Environmental Technology Verification

Test Report of Mobile Source Selective Catalytic Reduction

Johnson Matthey
SCCRT®, Version 1, Selective Catalytic Reduction Technology with a Catalyzed Continuously Regenerating Trap

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

INTERNATIONAL

ETV Joint Verification Statement

TECHNOLOGY TYPE:	**MOBILE DIESEL ENGINE AIR POLLUTION CONTROL**
APPLICATION:	**CONTROL OF EMISSIONS FROM MOBILE DIESEL ENGINES IN HIGHWAY USE BY SELECTIVE CATALYTIC REDUCTION AND A CATALYZED CONTINUOUSLY REGENERATING TRAP**
TECHNOLOGY NAME:	**SCCRT®, VERSION 1, SELECTIVE CATALYTIC REDUCTION WITH A CATALYZED CONTINUOUSLY REGENERATING TRAP**
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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, 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 Center (APCT Center), which is 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 emission control system consisting of a selective catalytic reduction (SCR) technology with a catalyzed continuously regenerating trap (CCRT).

ENVIRONMENTAL TECHNOLOGY VERIFICATION TEST DESCRIPTION

All tests were performed in accordance with the Test/QA Plan for the Verification Testing of Selective Catalytic Reduction Technologies for Highway, Nonroad and Stationary Use Diesel Engines and the Test-Specific Addendum to ETV Mobile Source Test/QA Plan for Johnson Matthey for the SCCRT®, v.1 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 in February 2011 at Southwest Research Institute. The performance verified was the percentage of emissions 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 also were made. A summary description of the ETV test is provided in **Table 1**.

Table 1. Summary of the Environmental Technology Verification Test

Test type	Highway Transient Federal Test Procedure
Engine family	6CEXH0661MAV
Engine make–model year	Cummins – 2006 ISM 330
Service class	Highway, heavy-duty diesel engine
Engine rated power	330 hp at 1800 rpm
Engine displacement	10.8 L, inline six cylinder
Technology	Johnson Matthey SCCRT®, v.1
Technology description	SCR combined with a CCRT
Test cycle or mode description	One cold-start and multiple hot-start tests according to FTP and one SET for baseline engine, degreened, and aged systems
Test fuel description	Ultra–low-sulfur diesel fuel with 15 ppm sulfur maximum
Critical measurements	PM, NO_x, HC, and CO
Ancillary measurements	CO_2, NO, NO_2 (by calculation), NH_3, soluble organic fraction of PM, exhaust backpressure, exhaust temperature, and fuel consumption

Note: CO_2 = carbon dioxide, FTP = Federal Test Procedure, hp = horsepower, NO = nitric oxide, NO_2 = nitrogen dioxide, NH_3 = ammonia, ppm = parts per million, rpm = revolutions per minute, SET = Supplemental Emission Test.
Beginning of table description. Table 1 is titled Summary of the Environmental Technology Verification Test. The table lists the type of test conducted, the critical and ancillary measurements taken, the characteristics of the test engine, and the technology undergoing verification testing. End of table description.

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

VERIFIED TECHNOLOGY DESCRIPTION

The Johnson Matthey SCCRT®, v.1 technology is a urea-based SCR system combined with a CCRT filter designed for on-highway light, medium, and heavy heavy-duty diesel, urban and non-urban bus, exhaust gas recirculation (EGR)- or non-EGR–equipped engines for use with commercial ultra–low-sulfur diesel fuel (ULSD) conforming to 40 *Code of Federal Regulations* 86.1313-2007.

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 SCCRT®, v.1 system on highway engines fueled by ULSD (15 parts per million [ppm] or less) fuel.

The monitoring and notification system that was functionally tested and used with this technology includes sensors for urea level and leakage detection and a mechanism to interrupt engine restart in the event of an empty urea tank.

VERIFICATION OF PERFORMANCE

The Johnson Matthey SCCRT®, v.1 system achieved the reduction in tailpipe emissions shown in **Table 2** compared to baseline operation without the system installed on the test engine. In Table 2, "degreened" refers to a system with 25-124 hours of accumulated run time while "aged" refers to a system with over 1000 hours of accumulated run time. Additionally, the functional test results indicated proper operation of the monitoring and warning system.

Table 2. Verified Emissions Reductions

Mean Emissions Reduction (%)

System Type	Fuel	PM	NO_x	HC	CO
Degreened	ULSD	94	76	94	89
Aged	ULSD	92	73	92	87

95% Confidence Limits on the Emissions Reduction (%)

System Type	Fuel	PM	NO_x	HC	CO
Degreened	ULSD	91 to 98	75 to 77	80 to [a]	69 to [a]
Aged	ULSD	89 to 95	72 to 74	77 to [a]	66 to [a]

[a] The upper limit of the emissions reduction could not be distinguished from 100% with 95% confidence.

Beginning of table description. Table 2 is titled Verified Emissions Reductions. The table describes the verified emissions reduction percentages for the degreened and aged systems for particulate matter, nitrogen oxides, hydrocarbons, and carbon monoxide. 95% confidence limits for these reductions are also listed. End of table description.

The APCT Center quality manager has reviewed the test results and quality control (QC) 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 SCCRT®, v.1 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 SCCRT®, v.1 system within the range of applicability of the statement.

signed by Sally Gutierrez	*8/22/2011*	*signed by Jason Hill*	*8/8/2011*
Sally Gutierrez	Date	Jason Hill	Date
Director		Director	
National Risk Management Research Laboratory		Air Pollution Control Technology Center	
Office of Research and Development		RTI International	
United States Environmental Protection Agency			

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.

Environmental Technology Verification Report

Mobile Source Selective Catalytic Reduction

Johnson Matthey

SCCRT®, Version 1
Selective Catalytic Reduction System with a
Catalyzed Continuously Regenerating Trap

Prepared by

RTI International

Southwest Research Institute

EPA Cooperative Agreement Nos. CR83191101-4 and CR83416901-0

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July 2011

Notice

This document was prepared by RTI International (RTI) and its subcontractor, Southwest Research Institute, with partial funding from Cooperative Agreement Nos. CR83191101-4 and CR83416901-0 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

Established by the U.S. Environmental Protection Agency (EPA), the Environmental Technology Verification (ETV) Program 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 to provide potential purchasers and permitters with an independent, credible assessment of the technology they are buying or permitting.

The Air Pollution Control Technology 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 emissions control technologies.

Retrofit air pollution control systems used to control emissions from mobile diesel engines are among the technologies evaluated by the APCT Center. The APCT Center has developed (and EPA has approved) the *Generic Verification Protocol for Determination of Emissions Reductions From Selective Catalytic Reduction Control Technologies for Highway, Nonroad, and Stationary 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 SCCRT®, v.1 system, comprising selective catalytic reduction technology and a continuously regenerating trap. ETV testing of this technology was conducted in March 2010 at SwRI. After the test, Johnson Matthey PLC personnel realized that an obsolete component was inadvertently included in the devices supplied to SwRI for testing. Johnson Matthey PLC chose to repeat the verification testing in February 2011 with the correct component. All testing was performed in accordance with an approved test/quality assurance plan that implements the requirements of the generic verification protocol at the test laboratory. This report describes both the March 2010 test and the February 2011 test.

Availability of Report

Copies of this verification report are available from the following:

- RTI International
  Discovery & Analytical Sciences
  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

This verification report is also available on the following EPA Web sites:

- http://www.epa.gov/etv/vt-apc.html#msscr (pdf format)
- http://www.epa.gov/ncepihom/

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Acronyms/Abbreviations

2-D	Type 2 diesel fuel
ºC	degrees Celsius
ºF	degrees Fahrenheit
APCT Center	Air Pollution Control Technology Center
ASTM	American Society for Testing and Materials
bhp-hr	brake horsepower-hour
BSFC	brake-specific fuel consumption
CCRT	catalyzed continuously regenerating trap
CFR	Code of Federal Regulations
CO	carbon monoxide
CO_2	carbon dioxide
CRT	continuously regenerating trap
DOC	diesel oxidation catalyst
EGR	exhaust gas recirculation
EPA	U.S. Environmental Protection Agency
ETV	environmental technology verification
ft-lb	foot-pound of torque
FTIR	Fourier transform infrared
FTP	Federal Test Procedure
g	gram(s)
g/bhp-hr	grams per brake horsepower-hour
g/hp-hr	grams per horsepower-hour
g/kWhr	grams per kilowatt-hour
HC	hydrocarbon(s)
HDDE	heavy-duty diesel engine
hp	horsepower
Hz	hertz
ID	identification
in. Hg	inch(es) mercury
kg	kilograms
kg/kWhr	kilograms per kilowatt hour
kPa	kilopascals

kWhr	kilowatt hour
L	liter(s)
lb/bhp-hr	pounds per brake horsepower-hour
NH_3	ammonia
NMHC	non-methane hydrocarbons
NO	nitric oxide
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
OTAQ	Office of Transportation and Air Quality
PM	particulate matter
ppm	parts per million
QA	quality assurance
QC	quality control
rpm	revolutions per minute
RTI	RTI International
SCR	selective catalytic reduction
SET	Supplemental Emission Test
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 Mr. Michael Kosusko, Project Officer, and Mr. Robert Wright, 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 PLC personnel who supported the test effort.

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  E-mail: joshia@jmusa.com
  Web site: http://www.jmusa.com

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

- Mr. Jason Hill
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  P.O. Box 12194
  Research Triangle Park, NC 27709-2194
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  E-mail: apctvc@rti.org
  ETV Program Web site: http://www.epa.gov/etv

1.0 Introduction

This Environmental Technology Verification (ETV) report reviews the performance of the Johnson Matthey SCCRT®, v.1 system, comprising selective catalytic reduction (SCR) technology and a catalyzed continuously regenerating trap (CCRT), submitted for testing by Johnson Matthey PLC. ETV testing of this technology was conducted during a series of tests in March 2010 and February 2011 by Southwest Research Institute (SwRI), under contract with the Air Pollution Control Technology Center (APCT Center). After the March 2010 test, Johnson Matthey PLC personnel realized that an obsolete component was inadvertently included in the devices supplied to SwRI for testing. In order for the verification test results to reflect the performance of the current design, Johnson Matthey PLC chose to repeat the verification test in February 2011 with the correct component. This verification report describes both the March 2010 test and the February 2011 test. However, to reflect the performance of the current component design, the associated verification statement only describes the February 2011 test results.

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 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, SCR systems, fuels additives, and engine modification control technologies for mobile diesel engines. Based on the activities of this technical panel, the *Generic Verification Protocol for Determination of Emissions Reductions from Selective Catalytic Reduction Control Technologies for Highway, Non-Road, and Stationary Use Diesel Engines* [1] was developed. This protocol was chosen as the best guide to verify the performance effects of the SCCRT®, v.1 system observable immediately after installation, as opposed to cumulative effects over a sustained period of operation. 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 SCCRT®, v.1 technology installed. The specific Test/Quality Assurance (QA) Plan addendum for the ETV test of the technology submitted by Johnson Matthey PLC was developed and approved in June 2009[2] for the March 2010 test event and revised in November 2010[3] for the February 2011 test event. The goal of the tests was to measure the emissions control performance of the SCCRT®, v.1 system and its emissions reduction relative to an uncontrolled engine.

Section 2.0 of this report describes the technology. ***Section 3.0*** documents the procedures and methods used for the tests and the conditions under which the tests were conducted. ***Section 4.0*** summarizes and discusses the results of the tests. ***Section 5.0*** presents the references used to compile this ETV report.

This report contains only summary data and the verification statement. Complete documentation of the test results is provided in separate test reports[4, 5] and internal audit of data quality reports.[6, 7] 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 and 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 SCCRT®, v.1 system on highway engines. This statement is applicable to engines fueled only by ultra–low-sulfur diesel (ULSD) (15 parts per million [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 SCCRT®, v.1 system combines SCR technology with a CCRT and is designed for light, medium, and heavy heavy-duty diesel on-highway urban bus and non-urban bus exhaust gas recirculation (EGR)- and non-EGR–equipped engines for use with commercial ULSD and conforming to 40 Code of Federal Regulations (CFR) 86.1313-2007.

2.1 Test Systems for March 2010

For the March 2010 test event, Johnson Matthey PLC provided a new SCCRT®, v.1 unit that had never been used before. The components of the SCCRT had the following serial numbers: 2315609R01 for the continuously regenerating trap (CRT) catalyst, 3309309R011 for the CRT filter, DP28707 and DP28708 for the SCR catalysts, 11476012X43 for the ammonia slip catalyst, and 966344950000245 for the urea injection pump. The unit was preconditioned ("degreened") by SwRI, in accordance with the requirements in Title 13, California Code of Regulations, Section 2706(a)(4). The degreened SCCRT®, v.1 system is shown installed in **Figure 1** in accordance with Johnson Matthey's installation manual.

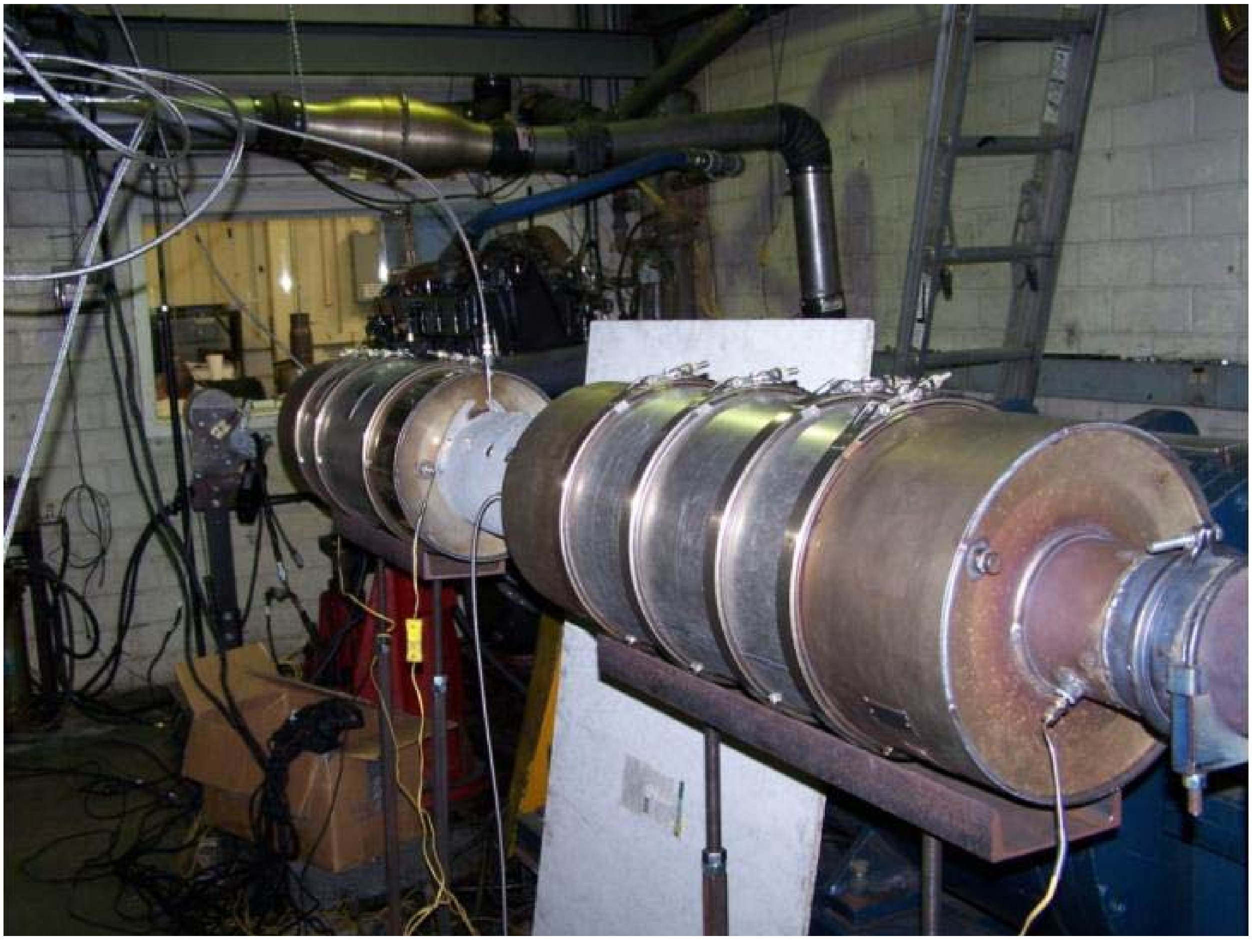

Figure 1. The degreened SCCRT®, v.1 system installed for emissions tests in March 2010.

Johnson Matthey PLC provided an "aged" SCCRT®, v.1 unit that had seen over 1,000 hours of service on a 2005 C13 engine installed in a Class-8 delivery tractor operated on an accelerated 1,000-hour durability trial. The components of the SCCRT had the following serial numbers: 272512 for the CRT catalyst, 273871 for the CRT filter, JF0134 and JF0137 for the SCR catalysts, 11476012X42 for the ammonia slip catalyst, and 966344950000161 for the urea injection pump. The aged SCCRT®, v.1 system is shown installed in **Figure 2** in a manner consistent with the installation on the engine during the durability trial.

Figure 2. The aged SCCRT®, v.1 system installed for emissions tests in March 2010.

2.2 Test Systems for February 2011

For the February 2011 test event, Johnson Matthey PLC provided a new SCCRT®, v.1 unit that had never been used before. The components of the SCCRT had the following serial numbers: 2303510R034 for the CRT catalyst, 3309309R014 for the CRT filter, 2318409R003 and 2318409R017 for the SCR catalysts, 2318409R104 for the ammonia slip catalyst, and 966344950000292 for the urea injection pump. The unit was preconditioned by SwRI in accordance with the requirements in Title 13, California Code of Regulations, Section 2706(a)(4). The degreened SCCRT®, v.1 system is shown installed in **Figure 3** in a manner consistent with the aged system's installation on the engine during the durability trial.

The February 2011 system differed physically from the March 2010 system in that the exhaust gas thermocouple had been changed and relocated in the new production design. These parts originally were redesigned prior to the March 2010 test, but the redesigned parts mistakenly were not included when the degreened and aged systems were sent to SwRI for testing. The new system provided for the February 2011 test event had the redesigned thermocouple and housing in place.

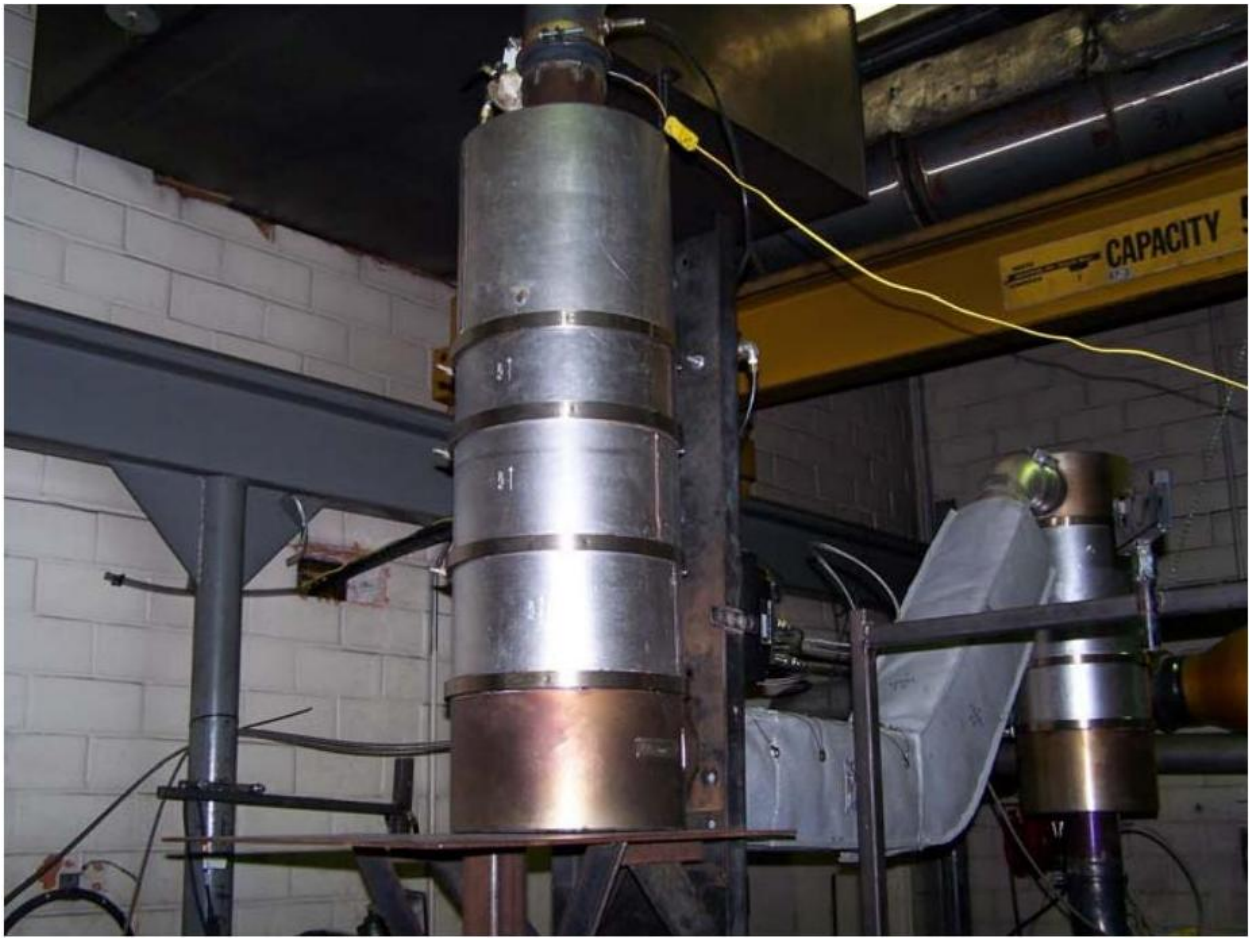

Figure 3. The degreened SCCRT®, v.1 system installed for emissions tests in February 2011.

The aged system was the same system that was tested in March 2010. Thermocouples were relocated to be consistent with the operation of the degreened device. Rather than using the thermocouple installation points on the original CRT inlet and SCR inlet heads supplied with the aged system, a ¼" port was welded into the inlet pipe of the CRT inlet and SCR inlet heads, and the aged fittings and thermocouples were installed in these locations.

3.0 Test Documentation

The ETV testing took place during March 2010 and February 2011 at SwRI under contract to the APCT Center. Testing was performed in accordance with the following:

- Generic Verification Protocol for Determination of Emissions Reductions From Selective Catalytic Reduction Control Technologies for Highway, Non-Road, and Stationary Use Diesel Engines[1]
- Test/QA Plan for the Verification Testing of Selective Catalytic Reduction Control Technologies for Highway, Non-Road, and Stationary Use Diesel Engines[8]
- Test-Specific Addendum to ETV Mobile Source Test/QA Plan for Johnson Matthey for the SCCRT®, v.1 System. [2, 3]

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

3.1 Engine Description

For both the March 2010 and February 2011 test events, ETV verification testing was performed on a 2006 Cummins ISM 330 in-line, 6-cylinder, direct injected, turbocharged heavy-duty diesel engine (HDDE), serial number 35080469, provided by Johnson Matthey. The 10.8-liter (L) engine had a nominal rated power of 330 horsepower (hp) at 1800 revolutions per minute (rpm), and a rated torque of 1,150 foot-pound (ft-lb). The EPA engine family identification (ID) was 6CEXH0661MAV. This engine was originally built in June 2003 as a 370 hp engine and was rebuilt at Cummins' Jamestown Engine Plant in October 2006 as an ISM 330. Engine fuel injection management was electronically controlled. The engine included a diesel oxidation catalyst (DOC), which was used during baseline testing but removed for installation of the SCCRT. The test fuel was an ULSD that met specifications in 40 CFR 86.1313-2007.[9]

Table 1 provides the engine ID details, and **Figure 4** shows the ID plate from the engine.

Table 1. Engine Identification Information

Engine serial number	35080469
Date of manufacture	October 2006
Make	Cummins
Model year	2006
Model	ISM 330
Engine displacement and configuration	10.8 L, inline six cylinder
Service class	Highway heavy-duty diesel engine
EPA engine family identification	6CEXH0661MAV (Engine Family Box OH-13)
Certification standards (g/hp-hr)	NO_x + NMHC = 2.5, CO = 15.5, PM = 0.1
Rated power (nameplate)	330 hp at 1800 rpm
Rated torque (nameplate)	1150 ft-lb at 1200 rpm
Certified emission control system	Engine Modification Electronic Control Direct Injection, Turbocharged Charged Air Cooling, DOC
Aspiration	Turbo with Air-to-Air Aftercooling
Fuel system	Electronic Direct

Note: CO = carbon monoxide, g/hp-hr = grams per horsepower-hour, NMHC = non-methane hydrocarbons, NO_x = nitrogen oxides, PM = particulate matter.

Beginning of table description. Table 1 is titled Engine Identification Information. The table lists the test engine's characteristics including engine serial number; date of manufacture; make, model, and model year; engine displacement and configuration; service class; performance characteristics; and standard emissions control, aspiration, and fuel systems. End of table description.

Figure 4. Identification label for 2006 Cummins ISM 330 engine.

3.2 Engine Fuel Description

All emissions testing was conducted with ULSD fuel meeting the 40 CFR 86.1313-2007 specification for emissions certified fuel.[9] Selected fuel properties from the supplier's analyses are summarized in **Table 2**. All testing during March 2010 was conducted using fuel from a single batch, identified as EM-6556-F, while all testing during February 2011 was conducted using fuel from a different batch, identified as EM-6417-F.

Table 2. Selected Fuel Properties and Specifications

Item	CFR Specification[a] ASTM	CFR Specification[a] Type 2-D	Test Fuel (March 2010) Diesel 2007 ULS Fuel	Test Fuel (February 2011) Diesel 2007 ULS Fuel
Cetane number	D613	40–50	46	43
Cetane index	D976	40–50	45.3	46.7
Distillation range:	—	—	—	—
Initial boiling point, ºC (ºF)	D86	171.1–204.4 (340–400)	180 (356)	177 (351)
10% point, ºC (ºF)	D86	204.4–237.8 (400–460)	207 (404)	208 (406)
50% point, ºC (ºF)	D86	243.3–282.2 (470–540)	253 (487)	252 (486)
90% point, ºC (ºF)	D86	293.3–332.2 (560–630)	307 (584)	303 (577)
End point, ºC (ºF)	D86	321.1–365.6 (610–690)	347 (656)	343 (650)
Gravity (American Petroleum Institute)	D287	32–37	35.8[b]	36.7[b]
Total sulfur, ppm	D2622	7–15	11.0[c]	10.2[c]
Hydrocarbon composition:				
Aromatics (minimum), %	D5186	27	29.3[e]	28.6[e]
Olefins, saturates %	D5186	d	70.7[e]	71.4[e]
Flash point (minimum), ºC (ºF)	D93	54.4 (130)	64 (148)	66 (151)
Viscosity, centistokes at 40ºC	D445	2.0–3.2	2.2	2.4

Note: ºC = degrees Celsius, ºF = degrees Fahrenheit, 2-D = Type 2 diesel fuel, ASTM = American Society for Testing and Materials, CFR = Code of Federal Regulations, ULS = ultra–low sulfur.

[a] 40 CFR 86.1313(b)(2) for heavy-duty diesel engines.[6]
[b] Measured per ASTM D4052.
[c] Measured per ASTM D5453; this method is an acceptable substitute for ASTM D2622.
[d] Remainder of the hydrocarbons.
[e] Measured per ASTM D1319.

Beginning of table description. Table 2 is titled Selected Fuel Properties and Specifications. The table lists the fuel specifications enumerated in the Code of Federal Regulations and the actual values for the fuels used during the March 2010 and February 2011 tests. The listed specifications include the cetane number, cetane index, distillation range, gravity, total sulfur content, hydrocarbon composition, flash point, and viscosity. The fuels used for both test events met all the specifications. End of table description.

3.3 Functional Tests

Functional tests were performed on the aged SCCRT. Results from the functional tests are given in **Table 3**. The table shows the tasks that were performed to force a diagnostic code for a specific monitoring system, the timing for systems diagnostic warning and alarm indications (lights), and passing criteria for systems diagnostic events. Table 3 also includes the observed diagnostic indication events and diagnostic codes monitored on the Mapper software provided by Johnson Matthey.

Table 3. Results from Functional Tests of the Aged SCCRT®, v.1

UREA TANK LEVEL SENSOR INDICATORS					
TASK	**TIME/EVENTS**	**VIEW DIAGNOSTIC LIGHTS**	**PASS CRITERIA**	**OBSERVED EVENTS**	**MAPPER CODES**
Fill tank so level sensor lite is on steady					
Start, run engine, >250°C SCR inlet	urea goes below sensor level	sensor light off, UREA LOW light within 1 min	When urea sensor light is steady off, the UREA LOW will illuminate within 1 minute	As urea sensor light turned off, the UREA LOW light illuminated within one minute	
Continue to run engine	system determines empty tank on cosumption	UREA LOW light is on, ALARM light is on	When urea tank is empty, the urea low light is lit and ALARM light will illuminate	UREA LOW light was lit for 3 hours and 4 minutes when ALARM light illumintated	SCR error code #44: urea empty alarm SCR diagnose: stop alarm
Shut off engine	wait 60 sec	engine starter circuit should be defeated	Engine should not start (replaced with light to show if starter is enabled)	Shut off enigne and waited 60 seconds, start enable light was still illuminated	
Fill urea tank	wait 60 sec	engine starter circuit should be enabled, ALARM and UREA LOW lights off	Engine should start, all diagnostic lights should not be lit	No diagnostic lights	
UREA SUPPLY LEAK DETECTION					
TASK	**TIME/EVENTS**	**VIEW DIAGNOSTIC LIGHTS**	**PASS CRITERIA**	**OBSERVED EVENTS**	**MAPPER CODES**
Engine off, shut off urea tank supply valve, disconnect tube from tank to pump					
Start engine, run idle	allow pump to prime 15-20 min	ACTUAL PUMP STATE = Ready, redo test or WARNING light on within 20 min	WARNING light illuminated within 20 minutes	WARNING light illuminated at 15 minutes	SCR error code #36: air/urea flow
Continue to let pump prime	allow pump to prime 1-5 min	ALARM light on within 5 min	ALARM light illuminated within 5 minutes	ALARM light illuminated at 1 added minute	SCR error code #36 and #50: dosing failure alarm
Shut off engine					
Reconnect tube to pump					
Clear code on Mapper					SCR error codes reset
Restart engine		WARNING and ALARM lights off	All diagnostic lights should not be lit	No diagnostic lights	SCR error codes: no error
AIR LEAK TO PUMP					
TASK	**TIME/EVENTS**	**VIEW DIAGNOSTIC LIGHTS**	**PASS CRITERIA**	**OBSERVED EVENTS**	**MAPPER CODES**
Engine off, disconnect air to pump					
Start engine	run 15-20 min	WARNING light on within 20 min	WARNING light illuminated within 20 minutes	WARNING light illuminated at 15 minutes	SCR error code #36: air/urea flow
Continue to run engine	run 1-5 min	ALARM light on within 5 min	ALARM light illuminated within 5 minutes	ALARM light illuminated at added 1 minute	SCR error code #36 and #50: dosing failure alarm
Shut off engine					
Reconnect air to pump					
Clear code on Mapper					SCR error codes reset
Restart engine		WARNING and ALARM lights off	All diagnostic lights should not be lit	No diagnostic lights	SCR error codes: no error

Table 3. Results from Functional Tests of the Aged SCCRT®, v.1 (continued)

LEAK BETWEEN PUMP AND INJECTION NOZZLE					
TASK	**TIME/EVENTS**	**VIEW DIAGNOSTIC LIGHTS**	**PASS CRITERIA**	**OBSERVED EVENTS**	**MAPPER CODES**
Engine off, disconnect tube to nozzle					
Start engine	allow pump to prime	ACTUAL PUMP STATE = Ready, then WARNING light on within 10 min	When pump is at Ready status, WARNING light illuminated within 10 minutes	WARNING light illuminated at 3 minutes	SCR error code #41: low nozzle press
Continue to run engine	run 1-5 min	ALARM light on within 5 min	ALARM light illuminated within 5 minutes	ALARM light illuminated at added 1 minute	SCR error code #41 and #51: low nozzle press alarm
Shut off engine					
Reconnect tube to nozzle					
Clear code on Mapper					SCR error codes reset
Restart engine		WARNING and ALARM lights off	All diagnostic lights should not be lit	No diagnostic lights	SCR error codes: no error
SENSOR MALFUNCTION MONITORING					
TASK	**TIME/EVENTS**	**VIEW DIAGNOSTIC LIGHTS**	**PASS CRITERIA**	**OBSERVED EVENTS**	**MAPPER CODES**
Remove electrical connector from exhaust pressure sensor					
Start engine	run 1 hr	WARNING light on within 1 hr	WARNING light illuminated within 60 minutes	WARNING light illuminated at 34 minutes	SCR error code #18: exh press sensor error
Continue to run engine	run 65 min	ALARM light on within 65 min	ALARM light illuminated within 65 minutes	ALARM light illuminated at added 1 hour 5 minutes	SCR error code #18 and #46: sensor failure alarm
Shut off engine					
Replace electrical connector					
Clear code on Mapper					SCR error codes reset
Restart engine		WARNING and ALARM lites off	All diagnostic lights should not be lit	No diagnostic lights	SCR error codes: no error
Remove electrical connector from urea level sensor					
Start engine	run at idle 5 min	UREA LOW light on within 5 min	UREA LOW light will illuminate within 5 minutes of startup	UREA LOW light illuminated immediately	SCR error code: no error
Continue to run engine, >250°C SCR inlet	use at least 20% of tank volume of urea	ALARM light on	When 20% of urea tank is used, ALARM light will illuminate	UREA LOW light was lit for 3 hours and 10 minutes when ALARM light illumintated	SCR error code #44: urea empty alarm
Shut off engine					
Replace electrical connector					
Check urea level, refill if necessary					
Restart engine, make sure starter circuit is enabled		WARNING and ALARM lights off	All diagnostic lights should not be lit, and engine should start	No diagnostic lights	SCR error code: no error

Table 3. Results from Functional Tests of the Aged SCCRT®, v.1 (continued)

INJECTION NOZZLE CLOGGING MONITOR					
TASK	**TIME/EVENTS**	**VIEW DIAGNOSTIC LIGHTS**	**PASS CRITERIA**	**OBSERVED EVENTS**	**MAPPER CODES**
Install clogged nozzle provided by JM					
Start and run engine	system will attempt to purge nozzle 10 times	WARNING light on after 10 purge attempts	When purge occurs 10 times, WARNING light will illuminate	WARNING light illuminated at 11 minutes	SCR error codes #38: nozzle purge count and #20: nozzle press sensor
Continue to run engine	after 5 min pause system will attempt to purge 10 times	no change	Purge attempts separated by 5 minute doing off period		
Continue to run engine	after 5 min pause system will attempt to purge 10 times	no change	Purge attempts separated by 5 minute dosing off period		
Continue to run engine	after 5 min pause system will attempt to purge 10 times	no change	Purge attempts separated by 5 minute dosing off period		
Continue to run engine	after 5 min pause system will attempt to purge 10 times	ALARM light on	After 5th purge attempt, dosing is off and ALARM light will illuminate	ALARM light illuminated at added 3 minutes	SCR error codes #20, #34: dosing unit and #50: dosing failure alarm
Shut off engine					
Replace injection nozzle					
Clear code on Mapper					
Restart engine		WARNING AND ALARM lights off	All diagnostic lights should not be lit	No diagnostic lights	SCR error codes: no error
ELECTRICAL FAILURES					
TASK	**TIME/EVENTS**	**VIEW DIAGNOSTIC LIGHTS**	**PASS CRITERIA**	**OBSERVED EVENTS**	**MAPPER CODES**
Remove large electrical connector from pump					
Start engine	run 1-2 min	WARNING light on within 1-2 min	WARNING light will illuminate within 1-2 minutes	WARNING light illuminated at 1 minute	SCR error code #34: dosing unit
Continue to run engine	run 1-2 min	ALARM light on in 1-2 min	ALARM light will illuminate within 1-2 minutes	ALARM light illuminated at added 1 minute	SCR error code #50: dosing failure alarm
Shut off engine					
Replace electrical connector					
Clear code on Mapper					
Restart engine		WARNING AND ALARM lights off	All diagnostic lights should not be lit	No diagnostic lights	SCR error codes: no error
Remove ECU fuse		UREA LOW, WARNING, and ALARM lights on	All diagnostic lights illuminated	All lights illuminated	cannot log-in Mapper
Replace ECU fuse		all lights off	All diagnostic lights should not be lit	No diagnostic lights	

3.4 Summary of Emissions Measurement Procedures

The ETV tests consisted of baseline “uncontrolled” tests of the engine with the stock DOC and tests with the control technology installed in place of the DOC. Engine operation and emissions sampling adhered to techniques developed by EPA in 40 CFR, Part 86, Subpart N.[10] Emissions were measured over a single cold-start and triplicate hot-start runs of the highway transient test cycle and a single run of the Supplemental Emission Test (SET) for the baseline, degreened SCCRT, and aged SCCRT exhaust configurations.

The 2006 Cummins ISM 330 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), oxides of nitrogen (NO_x), and particulate matter (PM), along with carbon dioxide (CO_2) and nitric oxide (NO). Nitrogen dioxide (NO_2) emissions were determined as the difference between NO_x and NO emissions. Gaseous emission levels were corrected for dilution air ambient (background) levels. Emissions of HC, CO, CO_2, NO_x, and NO were measured using a Horiba MEXA-7200 DEGR analyzer bench. The NO analyzer did not have a NO_2/NO converter. Engine baseline transient tests during the February 2011 test event included measurement of methane to determine non-methane hydrocarbon (NMHC) emissions. Due to an oversight, methane was not measured separately during the March 2010 test event, but was measured correctly during the 2011 test event. A sample pump drew dilute exhaust from the sample zone and filled a Tedlar polyvinyl fluoride sample bag. The bag sample was analyzed for methane using a gas chromatograph – flame ionization detector according to 40 CFR Part 86, section 1311-94 and SAE J1151. PM emissions were determined from the net weight gain of a single Pallflex TX40 Teflon coated borosilicate microfiber filter.

Soluble organic fraction (SOF) of the PM emissions was determined from the particulate-laden filter from emission tests. The SOF was extracted using toluene/ethanol solvent and a Soxhlet apparatus. To determine the mass of SOF, the filter set was reweighed after the extraction process. The weight difference between loaded and extracted conditions of the filters represented the mass of SOF.

Ammonia slip from the SCCRT system was measured directly from the exhaust stack downstream of the SCCRT using extractive Fourier transform infrared (FTIR) spectroscopy. The FTIR measurements were conducted according to EPA CTM-038 and 40 CFR Part 63, Appendix A, Method 320, with the exception that measurement is based on a continuous sampling and analysis giving results at a 1 hertz (Hz) rate. This method was performed instead of the techniques given in CTM-038, where the FTIR cell is evacuated and filled with sample gas or the cell is purged with 10 cell volumes of sample before the analysis of one composite sample gas.

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 5** depicts the sampling system and related components. The system is designed to comply with the requirements of 40 CFR, Part 86.[10]

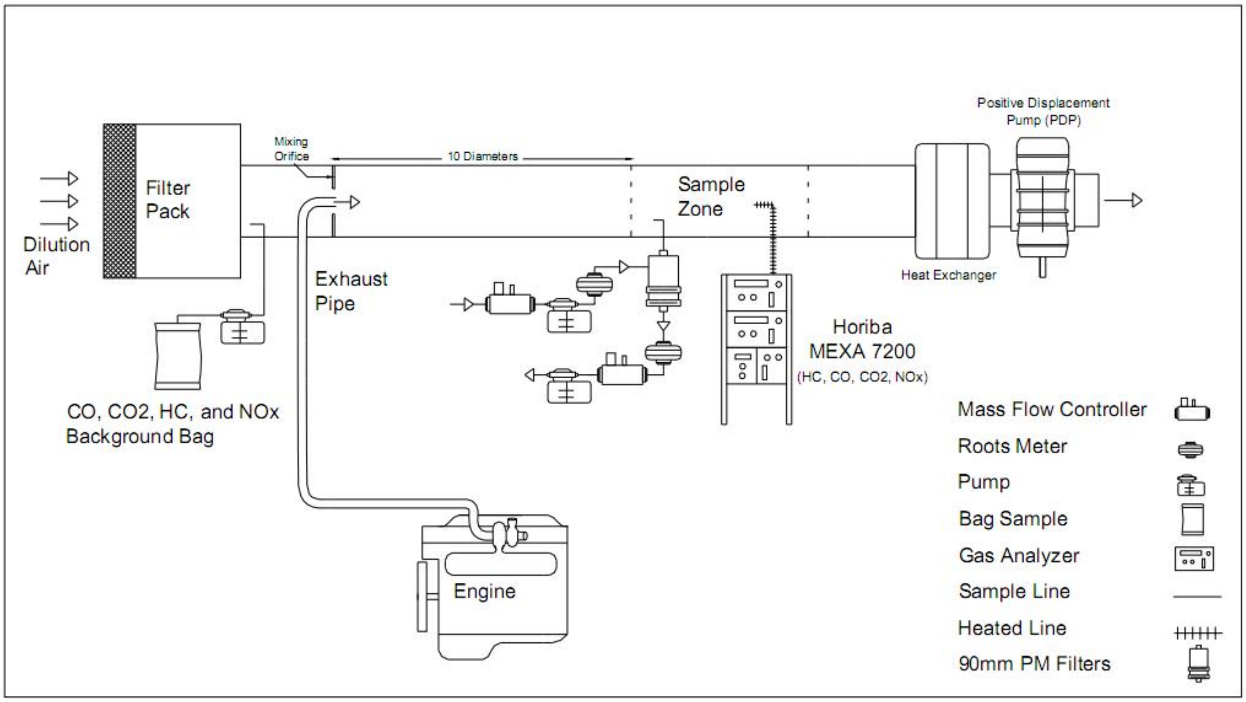

Figure 5. Schematic of emissions sampling system at SwRI.

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.[1] For MY 2004-2006 Non-Urban Bus + MY 2002–2003 Non-Urban Bus "Consent Decree Pull-Ahead" Engines, these certification standards are defined in EPA's on-highway engine family box OH-13. Furthermore, the Office of Transportation and Air Quality (OTAQ) assumes 5% reduction in PM emissions due to the use of ULSD fuel.

The criteria established to indicate the test engine was acceptable and that verification testing could proceed were that the baseline emissions from the engine using ULSD fuel cannot exceed 110% of OH-13 (1.1 x OH-13) for HC, CO, and NO_x, and also cannot exceed 110% of [(OH-13)-5%], or (1.045 x OH-13) for PM. Certification standards for OH-13 are NO_x + NMHC 2.5 grams per brake horsepower-hour (g/bhp-hr), CO 15.5 g/bhp-hr, and PM 0.1 g/bhp-hr. **The adjusted levels the test engine must not exceed are NO_x + NMHC 2.8 g/bhp-hr, CO 17.1 g/bhp-hr, and PM 0.1 g/bhp-hr.**

Table 4 presents the required emissions performance of the test engine, as well as the certification standards and baseline results for comparison.

Table 4. Test Engine Baseline Emissions Requirement for 2006 Cummins ISM 330

—	NOx + NMHC g/kWhr	NOx + NMHC g/bhp-hr	CO g/kWhr	CO g/bhp-hr	PM g/kWhr	PM g/bhp-hr
OH-13[a]	3.4	2.5	20.8	15.5	0.1	0.1
Acceptance criteria	3.7	2.8	22.9	17.1	0.1	0.1
Baseline results (March 2010)	2.96[b]	2.21[b]	0.381	0.284	0.047	0.035
Baseline results (February 2011)	2.96	2.20	0.215	0.160	0.045	0.033

Note: g/bhp-hr = grams per brake horsepower-hour, g/kWhr = grams per kilowatt-hour.

[a] Certification standards for EPA highway engine family box OH-13 for 2004–2006 Non-Urban Bus + MY 2002–2003 Non-Urban Bus "Consent Decree Pull-Ahead" Engines.

[b] Methane was not measured during the March 2010 test event; total HC is displayed instead of NMHC.

Beginning of table description. Table 4 is titled Test Engine Baseline Emissions Requirement for 2006 Cummins ISM 330. The table lists the certified emissions rates for engine category OH-13, to which the Cummins ISM 330 test engine belongs; the allowable acceptance criteria for maximum emissions for this category; and the actual results for the Cummins ISM 330 used during the March 2010 and February 2011 test events. The pollutants listed are nitrogen oxides plus non-methane hydrocarbons, carbon monoxide, and particulate matter, with units given in both grams per kilowatt hour and grams per brake horsepower-hour. For both test events, the baseline engine met the acceptance criteria. End of table description.

3.5 Deviations from the Test/QA Plan

After the emissions tests on the aged SCCRT system during the March 2010 test event, it was noted by SwRI test personnel that a piece of debris was loose inside the CRT stage. A fastener was found in the gap between the CRT catalyst and filter substrates. Photographs of the fastener and erosion to the catalyst substrate face are shown in **Figure 6** and **Figure 7**, respectively. No damage was found on the filter substrate, as shown in **Figure 8**; therefore, the test results were not considered invalidated by this issue.

Figure 6. Photograph of the loose fastener found in the aged CRT catalyst after the March 2010 emissions tests.

Figure 7. Photograph of the aged CRT catalyst erosion caused by the loose fastener.

Figure 8. Photograph of the aged CRT filter face.

A number of issues arose during the February 2011 test event, which resulted in non-compliant data and re-tests of certain test runs:

- An engine baseline test sequence on February 14 was stopped after the first hot-start test due to excessive (>2% of full scale) drift in the post-test span check of the NO analyzer. The drift problem was repaired by SwRI personnel, and the baseline test run was repeated the next day.
- After the baseline test sequence was completed on February 15, it was determined that the cold-start and second hot-start test runs experienced a breakdown of the PM sampling integrity. The PM filter showed evidence of dilute exhaust gas escaping around the filter edge. The SET PM filter did not have the sampling breakdown, so that test run was valid. However, the cold-start and three hot-start transient baseline tests were repeated on February 16.
- During the first hot-start test of the degreened SCCRT on February 18, there was a failure of the power supply for the FTIR analyzer. A fourth hot-start test was conducted to make up for the lost data from the first hot-start run. Repeating the hot-start portion of a highway transient Federal Test Procedure (FTP) is allowed by 40 CFR 1336-84.[11] If any test equipment malfunctions during the hot-start, the cycle is completed and the engine is shut down for a 20-minute soak. If the malfunction is corrected before the soak period ends, the hot-start tests may be re-run. Because of this re-run, the valid hot-start runs one through three correspond to SwRI run numbers 0469-901-H2, 0469-903-H3, and 0469-905-H4, respectively.
- The aged SCCRT test sequence was completed on February 23, but the SET failed to achieve PM sample proportionality. According to 40 CFR 1360-2007,[12] single-filter PM sampling over the SET modes must account for the weighting factors by proportioning sample mass flow during each mode. The SET was repeated on February 24, and it had acceptable proportionality.

3.6 Documented Test Conditions

Engine Performance

Figure 9 shows torque map information measured on the 2006 Cummins ISM 330 engine using the ULSD fuel during the March 2010 test event. **Figure 10** shows the same information as measured during the February 2011 test event. There were no significant differences in the torque maps between the two test events.

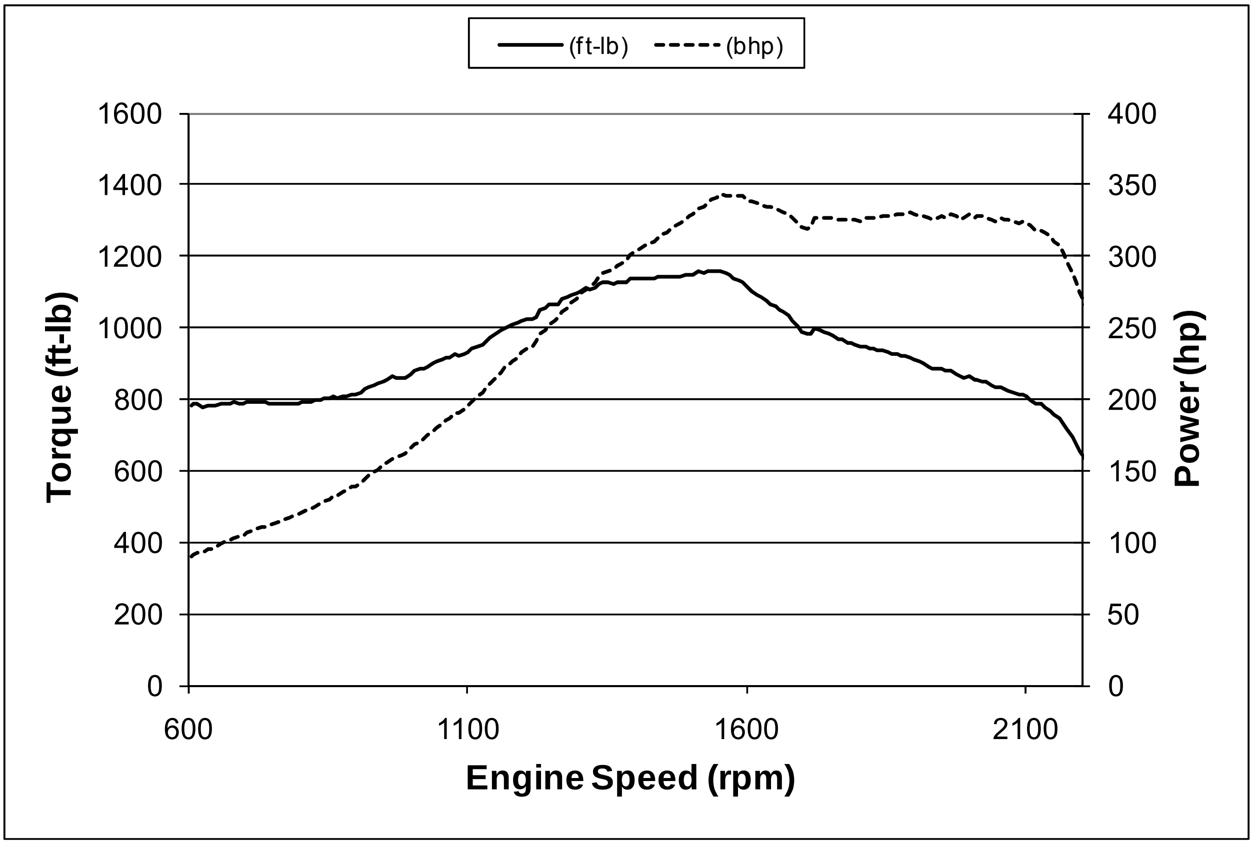

Figure 9. Torque map of 2006 Cummins ISM 330 engine using ULSD fuel during March 2010.

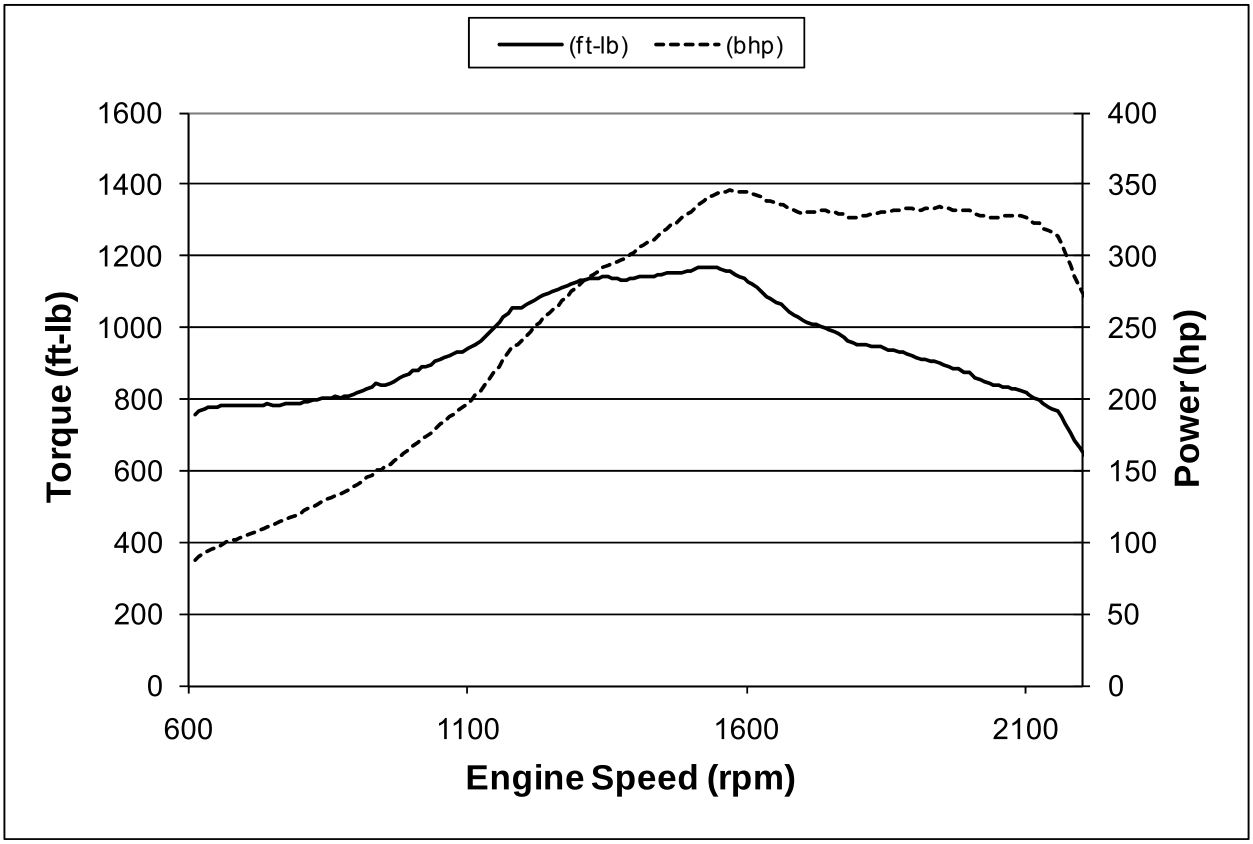

Figure 10. Torque map of 2006 Cummins ISM 330 engine using ULSD fuel during February 2011.

Engine Exhaust Backpressure and Exhaust Temperature

The engine backpressure for the 2006 Cummins ISM 330 engine was set in accordance with the engine manufacturer's specifications 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 FTP tests on the SCCRT®, v.1 systems are given in **Table 5** for the March 2010 test event and **Table 6** for the February 2011 test event. The degreened and aged SCCRT®, v.1 systems significantly increased exhaust backpressure over the transient test cycle. 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 SCCRT within 1 in. (2.54 cm) of the flange openings. Average inlet and outlet temperatures over the transient test cycle, shown in Table 5, were 440 ºF (227 ºC) and 437 ºF (225 ºC), respectively, during the March 2010 test. For the February 2011 test event, the average inlet and outlet temperatures, shown in Table 6, were 435 ºF (224 ºC) and 408 ºF (209 ºC), respectively.

Table 5. Engine Exhaust Backpressure and Average Device Inlet/Outlet Temperature during the March 2010 Test Event

Baseline with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine[a]

Test Number	Test Type	Test Date	Maximum Exhaust Backpressure (kPa)	Maximum Exhaust Backpressure (in. Hg)	Average Device Inlet Temp. (ºC)	Average Device Inlet Temp. (ºF)	Average Device Exhaust Temp. (ºC)	Average Device Exhaust Temp. (ºF)
0469-925-C1	Cold-Start	03/01/10	9.01	2.66	209.42	408.96	206.85	404.33
0469-927-H1	Hot-Start	03/01/10	8.94	2.64	222.73	432.92	235.49	455.87
0469-929-H2	Hot-Start	03/01/10	9.04	2.67	222.52	432.54	236.07	456.93
0469-931-H3	Hot-Start	03/01/10	9.04	2.67	222.17	431.91	235.77	456.38
—	—	Average	9.01	2.66	219.21	426.58	228.55	443.38

Degreened SCCRT with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine

Test Number	Test Type	Test Date	Maximum Exhaust Backpressure (kPa)	Maximum Exhaust Backpressure (in. Hg)	Average Device Inlet Temp. (ºC)	Average Device Inlet Temp. (ºF)	Average Device Exhaust Temp. (ºC)	Average Device Exhaust Temp. (ºF)
0469-956-C1	Cold-Start	03/03/10	12.2	3.61	218.27	424.89	197.25	387.06
0469-958-H1	Hot-Start	03/03/10	12.4	3.67	231.63	448.94	253.67	488.60
0469-960-H2	Hot-Start	03/03/10	12.7	3.74	230.27	446.49	254.53	490.15
0469-962-H3	Hot-Start	03/03/10	12.8	3.79	229.39	444.90	254.40	489.92
—	—	Average	12.5	3.70	227.39	441.30	239.96	463.93

Aged SCCRT with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine

Test Number	Test Type	Test Date	Maximum Exhaust Backpressure kPa	Maximum Exhaust Backpressure in. Hg	Average Device Inlet Temp. (ºC)	Average Device Inlet Temp. (ºF)	Average Device Exhaust Temp. (ºC)	Average Device Exhaust Temp. (ºF)
0469-983-C1	Cold-Start	03/05/10	12.1	3.56	216.98	422.57	170.78	339.41
0469-985-H1	Hot-Start	03/05/10	12.2	3.60	228.92	444.06	220.87	429.57
0469-987-H2	Hot-Start	03/05/10	12.2	3.61	228.21	442.77	223.09	433.57
0469-989-H3	Hot-Start	03/05/10	12.3	3.64	228.94	444.09	223.49	434.29
—	—	Average	12.2	3.60	225.76	438.37	209.56	409.21

Note: in. Hg = inches mercury, kPa = kilopascals.
[a] Baseline tests used the stock DOC; the stock DOC was not used with the SCCRT.

Beginning of table description. Table 5 is titled Engine Exhaust Backpressure and Average Device Inlet/Outlet Temperature during the March 2010 Test Event. The table lists the maximum exhaust backpressure, average device inlet temperature, and average device exhaust temperature for each individual cold-start and hot-start test run for the baseline, degreened, and aged systems. Results are given in both metric and U.S. common units. End of table description.

Table 6. Engine Exhaust Backpressure and Average Device Inlet/Outlet Temperature during the February 2011 Test Event

Baseline with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine[a]

Test Number	Test Type	Test Date	Maximum Exhaust Backpressure (kPa)	Maximum Exhaust Backpressure (in. Hg)	Average Device Inlet Temp. (ºC)	Average Device Inlet Temp. (ºF)	Average Device Exhaust Temp. (ºC)	Average Device Exhaust Temp. (ºF)
0469-876-C1	Cold-Start	02/16/11	9.04	2.67	214.00	417.20	209.56	409.22
0469-878-H1	Hot-Start	02/16/11	8.94	2.64	227.12	440.82	239.20	462.56
0469-880-H2	Hot-Start	02/16/11	9.01	2.66	227.07	440.73	239.88	463.79
0469-883-H3	Hot-Start	02/16/11	9.08	2.68	227.52	441.53	240.22	464.39
—	—	Average	9.02	2.66	223.93	435.07	232.22	449.99

Degreened SCCRT with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine

Test Number	Test Type	Test Date	Maximum Exhaust Backpressure (kPa)	Maximum Exhaust Backpressure (in. Hg)	Average Device Inlet Temp. (ºC)	Average Device Inlet Temp. (ºF)	Average Device Exhaust Temp. (ºC)	Average Device Exhaust Temp. (ºF)
0469-897-C1	Cold-Start	02/18/11	13.9	4.09	220.36	428.64	171.35	340.43
0469-901-H2	Hot-Start	02/18/11	14.0	4.12	227.02	440.64	227.74	441.93
0469-903-H3	Hot-Start	02/18/11	14.1	4.15	227.07	440.72	227.72	441.89
0469-905-H4	Hot-Start	02/18/11	14.1	4.17	227.00	440.59	227.78	442.01
—	—	Average	14.0	4.13	225.36	437.65	213.65	416.56

Aged SCCRT with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine

Test Number	Test Type	Test Date	Maximum Exhaust Backpressure (kPa)	Maximum Exhaust Backpressure (in. Hg)	Average Device Inlet Temp. (ºC)	Average Device Inlet Temp. (ºF)	Average Device Exhaust Temp. (ºC)	Average Device Exhaust Temp. (ºF)
0469-917-C1	Cold-Start	02/23/11	13.0	3.83	216.63	421.94	168.03	334.46
0469-919-H1	Hot-Start	02/23/11	13.2	3.89	224.33	435.80	214.07	417.32
0469-921-H2	Hot-Start	02/23/11	13.3	3.94	224.55	436.20	216.80	422.24
0469-923-H3	Hot-Start	02/23/11	13.5	3.99	224.90	436.82	218.12	424.62
—	—	Average	13.2	3.91	222.61	432.69	204.26	399.66

Note: in. Hg = inches mercury, kPa = kilopascals.
[a] Baseline tests used the stock DOC; the stock DOC was not used with the SCCRT.

Beginning of table description. Table 6 is titled Engine Exhaust Backpressure and Average Device Inlet/Outlet Temperature during the February 2011 Test Event. The table lists the maximum exhaust backpressure, average device inlet temperature, and average device exhaust temperature for each individual cold-start and hot-start test run for the baseline, degreened, and aged systems. Results are given in both metric and U.S. common units. End of table description.

For March 2010, **Figure 11** shows the inlet temperature over time for the degreened device, and **Figure 12** shows the inlet temperature over time for the aged device. These temperatures were measured by a thermocouple supplied by SwRI. The corresponding February 2011 data are shown in **Figure 13** and **Figure 14**. In all four figures, the hot-start profile is the average of the three hot-start tests.

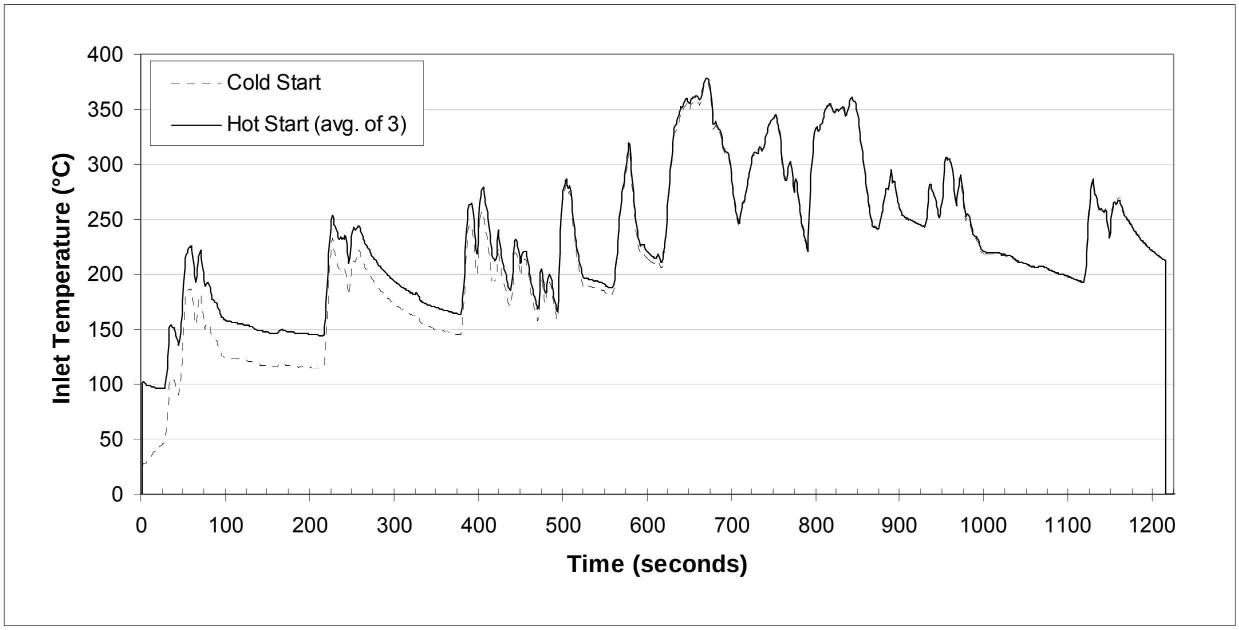

Figure 11. Inlet temperature profile of degreened SCCRT®, v.1 system during March 2010.

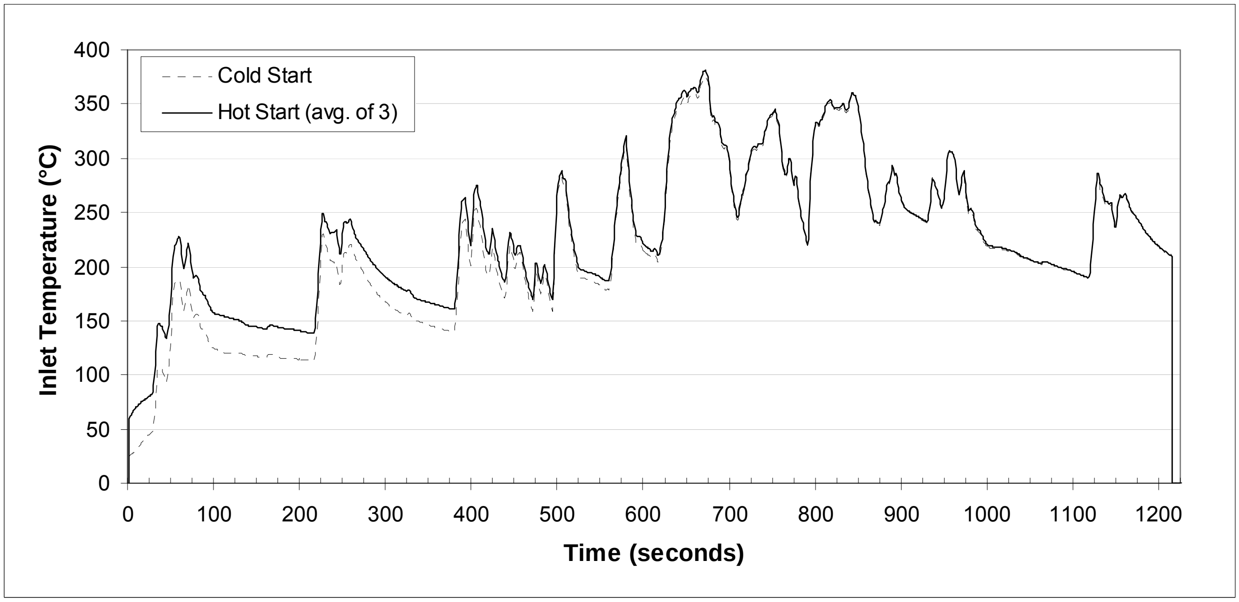

Figure 12. Inlet temperature profile of aged SCCRT®, v.1 system during March 2010.

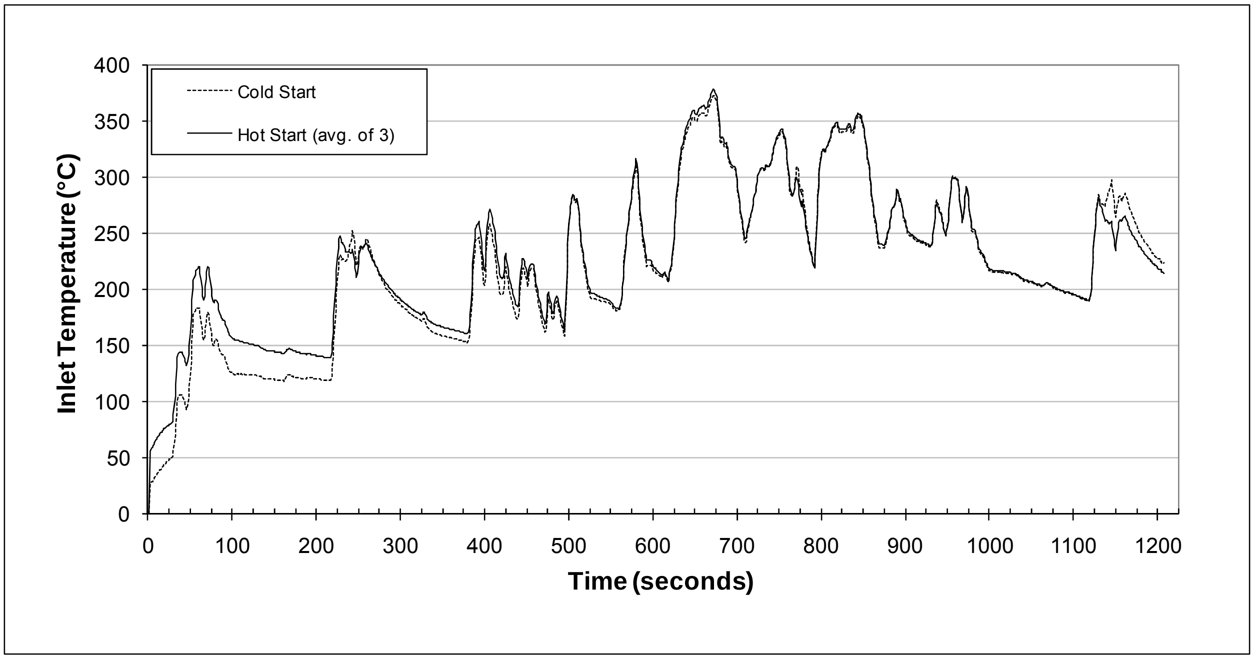

Figure 13. Inlet temperature profile of degreened SCCRT®, v.1 system during February 2011.

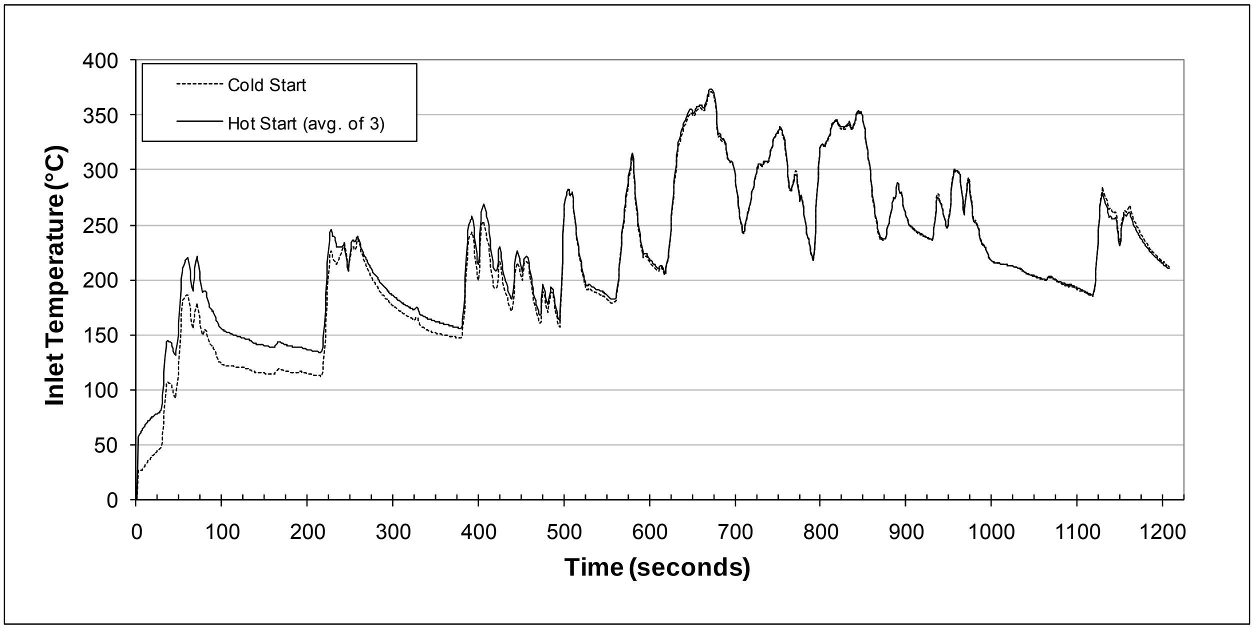

Figure 14. Inlet temperature profile of aged SCCRT®, v.1 system during February 2011.

Soluble Organic Fraction

On each test, the particulate material was tested for SOF. **Table 7** reports the results for March 2010, and **Table 8** reports the results for February 2011. Due to very low PM accumulations with the SCCRT systems, accurate SOF results could not be obtained for the degreened or aged devices.

Table 7. Particulate Characterization—Soluble Organic Fraction from Each Test during March 2010

Baseline with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine

Test Number	Test Type	PM grams	PM % SOF
0469-925-C1	Cold-Start	1.06	12.2
0469-927-H1	Hot-Start	0.855	8.0
0469-929-H2	Hot-Start	0.785	15.1
0469-931-H3	Hot-Start	0.773	13.9
0469-045-ESC	SET	1.36	13.4

Degreened SCCRT with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine

Test Number	Test Type	PM grams	PM % SOF
0469-956-C1	Cold-Start	0.0739	a
0469-958-H1	Hot-Start	0.0452	a
0469-960-H2	Hot-Start	0.0574	a
0469-962-H3	Hot-Start	0.0440	a
0469-972-ESC	SET	0.0610	a

Aged SCCRT with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine

Test Number	Test Type	PM grams	PM % SOF
0469-983-C1	Cold-Start	0.0613	a
0469-985-H1	Hot-Start	0.0316	a
0469-987-H2	Hot-Start	0.0318	a
0469-989-H3	Hot-Start	0.0461	a
0469-041-ESC	SET	0.0651	a

[a] SOF analysis was completed, but the PM sample's accumulation was too low to give accurate results.

Beginning of table description. Table 7 is titled Particulate Characterization—Soluble Organic Fraction from Each Test during March 2010. The table lists the mass of particulate matter emissions in grams and the percent soluble organic fraction from each individual cold-start, hot-start, and SET for the baseline, degreened, and aged systems. End of table description.

Table 8. Particulate Characterization—Soluble Organic Fraction from Each Test during February 2011

Baseline with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine			
Test Number	**Test Type**	**PM grams**	**PM % SOF**
0469-876-C1	Cold-Start	0.908	12.7
0469-878-H1	Hot-Start	0.785	6.4
0469-880-H2	Hot-Start	0.807	13.2
0469-883-H3	Hot-Start	0.781	14.6
0469-870-ESC1	SET	1.22	13.3
Degreened SCCRT with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine			
Test Number	**Test Type**	**PM grams**	**PM % SOF**
0469-897-C1	Cold-Start	0.0720	a
0469-901-H2	Hot-Start	0.0357	a
0469-903-H3	Hot-Start	0.0482	a
0469-905-H4	Hot-Start	0.0489	a
0469-907-ESC1	SET	0.0351	a
Aged SCCRT with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine			
Test Number	**Test Type**	**PM grams**	**PM % SOF**
0469-917-C1	Cold-Start	0.0651	a
0469-919-H1	Hot-Start	0.0712	a
0469-921-H2	Hot-Start	0.0618	a
0469-923-H3	Hot-Start	0.0705	a
0469-933-ESC1	SET	0.0331	a

[a] SOF analysis was completed, but the PM sample's accumulation was too low to give accurate results.

Beginning of table description. Table 8 is titled Particulate Characterization—Soluble Organic Fraction from Each Test during February 2011. The table lists the mass of particulate matter emissions in grams and the percent soluble organic fraction from each individual cold-start, hot-start, and SET for the baseline, degreened, and aged systems. End of table description.

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 CO_2] 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 9** shows the weighted BSFC calculations for the March 2010 test event, while **Table 10** shows those calculations for February 2011. **Table 11** summarizes the results of these calculations and compares the fuel consumption during the baseline runs with that measured during the tests with the SCCRT®, v.1 units installed. The SCCRT systems did not have a substantial effect on fuel consumption.

Table 9. Brake-Specific Fuel Consumption (by Carbon Balance) during March 2010

Baseline with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine

Test Number	Test Type	Test Date	BSFC (lb/bhp-hr)	BSFC (kg/kWhr)	Weighted BSFC (lb/bhp-hr)	Weighted BSFC (kg/kWhr)
0469-925-C1	Cold-Start	3/1/2010	0.430	0.261	—	—
0469-927-H1	Hot-Start	3/1/2010	0.413	0.251	0.416	0.253
0469-929-H2	Hot-Start	3/1/2010	0.415	0.252	0.417	0.253
0469-931-H3	Hot-Start	3/1/2010	0.415	0.252	0.417	0.254
Mean	—	—	—	—	0.417	0.253

Degreened SCCRT with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine

Test Number	Test Type	Test Date	BSFC (lb/bhp-hr)	BSFC (kg/kWhr)	Weighted BSFC (lb/bhp-hr)	Weighted BSFC (kg/kWhr)
0469-958-H1	Hot-Start	3/3/2010	0.420	0.255	0.422	0.257
0469-960-H2	Hot-Start	3/3/2010	0.418	0.254	0.421	0.256
0469-962-H3	Hot-Start	3/3/2010	0.414	0.252	0.417	0.254
Mean	—	—	—	—	0.420	0.255

Aged SCCRT with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine

Test Number	Test Type	Test Date	BSFC (lb/bhp-hr)	BSFC (kg/kWhr)	Weighted BSFC (lb/bhp-hr)	Weighted BSFC (kg/kWhr)
0469-985-H1	Hot-Start	3/5/2010	0.410	0.249	0.412	0.251
0469-987-H2	Hot-Start	3/5/2010	0.408	0.248	0.410	0.249
0469-989-H3	Hot-Start	3/5/2010	0.409	0.249	0.411	0.250
Mean	—	—	—	—	0.411	0.250

Note: lb/bhp-hr = pounds per brake horsepower-hour, kg/kWhr = kilograms per kilowatt hour.

Beginning of table description. Table 9 is titled Brake-Specific Fuel Consumption (by Carbon Balance) during March 2010. The table lists the calculated results for brake-specific fuel consumption for each individual cold-start and hot-start test for the baseline, degreened, and aged systems. The mean weighted brake-specific fuel consumption is also listed for each system. Results are shown in both U.S. common and metric units. End of table description.

Table 10. Brake-Specific Fuel Consumption (by Carbon Balance) during February 2011

Baseline with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine

Test Number	Test Type	Test Date	BSFC (lb/bhp-hr)	BSFC (kg/kWhr)	Weighted BSFC (lb/bhp-hr)	Weighted BSFC (kg/kWhr)
0469-876-C1	Cold-Start	2/16/2011	0.428	0.260	—	—
0469-878-H1	Hot-Start	2/16/2011	0.415	0.252	0.417	0.253
0469-880-H2	Hot-Start	2/16/2011	0.415	0.252	0.417	0.254
0469-883-H3	Hot-Start	2/16/2011	0.414	0.252	0.416	0.253
Mean	—	—	—	—	0.416	0.253

Degreened SCCRT with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine

Test Number	Test Type	Test Date	BSFC (lb/bhp-hr)	BSFC (kg/kWhr)	Weighted BSFC (lb/bhp-hr)	Weighted BSFC (kg/kWhr)
0469-897-C1	Cold-Start	2/18/2011	0.431	0.262	—	—
0469-901-H2	Hot-Start	2/18/2011	0.415	0.252	0.417	0.253
0469-903-H3	Hot-Start	2/18/2011	0.416	0.253	0.419	0.255
0469-905-H4	Hot-Start	2/18/2011	0.417	0.254	0.419	0.255
Mean	—	—	—	—	0.418	0.254

Aged SCCRT with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine

Test Number	Test Type	Test Date	BSFC (lb/bhp-hr)	BSFC (kg/kWhr)	Weighted BSFC (lb/bhp-hr)	Weighted BSFC (kg/kWhr)
0469-917-C1	Cold-Start	2/23/2011	0.421	0.256	—	—
0469-919-H1	Hot-Start	2/23/2011	0.408	0.248	0.409	0.249
0469-921-H2	Hot-Start	2/23/2011	0.411	0.250	0.412	0.251
0469-923-H3	Hot-Start	2/23/2011	0.410	0.249	0.412	0.250
Mean	—	—	—	—	0.411	0.250

Note: lb/bhp-hr = pounds per brake horsepower-hour, kg/kWhr = kilograms per kilowatt hour.

Beginning of table description. Table 10 is titled Brake-Specific Fuel Consumption (by Carbon Balance) during February 2011. The table lists the calculated results for brake-specific fuel consumption for each individual cold-start and hot-start test for the baseline, degreened, and aged systems. The mean weighted brake-specific fuel consumption is also listed for each system. Results are shown in both U.S. common and metric units. End of table description.

Table 11. Summary of Fuel Consumption Reductions

Device Type	Fuel	% Reduction	95% Confidence Limits
March 2010			
Degreened	ULSD	−0.85	a
Aged	ULSD	1.3	0.71 to 2.0
February 2011			
Device Type	**Fuel**	**% Reduction**	**95% Confidence Limits**
Degreened	ULSD	-0.41	a
Aged	ULSD	1.3	0.25 to 2.3

[a] The fuel consumption reduction cannot be distinguished from zero with 95% confidence.

Beginning of table description. Table 11 is titled Summary of Fuel Consumption Reductions. The table lists the percent fuel reduction with ULSD fuel for the degreened and aged systems during the March 2010 and February 2011 test events. 95% confidence limits for the percent reductions are also provided. End of table description.

4.0 Summary and Discussion of Emissions Results

Table 12 (March 2010) and **Table 13** (February 2011) report the emissions from the highway transient FTP tests that were conducted: baseline; with a degreened SCCRT®, v.1 system installed; and with an aged SCCRT®, v.1 system installed. The concentration measurements were converted to units of total grams per test for most species, with CO_2 [kilograms (kg)] and ammonia (NH_3) (ppm) as the exceptions. The work values in units of kilowatt hour (kWhr) and brake horsepower-hour (bhp-hr) are also shown in these tables. The NH_3 levels are an average of the raw exhaust measurements using FTIR. Since the detection limit of NH_3 is 2 ppm, ammonia slip levels less than 2 ppm are considered as detected, but not accurately quantified. Additionally, the PM samples from the highway FTP tests with the SCCRT systems had accumulations too low for accurate SOF analysis.

Table 12. Highway FTP Emissions Data during March 2010

Baseline with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine

Test Number	Test Type	PM (g)	PM (% SOF)	NO_x (g)	NO (g)	NO_2[a] (g)	NO_2/NO_x (%)	HC (g)	CO (g)	CO_2 (kg)	NH_3 (ppm)	Work kWhr (bhp-hr)
0469-925-C1	Cold-Start	1.06	12.2	55.7	54.0	1.67	2.99	1.69	13.6	14.2	<2	17.1 (22.9)
0469-927-H1	Hot-Start	0.855	8.00	48.9	48.0	0.879	1.80	1.54	6.69	13.7	<2	17.2 (23.1)
0469-929-H2	Hot-Start	0.785	15.1	48.8	47.9	0.819	1.68	1.57	6.39	13.8	<2	17.2 (23.0)
0469-931-H3	Hot-Start	0.773	13.9	49.6	48.7	0.872	1.76	1.62	6.63	13.8	<2	17.2 (23.1)

Degreened SCCRT with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine

Test Number	Test Type	PM (g)	PM (% SOF)	NO_x (g)	NO (g)	NO_2[a] (g)	NO_2/NO_x (%)	HC (g)	CO (g)	CO_2 (kg)	NH_3 (ppm)	Work kWhr (bhp-hr)
0469-956-C1	Cold-Start	0.0739	b	37.0	20.6	16.4	44.3	0.0700	3.01	14.4	<2	17.1 (22.9)
0469-958-H1	Hot-Start	0.0452	b	20.9	8.47	12.4	59.4	0.000	0.166	14.0	<2	17.2 (23.1)
0469-960-H2	Hot-Start	0.0574	b	21.2	8.57	12.6	59.6	0.000	0.000	13.9	<2	17.2 (23.1)
0469-962-H3	Hot-Start	0.0440	b	20.6	8.50	12.1	58.7	0.000	0.259	13.8	<2	17.2 (23.0)

Aged SCCRT with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine

Test Number	Test Type	PM (g)	PM (% SOF)	NO_x (g)	NO (g)	NO_2[a] (g)	NO_2/NO_x (%)	HC (g)	CO (g)	CO_2 (kg)	NH_3 (ppm)	Work kWhr (bhp-hr)
0469-983-C1	Cold-Start	0.0613	b	38.3	22.4	16.0	41.7	0.120	4.07	13.9	<2	17.1 (22.9)
0469-985-H1	Hot-Start	0.0316	b	23.1	8.62	14.5	62.7	0.000	0.175	13.6	<2	17.1 (23.0)
0469-987-H2	Hot-Start	0.0318	b	21.4	7.56	13.9	64.7	0.000	0.000	13.6	<2	17.2 (23.1)
0469-989-H3	Hot-Start	0.0461	b	22.7	8.32	14.3	63.2	0.000	0.000	13.6	<2	17.2 (23.1)

Note: g = grams.
[a] NO_2 calculated as NO_x−NO
[b] SOF analysis was completed, but the PM sample's accumulation was too low to give accurate results.

Beginning of table description. Table 12 is titled Highway FTP Emissions Data during March 2010. The table provides the pollutant emissions results from the individual cold-start and hot-start test runs for the baseline, degreened, and aged systems. Results are provided for the following: PM in grams and the PM % soluble organic fraction; NOx, NO, and NO2 in grams; NO2/NOx ratio as a percentage; HC in grams; CO in grams; CO2 in kilograms; NH3 in parts per million; and work in both kilowatt hours and break horsepower-hours. End of table description.

Table 13. Highway FTP Emissions Data during February 2011

Baseline with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine

Test Number	Test Type	PM (g)	PM (% SOF)	NO_x (g)	NO (g)	NO_2[a] (g)	NO_2/NO_x (%)	HC (g)	CO (g)	CO_2 (kg)	NH_3 (ppm)	Work kWhr (bhp-hr)
0469-876-C1	Cold-Start	0.908	12.7	56.6	54.4	2.25	3.97	1.33	9.43	14.2	<2	17.2 (23.0)
0469-878-H1	Hot-Start	0.785	6.4	49.2	47.3	1.94	3.94	1.23	3.29	13.8	<2	17.2 (23.1)
0469-880-H2	Hot-Start	0.807	13.2	49.7	47.7	1.98	3.99	1.34	3.08	13.8	<2	17.2 (23.1)
0469-883-H3	Hot-Start	0.781	14.6	49.2	47.3	1.92	3.91	1.41	3.89	13.8	<2	17.2 (23.1)

Degreened SCCRT with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine

Test Number	Test Type	PM (g)	PM (% SOF)	NO_x (g)	NO (g)	NO_2[a] (g)	NO_2/NO_x (%)	HC (g)	CO (g)	CO_2 (kg)	NH_3 (ppm)	Work kWhr (bhp-hr)
0469-897-C1	Cold-Start	0.0720	b	28.5	19.5	9.04	31.7	0.0940	3.02	14.3	<2	17.1 (23.0)
0469-901-H2	Hot-Start	0.0357	b	10.9	5.78	5.12	47.0	0.0530	0.000	13.8	<2	17.2 (23.0)
0469-903-H3	Hot-Start	0.0482	b	10.6	5.69	4.94	46.5	0.123	0.000	13.9	<2	17.2 (23.0)
0469-905-H4	Hot-Start	0.0489	b	10.1	5.30	4.80	47.5	0.0770	0.000	13.9	<2	17.2 (23.1)

Aged SCCRT with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine

Test Number	Test Type	PM (g)	PM (% SOF)	NO_x (g)	NO (g)	NO_2[a] (g)	NO_2/NO_x (%)	HC (g)	CO (g)	CO_2 (kg)	NH_3 (ppm)	Work kWhr (bhp-hr)
0469-917-C1	Cold-Start	0.0651	b	29.0	20.1	8.87	30.6	0.131	4.05	13.9	<2	17.1 (23.0)
0469-919-H1	Hot-Start	0.0712	b	12.7	5.89	6.84	53.7	0.116	0.000	13.5	<2	17.2 (23.0)
0469-921-H2	Hot-Start	0.0618	b	11.2	5.09	6.09	54.5	0.0870	0.000	13.7	<2	17.2 (23.0)
0469-923-H3	Hot-Start	0.0705	b	10.6	4.20	6.42	60.5	0.143	0.000	13.7	<2	17.2 (23.1)

Note: g = grams.
[a] NO_2 calculated as $NO_x - NO$
[b] SOF analysis was completed, but the PM sample's accumulation was too low to give accurate results.

Beginning of table description. Table 13 is titled Highway FTP Emissions Data during February 2011. The table provides the pollutant emissions results from the individual cold-start and hot-start test runs for the baseline, degreened, and aged systems. Results are provided for the following: PM in grams and the PM % soluble organic fraction; NOx, NO, and NO2 in grams; NO2/NOx ratio as a percentage; HC in grams; CO in grams; CO2 in kilograms; NH3 in parts per million; and work in both kilowatt hours and break horsepower-hours. End of table description.

Table 14 (March 2010) and **Table 15** (February 2011) report the emissions from the SET tests that were conducted: baseline; with a degreened SCCRT®, v.1 system installed; and with an aged SCCRT®, v.1 system installed.

Table 14. Multimode SET Results during March 2010

Test Number: 0469-045-ESC (Baseline)

Mode	Target %	Weight	PM (g)	NO_x (g)	NO (g)	NO_2[a] (g)	HC (g)	CO (g)	CO_2 (kg)	NH_3 (ppm)	Work kWhr (bhp-hr)
1	(idle)	0.15	1.36	0.743	0.271	0.471	0.000	0.000	0.168	<2	0.0902 (0.121)
2	100	0.08	1.36	11.2	10.4	0.788	0.0406	0.168	3.44	<2	4.65 (6.24)
3	50	0.10	1.36	7.96	7.55	0.415	0.0693	0.109	2.65	<2	3.43 (4.60)
4	75	0.10	1.36	11.8	11.5	0.331	0.0880	0.195	3.79	<2	5.19 (6.96)
5	50	0.05	1.36	3.70	3.32	0.381	0.00556	0.0264	1.04	<2	1.44 (1.93)
6	75	0.05	1.36	4.91	4.58	0.325	0.0129	0.0708	1.56	<2	2.18 (2.93)
7	25	0.05	1.36	2.11	1.79	0.318	0.000	0.0084	0.560	<2	0.708 (0.95)
8	100	0.09	1.36	18.3	17.5	0.880	0.0794	0.308	4.36	<2	6.37 (8.54)
9	25	0.10	1.36	5.78	5.44	0.336	0.0392	0.0611	1.55	<2	1.71 (2.29)
10	100	0.08	1.36	15.2	14.3	0.867	0.0945	0.376	4.03	<2	5.47 (7.34)
11	25	0.05	1.36	3.58	3.51	0.0683	0.0680	0.070	0.853	<2	0.850 (1.14)
12	75	0.05	1.36	7.66	7.53	0.130	0.0841	0.130	1.94	<2	2.53 (3.39)
13	50	0.05	1.36	4.91	4.81	0.103	0.0753	0.086	1.38	<2	1.68 (2.25)

Test Number: 0469-972-ESC (Degreened)

Mode	Target %	Weight	PM (g)	NO_x (g)	NO (g)	NO_2[a] (g)	HC (g)	CO (g)	CO_2 (kg)	NH_3 (ppm)	Work kWhr (bhp-hr)
1	(idle)	0.15	0.0610	0.054	0.000	0.0543	0.000	0.000	0.186	<2	0.0746 (0.100)
2	100	0.08	0.0610	3.33	1.84	1.49	0.000	0.0512	3.45	<2	4.57 (6.13)
3	50	0.10	0.0610	2.69	1.22	1.46	0.000	0.0279	2.74	<2	3.47 (4.66)
4	75	0.10	0.0610	5.25	2.40	2.84	0.000	0.0790	3.91	<2	5.27 (7.07)
5	50	0.05	0.0610	1.25	0.479	0.771	0.000	0.0182	1.08	<2	1.46 (1.96)
6	75	0.05	0.0610	2.11	1.06	1.05	0.000	0.0322	1.59	<2	2.18 (2.93)
7	25	0.05	0.0610	0.768	0.313	0.454	0.000988	0.00988	0.592	<2	0.730 (0.98)
8	100	0.09	0.0610	10.7	6.97	3.72	0.00276	0.126	4.35	<2	6.29 (8.43)
9	25	0.10	0.0610	2.12	0.970	1.15	0.000	0.0419	1.60	<2	1.74 (2.34)
10	100	0.08	0.0610	10.0	6.64	3.40	0.000	0.0737	4.06	<2	5.48 (7.35)
11	25	0.05	0.0610	1.38	0.606	0.777	0.000	0.0140	0.887	<2	0.850 (1.14)
12	75	0.05	0.0610	3.30	1.23	2.07	0.000	0.0422	1.98	<2	2.55 (3.42)
13	50	0.05	0.0610	2.03	0.601	1.43	0.000	0.0196	1.41	<2	1.69 (2.27)

Table 14. Multimode SET Results during March 2010 (continued)

Test Number: 0469-041-ESC (Aged)

Mode	Target %	Weight	PM (g)	NO_x (g)	NO (g)	NO_2[a] (g)	HC (g)	CO (g)	CO_2 (kg)	NH_3 (ppm)	Work kWhr (bhp-hr)
1	(idle)	0.15	0.0651	0.288	0.167	0.121	0.000	0.000	0.192	<2	0.0805 (0.108)
2	100	0.08	0.0651	1.06	0.689	0.373	0.000	0.0356	3.34	<2	4.53 (6.08)
3	50	0.10	0.0651	1.65	0.793	0.854	0.000	0.0223	2.69	<2	3.46 (4.64)
4	75	0.10	0.0651	2.29	0.991	1.30	0.000	0.0334	3.78	<2	5.21 (6.99)
5	50	0.05	0.0651	0.595	0.241	0.354	0.000	0.0112	1.05	<2	1.45 (1.95)
6	75	0.05	0.0651	0.630	0.322	0.308	0.000	0.0153	1.56	<2	2.18 (2.92)
7	25	0.05	0.0651	0.501	0.219	0.282	0.000	0.0000	0.583	<2	0.724 (0.97)
8	100	0.09	0.0651	3.91	2.59	1.32	0.000	0.0601	4.22	<2	6.24 (8.37)
9	25	0.10	0.0651	2.60	1.23	1.36	0.000	0.0111	1.58	<2	1.72 (2.30)
10	100	0.08	0.0651	4.40	2.88	1.53	0.000	0.0757	3.91	<2	5.41 (7.25)
11	25	0.05	0.0651	1.79	0.697	1.09	0.000	0.0292	0.865	<2	0.835 (1.12)
12	75	0.05	0.0651	1.97	0.584	1.38	0.000	0.0600	1.94	<2	2.55 (3.42)
13	50	0.05	0.0651	1.66	0.441	1.21	0.000	0.0544	1.38	<2	1.69 (2.26)

Note: g = grams.
[a] NO_2 calculated as $NO_x - NO$

Beginning of table description. Table 14 is titled Multimode SET Results during March 2010. The table provides the pollutant emissions results from the thirteen individual test modes of the supplemental emissions test for the baseline, degreened, and aged systems. Results are provided for the following: PM, NOx, NO, NO2, HC, and CO in grams; CO2 in kilograms; NH3 in parts per million; and work in both kilowatt hours and break horsepower-hours. End of table description.

Table 15. Multimode SET Results during February 2011

Test Number: 0469-870-ESC1 (Baseline)

Mode	Target %	Weight	PM (g)	NO_x(g)	NO (g)	NO_2[a] (g)	HC (g)	CO (g)	CO_2 (kg)	NH_3 (ppm)	Work kWhr (bhp-hr)
1	(idle)	0.15	1.22	0.831	0.434	0.397	0.000835	0.000	0.118	<2	0.0218 (0.0292)
2	100	0.08	1.22	10.1	9.31	0.834	0.0513	0.125	3.48	<2	4.76 (6.38)
3	50	0.10	1.22	8.07	7.48	0.588	0.0847	0.000	2.67	<2	3.55 (4.76)
4	75	0.10	1.22	12.5	11.8	0.695	0.116	0.0556	3.81	<2	5.28 (7.08)
5	50	0.05	1.22	3.91	3.46	0.454	0.0218	0.000	1.05	<2	1.49 (2.00)
6	75	0.05	1.22	4.52	4.14	0.381	0.0249	0.0333	1.59	<2	2.24 (3.00)
7	25	0.05	1.22	2.11	1.77	0.331	0.0102	0.000	0.573	<2	0.746 (1.00)
8	100	0.09	1.22	17.2	16.2	1.06	0.103	0.208	4.34	<2	6.37 (8.54)
9	25	0.10	1.22	5.66	5.18	0.475	0.0692	0.000	1.52	<2	1.77 (2.38)
10	100	0.08	1.22	16.7	15.5	1.18	0.119	0.314	4.07	<2	5.56 (7.46)
11	25	0.05	1.22	3.55	3.33	0.220	0.0689	0.000	0.815	<2	0.865 (1.16)
12	75	0.05	1.22	7.80	7.45	0.347	0.0882	0.0738	1.94	<2	2.59 (3.47)
13	50	0.05	1.22	4.93	4.68	0.253	0.0771	0.0390	1.39	<2	1.73 (2.32)

Test Number: 0469-907-ESC1 (Degreened)

Mode	Target %	Weight	PM (g)	NO_x(g)	NO (g)	NO_2[a] (g)	HC (g)	CO (g)	CO_2 (kg)	NH_3 (ppm)	Work kWhr (bhp-hr)
1	(idle)	0.15	0.0351	0.125	0.0250	0.100	0.0158	0.000	0.126	<2	0.0062 (0.0083)
2	100	0.08	0.0351	0.311	0.173	0.138	0.000	0.0133	3.42	<2	4.67 (6.26)
3	50	0.10	0.0351	1.01	0.562	0.448	0.000	0.0529	2.68	<2	3.52 (4.72)
4	75	0.10	0.0351	0.607	0.303	0.303	0.000	0.0585	3.80	<2	5.29 (7.09)
5	50	0.05	0.0351	0.223	0.110	0.113	0.000	0.0265	1.06	<2	1.48 (1.99)
6	75	0.05	0.0351	0.434	0.259	0.174	0.000	0.0279	1.57	<2	2.23 (2.99)
7	25	0.05	0.0351	0.498	0.238	0.259	0.000	0.000	0.578	<2	0.738 (0.99)
8	100	0.09	0.0351	2.11	1.51	0.601	0.000	0.0576	4.26	<2	6.30 (8.45)
9	25	0.10	0.0351	1.12	0.576	0.548	0.000	0.0111	1.57	<2	1.76 (2.36)
10	100	0.08	0.0351	2.11	1.50	0.615	0.000	0.0468	4.00	<2	5.50 (7.38)
11	25	0.05	0.0351	0.650	0.337	0.312	0.000	0.00279	0.854	<2	0.858 (1.15)
12	75	0.05	0.0351	0.540	0.188	0.351	0.000	0.0279	1.94	<2	2.58 (3.46)
13	50	0.05	0.0351	0.600	0.245	0.354	0.000	0.0237	1.39	<2	1.72 (2.30)

Table 15. Multimode SET Results during February 2011 (continued)

Test Number: 0469-933-ESC1 (Aged)

Mode	Target %	Weight	PM (g)	NO_x(g)	NO (g)	NO_2[a] (g)	HC (g)	CO (g)	CO_2 (kg)	NH_3 (ppm)	Work kWhr (bhp-hr)
1	(idle)	0.15	0.0331	0.0834	0.000	0.0834	0.00626	0.000	0.206	<2	0.1860 (0.2500)
2	100	0.08	0.0331	0.902	0.608	0.294	0.000	0.00223	3.41	<2	4.66 (6.25)
3	50	0.10	0.0331	1.41	0.696	0.710	0.000	0.000	2.69	<2	3.53 (4.74)
4	75	0.10	0.0331	1.87	0.913	0.960	0.000	0.000	3.79	<2	5.29 (7.09)
5	50	0.05	0.0331	0.480	0.208	0.272	0.0209	0.000	1.07	<2	1.49 (2.00)
6	75	0.05	0.0331	0.674	0.404	0.269	0.0137	0.000	1.60	<2	2.24 (3.00)
7	25	0.05	0.0331	0.452	0.188	0.264	0.00251	0.000	0.590	<2	0.753 (1.01)
8	100	0.09	0.0331	2.85	1.99	0.859	0.000	0.000	4.24	<2	6.29 (8.43)
9	25	0.10	0.0331	1.84	0.857	0.983	0.000	0.000	1.57	<2	1.76 (2.36)
10	100	0.08	0.0331	3.45	2.33	1.12	0.000	0.000	3.96	<2	5.49 (7.36)
11	25	0.05	0.0331	1.48	0.661	0.814	0.000	0.000	0.851	<2	0.865 (1.16)
12	75	0.05	0.0331	1.38	0.534	0.848	0.000	0.000	1.92	<2	2.57 (3.45)
13	50	0.05	0.0331	1.25	0.442	0.803	0.000	0.000	1.39	<2	1.73 (2.32)

Note: g = grams.
[a] NO_2 calculated as NO_x−NO

Beginning of table description. Table 15 is titled Multimode SET Results during February 2011. The table provides the pollutant emissions results from the thirteen individual test modes of the supplemental emissions test for the baseline, degreened, and aged systems. Results are provided for the following: PM, NOx, NO, NO2, HC, and CO in grams; CO2 in kilograms; NH3 in parts per million; and work in both kilowatt hours and break horsepower-hours. End of table description.

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

$$(E_{COMP})_m = \frac{\frac{1}{7} \bullet E_{COLD} + \frac{6}{7} \bullet (E_{HOT})_m}{\frac{1}{7} \bullet W_{COLD} + \frac{6}{7} \bullet (W_{HOT})_m} \qquad \text{(Eq. 1)}$$

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

A weighted emissions rate for each pollutant in the SET test was calculated as follows:

$$E_{SET} = \sum_{j=1}^{k} f_j \bullet E_{MODE_j} \tag{Eq. 2}$$

where

E_{SET} = weighted emissions rate for the SET test
f_i = mode weighting factor from 40 CFR 86.1360-2007[12] for j^{th} mode
E_{MODEj} = pollutant emissions rate during j^{th} mode
k = total number of modes for intended application[12]

The composite emissions rates from the highway transient FTP are then combined with the weighted emissions rate from the SET test to result in a combined emission rate as follows:

$$E_i = 0.85 \bullet (E_{COMP})_i + 0.15 \bullet E_{SET} \tag{Eq. 3}$$

for i = 1 to n tests required at the test point (n = 3 for this verification).

These combined emissions rates are shown in **Table 16** and **Table 17** for the March 2010 test event and in **Table 18** and **Table 19** for the February 2011 test event 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[1] and test/QA plan addenda.[2,3]

Table 16. Combined Emissions Rates (U.S. Common Units) during March 2010

Baseline with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine

Test	Exhaust PM (g/bhp-hr)	NO_x (g/bhp-hr)	NO (g/bhp-hr)	NO_2[a] (g/bhp-hr)	NO_2/NO_x (%)	HC (g/bhp-hr)	CO (g/bhp-hr)	CO_2 (g/bhp-hr)
Hot-Start #1	0.0368	2.14	2.09	0.0532	2.51	0.0594	0.288	593
Hot-Start #2	0.0347	2.14	2.09	0.0514	2.43	0.0608	0.279	595
Hot-Start #3	0.0342	2.16	2.11	0.0530	2.48	0.0620	0.286	596

Degreened SCCRT with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine

Test	Exhaust PM (g/bhp-hr)	NO_x (g/bhp-hr)	NO (g/bhp-hr)	NO_2[a] (g/bhp-hr)	NO_2/NO_x (%)	HC (g/bhp-hr)	CO (g/bhp-hr)	CO_2 (g/bhp-hr)
Hot-Start #1	0.00200	0.993	0.451	0.542	54.5	0.000369	0.0228	604
Hot-Start #2	0.00239	1.00	0.455	0.550	54.6	0.000369	0.0175	602
Hot-Start #3	0.00197	0.985	0.453	0.532	53.9	0.000369	0.0257	598

Aged SCCRT with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine

Test	Exhaust PM (g/bhp-hr)	NO_x (g/bhp-hr)	NO (g/bhp-hr)	NO_2[a] (g/bhp-hr)	NO_2/NO_x (%)	HC (g/bhp-hr)	CO (g/bhp-hr)	CO_2 (g/bhp-hr)
Hot-Start #1	0.00153	1.01	0.428	0.580	56.8	0.000634	0.0283	589
Hot-Start #2	0.00153	0.952	0.394	0.558	57.9	0.000633	0.0227	587
Hot-Start #3	0.00198	0.991	0.418	0.573	57.1	0.000633	0.0227	588

[a] NO_2 calculated as NO_x−NO.

Beginning of table description. Table 16 is titled Combined Emissions Rates (U.S. Common Units) during March 2010. The table provides the combined emissions rates for each individual hot-start test of the baseline, degreened, and aged systems. Results are provided for the following: exhaust PM, NOx, NO, and NO2 in grams per brake horsepower-hour; the NO2/NOx ratio as a percentage; and HC, CO, and CO2 in grams per brake horsepower-hour. End of table description.

Table 17. Combined Emissions Rates (Metric Units) during March 2010

Baseline with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine

Test	Exhaust PM (g/kWhr)	NO_x (g/kWhr)	NO (g/kWhr)	NO_2[a] (g/kWhr)	NO_2/NO_x (%)	HC (g/kWhr)	CO (g/kWhr)	CO_2 (g/kWhr)
Hot-Start #1	0.0493	2.87	2.803	0.0713	2.51	0.0797	0.386	795
Hot-Start #2	0.0465	2.87	2.803	0.0689	2.43	0.0815	0.374	798
Hot-Start #3	0.0459	2.90	2.830	0.0711	2.48	0.0831	0.384	799

Degreened SCCRT with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine

Test	Exhaust PM (g/kWhr)	NO_x (g/kWhr)	NO (g/kWhr)	NO_2[a] (g/kWhr)	NO_2/NO_x (%)	HC (g/kWhr)	CO (g/kWhr)	CO_2 (g/kWhr)
Hot-Start #1	0.00268	1.33	0.605	0.727	54.5	0.000495	0.0306	810
Hot-Start #2	0.00321	1.34	0.610	0.738	54.6	0.000495	0.0235	807
Hot-Start #3	0.00264	1.32	0.607	0.713	53.9	0.000495	0.0345	802

Aged SCCRT with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine

Test	Exhaust PM (g/kWhr)	NO_x (g/kWhr)	NO (g/kWhr)	NO_2[a] (g/kWhr)	NO_2/NO_x (%)	HC (g/kWhr)	CO (g/kWhr)	CO_2 (g/kWhr)
Hot-Start #1	0.00205	1.35	0.574	0.778	56.8	0.000850	0.0380	790
Hot-Start #2	0.00205	1.28	0.528	0.748	57.9	0.000849	0.0304	787
Hot-Start #3	0.00266	1.33	0.561	0.768	57.1	0.000849	0.0304	789

Note: g/kWhr = grams per kilowatt-hour.
[a] NO_2 calculated as NO_x-NO

Beginning of table description. Table 17 is titled Combined Emissions Rates (Metric Units) during March 2010. The table provides the combined emissions rates for each individual hot-start test of the baseline, degreened, and aged systems. Results are provided for the following: exhaust PM, NOx, NO, and NO2 in grams per kilowatt hour; the NO2/NOx ratio as a percentage; and HC, CO, and CO2 in grams per kilowatt hour. End of table description.

Table 18. Combined Emissions Rates (U.S. Common Units) during February 2011

Baseline with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine

Test	Exhaust PM (g/bhp-hr)	NO_x (g/bhp-hr)	NO (g/bhp-hr)	NO_2[a] (g/bhp-hr)	NO_2/NO_x (%)	HC (g/bhp-hr)	CO (g/bhp-hr)	CO_2 (g/bhp-hr)
Hot-Start #1	0.0332	2.15	2.05	0.0948	4.46	0.0483	0.156	593
Hot-Start #2	0.0339	2.16	2.07	0.0961	4.50	0.0517	0.149	594
Hot-Start #3	0.0331	2.15	2.05	0.0943	4.44	0.0542	0.175	592

Degreened SCCRT with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine

Test	Exhaust PM (g/bhp-hr)	NO_x (g/bhp-hr)	NO (g/bhp-hr)	NO_2[a] (g/bhp-hr)	NO_2/NO_x (%)	HC (g/bhp-hr)	CO (g/bhp-hr)	CO_2 (g/bhp-hr)
Hot-Start #1	0.00162	0.527	0.304	0.223	42.3	0.00217	0.0170	595
Hot-Start #2	0.00201	0.518	0.301	0.217	41.9	0.00439	0.0170	597
Hot-Start #3	0.00203	0.501	0.289	0.213	42.3	0.00293	0.0170	597

Aged SCCRT with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine

Test	Exhaust PM (g/bhp-hr)	NO_x (g/bhp-hr)	NO (g/bhp-hr)	NO_2[a] (g/bhp-hr)	NO_2/NO_x (%)	HC (g/bhp-hr)	CO (g/bhp-hr)	CO_2 (g/bhp-hr)
Hot-Start #1	0.00270	0.611	0.323	0.289	47.1	0.00436	0.0214	585
Hot-Start #2	0.00240	0.561	0.297	0.265	47.0	0.00344	0.0213	588
Hot-Start #3	0.00267	0.543	0.269	0.275	50.3	0.00521	0.0213	588

[a] NO_2 calculated as NO_x−NO.

Beginning of table description. Table 18 is titled Combined Emissions Rates (U.S. Common Units) during February 2011. The table provides the combined emissions rates for each individual hot-start test of the baseline, degreened, and aged systems. Results are provided for the following: exhaust PM, NOx, NO, and NO2 in grams per brake horsepower-hour; the NO2/NOx ratio as a percentage; and HC, CO, and CO2 in grams per brake horsepower-hour. End of table description.

Table 19. Combined Emissions Rates (Metric Units) during February 2011

Baseline with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine

Test	Exhaust PM (g/kWhr)	NO_x (g/kWhr)	NO (g/kWhr)	NO_2[a] (g/kWhr)	NO_2/NO_x (%)	HC (g/kWhr)	CO (g/kWhr)	CO_2 (g/kWhr)
Hot-Start #1	0.0445	2.88	2.749	0.127	4.46	0.0648	0.209	795
Hot-Start #2	0.0455	2.90	2.776	0.129	4.50	0.0693	0.200	797
Hot-Start #3	0.0444	2.88	2.749	0.126	4.44	0.0727	0.235	794

Degreened SCCRT with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine

Test	Exhaust PM (g/kWhr)	NO_x (g/kWhr)	NO (g/kWhr)	NO_2[a] (g/kWhr)	NO_2/NO_x (%)	HC (g/kWhr)	CO (g/kWhr)	CO_2 (g/kWhr)
Hot-Start #1	0.00217	0.707	0.408	0.299	42.3	0.00291	0.0228	798
Hot-Start #2	0.00270	0.695	0.404	0.291	41.9	0.00589	0.0228	801
Hot-Start #3	0.00272	0.672	0.388	0.286	42.3	0.00393	0.0228	801

Aged SCCRT with ULSD Fuel on a 2006 Cummins ISM 330 Test Engine

Test	Exhaust PM (g/kWhr)	NO_x (g/kWhr)	NO (g/kWhr)	NO_2[a] (g/kWhr)	NO_2/NO_x (%)	HC (g/kWhr)	CO (g/kWhr)	CO_2 (g/kWhr)
Hot-Start #1	0.00362	0.819	0.433	0.388	47.1	0.00585	0.0287	784
Hot-Start #2	0.00322	0.752	0.398	0.355	47.0	0.00461	0.0286	789
Hot-Start #3	0.00358	0.728	0.361	0.369	50.3	0.00699	0.0286	789

Note: g/kWhr = grams per kilowatt-hour.
[a] NO_2 calculated as $NO_x - NO$

Beginning of table description. Table 19 is titled Combined Emissions Rates (Metric Units) during February 2011. The table provides the combined emissions rates for each individual hot-start test of the baseline, degreened, and aged systems. Results are provided for the following: exhaust PM, NOx, NO, and NO2 in grams per kilowatt hour; the NO2/NOx ratio as a percentage; and HC, CO, and CO2 in grams per kilowatt hour. End of table description.

The mean combined emission rates for both test events presented below in **Table 20** and **Table 21** 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 4 threshold.

Table 20. Summary of Verification Test Data (U.S. Common Units)

March 2010

Device Type	Fuel	PM Mean Combined Emission Rate (g/bhp-hr)	NO_x Mean Combined Emission Rate (g/bhp-hr)	NO Mean Combined Emission Rate (g/bhp-hr)	NO_2[a] Mean Combined Emission Rate (g/bhp-hr)	HC Mean Combined Emission Rate (g/bhp-hr)	CO Mean Combined Emission Rate (g/bhp-hr)	CO_2 Mean Combined Emission Rate (g/bhp-hr)
Baseline	ULSD	0.0352	2.15	2.09	0.0525	0.0607	0.284	595
Degreened	ULSD	0.00212	0.994	0.453	0.541	0.000369	0.0220	601
Aged	ULSD	0.00168	0.984	0.413	0.570	0.000633	0.0246	588

February 2011

Device Type	Fuel	PM Mean Combined Emission Rate (g/bhp-hr)	NO_x Mean Combined Emission Rate (g/bhp-hr)	NO Mean Combined Emission Rate (g/bhp-hr)	NO_2[a] Mean Combined Emission Rate (g/bhp-hr)	HC Mean Combined Emission Rate (g/bhp-hr)	CO Mean Combined Emission Rate (g/bhp-hr)	CO_2 Mean Combined Emission Rate (g/bhp-hr)
Baseline	ULSD	0.0334	2.15	2.06	0.0951	0.0514	0.160	593
Degreened	ULSD	0.00189	0.516	0.298	0.218	0.00316	0.0170	596
Aged	ULSD	0.00259	0.572	0.296	0.276	0.00434	0.0213	587

[a] NO_2 calculated as NO_x−NO

Beginning of table description. Table 20 is titled Summary of Verification Test Data (U.S. Common Units). The table lists the mean combined emission rates for the baseline, degreened, and aged systems during both the March 2010 and February 2011 test events. Results are provided for PM, NOx, NO, NO2, HC, CO, and CO2 in grams per brake horsepower-hour. End of table description.

Table 21. Summary of Verification Test Data (Metric Units)

Device Type	Fuel	PM Mean Combined Emission Rate (g/kWhr)	NO_x Mean Combined Emission Rate (g/kWhr)	NO Mean Combined Emission Rate (g/kWhr)	NO_2[a] Mean Combined Emission Rate (g/kWhr)	HC Mean Combined Emission Rate (g/kWhr)	CO Mean Combined Emission Rate (g/kWhr)	CO_2 Mean Combined Emission Rate (g/kWhr)
March 2010								
Baseline	ULSD	0.0472	2.88	2.81	0.0704	0.0814	0.381	797
Degreened	ULSD	0.00285	1.33	0.608	0.726	0.000495	0.0295	806
Aged	ULSD	0.00225	1.32	0.554	0.765	0.000849	0.0330	789
February 2011								
Baseline	ULSD	0.0448	2.89	2.76	0.128	0.0689	0.215	796
Degreened	ULSD	0.00253	0.691	0.400	0.292	0.00424	0.0227	800
Aged	ULSD	0.00347	0.767	0.397	0.370	0.00582	0.0286	788

[a] NO_2 calculated as NO_x−NO
Note: g/kWhr = grams per kilowatt-hour.

Beginning of table description. Table 21 is titled Summary of Verification Test Data (Metric Units). The table lists the mean combined emission rates for the baseline, degreened, and aged systems during both the March 2010 and February 2011 test events. Results are provided for PM, NOx, NO, NO2, HC, CO, and CO2 in grams per kilowatt hour. End of table description.

The combined emission rates were also used to calculate the average incremental increase in NO_2 according to the formula specified by the California Code of Regulations: [13]

$$\%\ Increase = 100\% \times 0.5 \times \left[\left(NO_2^{\ i} - NO_2^{\ b} \right) + \left(NO_2^{\ f} - NO_2^{\ b} \right) \right] / NO_x^{\ b} \qquad \text{(Eq. 4)}$$

Where the superscripts *i*, *b*, and *f* represent the initial test (degreened device), final test (aged device), and baseline test, respectively. For the March 2010 test, the average incremental increase in NO_2 was 23.4%, while this value was 7.0% for the February 2011 test. The large incremental increase from the 2010 test can be accounted for by improper SCCRT operation to the obsolete thermocouple and housing design.

Table 22 summarizes the emissions reductions that were achieved by the use of the SCCRT®, v.1 system. The February 2011 results are the "verified emissions reductions" reported in Table 2 of the ETV Joint Verification Statement.

Table 22. Summary of Verification Test Emissions Reductions

March 2010

System Type	Fuel	PM Mean Emissions Reduction (%)	NO_x Mean Emissions Reduction (%)	HC Mean Emissions Reduction (%)	CO Mean Emissions Reduction (%)	PM 95% Confidence Limits on the Emissions Reduction (%)	NO_x 95% Confidence Limits on the Emissions Reduction (%)	HC 95% Confidence Limits on the Emissions Reduction (%)	CO 95% Confidence Limits on the Emissions Reduction (%)
Degreened	ULSD	94	54	99	92	84 to [a]	52 to 55	94 to [a]	88 to 96
Aged	ULSD	95	54	99	91	86 to [a]	53 to 56	94 to [a]	87 to 95

February 2011

System Type	Fuel	PM Mean Emissions Reduction (%)	NO_x Mean Emissions Reduction (%)	HC Mean Emissions Reduction (%)	CO Mean Emissions Reduction (%)	PM 95% Confidence Limits on the Emissions Reduction (%)	NO_x 95% Confidence Limits on the Emissions Reduction (%)	HC 95% Confidence Limits on the Emissions Reduction (%)	CO 95% Confidence Limits on the Emissions Reduction (%)
Degreened	ULSD	94	76	94	89	91 to 98	75 to 77	80 to [a]	69 to [a]
Aged	ULSD	92	73	92	87	89 to 95	72 to 74	77 to [a]	66 to [a]

[a] The upper limit of the emissions reduction could not be distinguished from 100% with 95% confidence.

Beginning of table description. Table 22 is titled Summary of Verification Test Emissions Reductions. The table describes the emissions reduction percentages from the verification tests of the degreened and aged systems during both March 2010 and February 2011. Results are presented for particulate matter, nitrogen oxides, hydrocarbons, and carbon monoxide. 95% confidence limits for these reductions are also listed. End of table description.

In summary, the SCCRT systems reduced HC, CO, PM, and NO_x emissions. In comparing the aged to degreened results, the 95% confidence limits for the percent reduction of PM, HC, and CO overlapped each other, while a very slight degradation in NOx reduction performance was measured for the aged system relative to the degreened system. The effect of the obsolete thermocouple and housing from the March 2010 test is apparent in the poorer NO_x reduction and higher incremental increase in NO_2 relative to the February 2011 test. Ammonia slip levels, measured in the exhaust downstream of the SCCRT, were less than 2 ppm for each emissions test. With the SCCRT system in place, the soluble organic fraction of the PM emissions was too low to quantify. The SCCRT systems did not have a significant effect on fuel consumption or CO_2 emissions.

4.1 Quality Assurance

The ETV of the SCCRT®, v.1 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.[2, 3] An internal audit of data quality conducted by SwRI personnel[6, 7] 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[8] 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. RTI QA staff conducted an audit of SwRI's technical systems in March 2010 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

1. RTI International. 2003. *Generic Verification Protocol for Determination of Emissions Reductions from Selective Catalytic Reduction Control Technologies for Highway, Non-Road, and Stationary Use Diesel Engines.* Research Triangle Park, NC, September. Available at: http://www.epa.gov/etv/pubs/05_vp_emissions.pdf (accessed April 19, 2011).
2. RTI International. 2008. *Test-Specific Addendum to ETV SCR Test/QA Plan for Johnson Matthey for the SCCRT v.1 System.* Research Triangle Park, NC, June 2009 (revised July 2009).
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