V.2 System with ULSD Fuel on a 2000 Cummins ISM350 Engine						
0079-C2	Cold Start	8/14/2008	0.410	0.249		
0079-H4	Hot Start	8/14/2008	0.398	0.242	0.400	0.243
0079-H5	Hot Start	8/14/2008	0.396	0.241	0.398	0.242
0079-H6	Hot Start	8/14/2008	0.399	0.243	0.400	0.243
Mean					0.399	0.243

**Table 7. Summary of Fuel Consumption Reductions**

Device type	Fuel	% Reduction	95% Confidence Limits
Degreened	ULSD	-0.60	- <sup>a</sup>
Aged	ULSD	-1.7	- <sup>a</sup>

<sup>a</sup> The fuel consumption reduction cannot be distinguished from zero with 95% confidence.



#### 4.0 SUMMARY AND DISCUSSION OF EMISSIONS RESULTS

**Table 8** reports the emissions from the tests that were conducted: baseline, with a degreened PCRT2<sup>®</sup> 1000, v.2 system installed and with an aged PCRT2<sup>®</sup> 1000, v.2 system installed. The concentration measurements were converted to units of total grams per test for all species. The “bhp from work” (i.e., the integrated measured power during each test period) values are also shown in these tables.

**Table 8. Emissions Data**

Test Number	Test Type	PM		NO <sub>x</sub>	NO	NO <sub>2</sub> <sup>a</sup>	NO <sub>2</sub> /NO <sub>x</sub>	HC	CO	CO <sub>2</sub>	Work
		g	% SOF	g			%	g		kg	kWh (bhp-hr)
Baseline with ULSD Fuel on a 2000 Cummins ISM350 Engine											
BASE-C1	Cold Start	1.83	34.0	109	94.4	15.0	13.7	5.81	29.8	13.9	17.8 (23.9)
BASE-H1	Hot Start	2.02	30.0	95.4	82.2	13.2	13.9	6.99	24.7	13.5	17.9 (24.0)
BASE-H2	Hot Start	2.03	28.0	94.8	81.5	13.2	14.0	7.16	24.4	13.5	17.9 (24.0)
BASE-H3	Hot Start	2.33	24.0	94.2	80.8	13.4	14.2	7.37	24.7	13.4	17.9 (24.0)
Degreened PCRT2 <sup>®</sup> 1000, V.2 System with ULSD Fuel on a 2000 Cummins ISM350 Engine											
0138-C1	Cold Start	0.793	15.0	110	60.7	49.4	44.9	0.467	9.97	14.0	17.7 (23.7)
0138-H1	Hot Start	0.881	15.0	93.4	45.5	47.9	51.3	0.414	5.62	13.6	17.9 (23.9)
0138-H2	Hot Start	0.956	12.0	92.6	45.4	47.2	51.0	0.166	6.48	13.5	17.8 (23.9)
0138-H3	Hot Start	1.01	2.00	92.8	45.8	47.0	50.6	0.267	5.63	13.5	17.8 (23.9)
Aged PCRT2 <sup>®</sup> 1000, V.2 System with ULSD Fuel on a 2000 Cummins ISM350 Engine											
0079-C2	Cold Start	1.05	9.00	107	72.5	34.6	32.3	0.764	11.4	14.0	17.6 (23.6)
0079-H4	Hot Start	1.15	4.00	95.0	60.5	34.6	36.4	0.589	7.65	13.7	17.8 (23.9)
0079-H5	Hot Start	1.22	0.00	94.6	59.9	34.6	36.6	0.520	7.58	13.6	17.8 (23.9)
0079-H6	Hot Start	1.21	3.00	94.5	60.1	34.4	36.4	0.549	7.68	13.8	17.8 (23.9)

<sup>a</sup> NO<sub>2</sub> calculated as NO<sub>x</sub>-NO

For each pollutant/hot-start test combination, the transient composite-weighted emissions per work brake horsepower-hour (bhp-hr) were then calculated following the fractional calculation for highway engines as follows:

$$(E_{COMP})_m = \frac{\frac{1}{7} \bullet E_{COLD} + \frac{6}{7} \bullet (E_{HOT})_m}{\frac{1}{7} \bullet W_{COLD} + \frac{6}{7} \bullet (W_{HOT})_m} \quad (1)$$

Where

$E_{COMP}$  = composite emissions rate, g/bhp-hr

$m$  = one, two, or three hot-start tests

$E_{COLD}$  = cold-start mass emissions level, g

$E_{HOT}$  = hot-start mass emissions level, g

$W_{COLD}$  = cold-start bhp-hr

$W_{HOT}$  = hot-start bhp-hr

These composite-weighted emissions rates are shown in **Table 9** and **Table 10** and were used to calculate the mean and standard deviations for the baseline and controlled emissions rates. These data were in turn used to calculate mean emissions reductions and 95% confidence limits. These calculations are based on the generic verification protocol<sup>1</sup> and test/QA plan.<sup>2</sup>

**Table 9. Composite Weighted Emissions Rates (U.S. Common Units)**

Test Number	Exhaust PM	NO <sub>x</sub>	NO	NO <sub>2</sub> <sup>a</sup>	NO <sub>2</sub> /NO <sub>x</sub>	HC	CO	CO <sub>2</sub>
	g/bhp-hr				%	g/bhp-hr		
Baseline with ULSD Fuel on a 2000 Cummins ISM350 Engine								
BASE-H1	0.0832	4.06	3.50	0.561	13.8	0.284	1.06	565
BASE-H2	0.0834	4.03	3.47	0.561	13.9	0.290	1.05	564
BASE-H3	0.0940	4.01	3.45	0.567	14.1	0.298	1.06	562
Degreened PCRT2 <sup>®</sup> 1000, V.2 System with ULSD Fuel on a 2000 Cummins ISM350 Engine								
0138-H1	0.0363	4.01	1.99	2.01	50.2	0.0176	0.261	571
0138-H2	0.0391	3.99	1.99	1.99	50.0	0.00876	0.292	568
0138-H3	0.0409	3.99	2.01	1.98	49.7	0.0124	0.262	569
Aged PCRT2 <sup>®</sup> 1000, V.2 System with ULSD Fuel on a 2000 Cummins ISM350 Engine								
0079-H4	0.0478	4.06	2.61	1.45	35.7	0.0258	0.343	577
0079-H5	0.0500	4.04	2.59	1.45	35.9	0.0233	0.341	573
0079-H6	0.0496	4.03	2.59	1.44	35.7	0.0243	0.344	577

<sup>a</sup> NO<sub>2</sub> calculated as NO<sub>x</sub>-NO

**Table 10. Composite Weighted Emissions Rates (Metric Units)**

Test Number	Exhaust PM	NO <sub>x</sub>	NO	NO <sub>2</sub> <sup>a</sup>	NO <sub>2</sub> /NO <sub>x</sub>	HC	CO	CO <sub>2</sub>
	g/kWh				%	g/kWh		
Baseline with ULSD Fuel on a 2000 Cummins ISM350 Engine								
BASE-H1	0.112	5.44	4.694	0.752	13.8	0.381	1.42	758
BASE-H2	0.112	5.40	4.653	0.752	13.9	0.389	1.41	756
BASE-H3	0.126	5.38	4.627	0.760	14.1	0.400	1.42	754
Degreened PCRT2 <sup>®</sup> 1000, V.2 System with ULSD Fuel on a 2000 Cummins ISM350 Engine								
0138-H1	0.0487	5.38	2.669	2.70	50.2	0.0236	0.350	766
0138-H2	0.0524	5.35	2.669	2.67	50.0	0.0117	0.392	762
0138-H3	0.0548	5.35	2.695	2.66	49.7	0.0166	0.351	763
Aged PCRT2 <sup>®</sup> 1000, V.2 System with ULSD Fuel on a 2000 Cummins ISM350 Engine								
0079-H4	0.0641	5.44	3.500	1.94	35.7	0.0346	0.460	774
0079-H5	0.0671	5.42	3.473	1.94	35.9	0.0312	0.457	768
0079-H6	0.0665	5.40	3.473	1.93	35.7	0.0326	0.461	774

<sup>a</sup> NO<sub>2</sub> calculated as NO<sub>x</sub>-NO

The mean composite weighted emissions rates from **Table 11** and **Table 12** are the key values for the verification test.. The first line shows the baseline engine results; the emissions in all categories are below the Table 3 threshold.

**Table 11. Summary of Verification Test Data (U.S. Common Units)**

Device type	Fuel	Mean Composite Weighted Emissions Value				
		PM	NO <sub>x</sub>	HC	CO	CO <sub>2</sub>
		g/bhp-hr				
Baseline	ULSD	0.0868	4.03	0.290	1.05	564
Degreened	ULSD	0.0388	3.99	0.0129	0.272	569
Aged	ULSD	0.0491	4.04	0.0244	0.343	576

**Table 12. Summary of Verification Test Data (Metric Units)**

Device type	Fuel	Mean Composite Weighted Emissions Value				
		PM	NO <sub>x</sub>	HC	CO	CO <sub>2</sub>
		g/kWh				
Baseline	ULSD	0.116	5.41	0.390	1.41	756
Degreened	ULSD	0.0520	5.36	0.0173	0.364	763
Aged	ULSD	0.0659	5.42	0.0328	0.459	772

**Table 13** summarizes the emissions reductions that were achieved by the use of the PCRT2<sup>®</sup> 1000, v.2 system. These are the “verified emissions reductions” reported in Table 2 of the ETV Joint Verification Statement.

**Table 13. Summary of Verification Test Emissions Reductions**

Device Type	Fuel	Mean Emissions Reduction (%)				95% Confidence Limits on the Emissions Reduction (%)			
		PM	NO <sub>x</sub>	HC	CO	PM	NO <sub>x</sub>	HC	CO
Degreened	ULSD	55	0.99	96	74	37–73	– <sup>a</sup>	– <sup>b</sup>	73–75
Aged	ULSD	43	–0.24	92	68	26–61	– <sup>a</sup>	86–97	66–69

<sup>a</sup> The emissions reduction could not be distinguished from zero with 95% confidence.

<sup>b</sup> The emissions reduction could not be quantified or distinguished from 100% with 95% confidence.

## 4.1 Quality Assurance

The ETV of the PCRT2<sup>®</sup> 1000, v.2 system with ULSD fuel for heavy-duty highway diesel engines was performed in accordance with the approved test/QA plan and the test-specific addendum.<sup>2</sup> An audit of data quality included the review of equipment, 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<sup>5</sup> 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 at that time. The equipment was appropriate for the verification testing, and it was operating satisfactorily.

## 5.0 REFERENCES

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